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A Coupled Thermal-Hydraulic-Electromagnetic Network Approach for Three-Dimensional Hotspot Calculation of Transformers

Ali Al-Abadi, Wei Wu, Irene Woyna

Summary **—Accurate hotspot prediction is essential for ensuring the reliability and lifetime of transformers. This paper presents a coupled thermal-hydraulic and thermal network model for predicting temperature distribution within transformer windings. The methodology incorporates non-uniform loss distributions obtained from electromagnetic simulations and represents heat transfer through interconnected conductor and insulation nodes. By coupling winding thermal behaviour with oil flow and cooling performance, the model captures both radial and axial temperature gradients and identifies hotspot locations with high accuracy. Validation against heat-run test measurements from a 630 kVA ester-filled distribution transformer equipped with fibre-optic sensors shows good agreement for both LV and HV windings. The proposed approach provides a computationally efficient and accurate tool for transformer thermal design, hotspot assessment, and cooling optimization.**

Keywords **— Transformer, temperature distribution, thermal network, winding hotspot.**

I. Introduction

Transformers temperature rises are important factors in the design and operation of distribution and power transformers. They affect the efficiency, reliability and lifespan of a transformer unit. In particular, hotspots within transformer windings can cause significant issues, including increased local temperatures, reduced insulation life, and even equipment failure. The primary reason for these issues is that transformers operate under high temperatures due to the currents they carry. The temperature distribution within a transformer winding is affected by various factors such as the insulation material used, the cooling system design, the ambient temperature, the load conditions and so on. Accurate identification of hotspots is crucial for the design, operation and maintenance of transformers. Hotspots can be identified through a variety of methods, including computational fluid dynamics (CFD) simulations or thermal imaging and infrared thermography after a transformer is manufactured. However, these methods have limitations in terms of accuracy and computational cost. Thermal-hydraulic network models (THNMs), however, offer a more efficient alternative, and they are acceptably accurate in comparison with CFD simulations. Moreover, available commercial CFD software is expensive with longer computational time, making it impractical for daily design and only limited to special required calculations, detailed investigations, validations, or parametric studies.

Transformer thermal modelling has advanced significantly, improving hotspot temperature predictions. Fiber Optical Sensors (FOS) were used to measure thermal hotspots in a 154kV, 15/20MVA transformer, finding discrepancies that could affect lifespan and efficiency [1]. The study's findings indicate the need for updated thermal modelling and testing standards, suggesting the potential for improved maintenance planning and enhanced transformer health management. Another study used CFD to predict coolant flow in a low-voltage transformer, identifying that hot plumes can cause local hotspots and thermal degradation of paper insulation and exhibit strong coupling between passes via persistent hot-streak. These findings suggest current industry methods may need updating to consider perfect mixing and homogeneous flow quantities, which may need to be revised to account for the observed inhomogeneities [2]. Hotspot factors can be applied to quickly estimate hotspot temperature rises. One method increased a hydro power station's capacity by 12%, recommending transformer reconstruction [3]. The study developed a model for predicting hotspot temperatures in traction transformers, validating it with a 3.4% average error. A fluid-thermal analysis method for ONAN transformers matched well with experimental results, aiding design optimization. The Finite Volume Method (FVM) was also used to improve temperature calculations, enhancing accuracy. A recent thermal model aims to better understand transformer hotspot temperatures, crucial for assessing aging and ensuring reliability [4]. The study investigated the impact of traction load's impact on hotspot, analyzing both steady and step loads to simulate real operating conditions. A fluid-thermal coupled analysis method to compute temperature distribution in an oil natural air natural (ONAN) transformer and convective heat transfer, radiation, and oil flow were investigated by using finite volume method was presented in [5]. To validate the method, a temperature measuring system is constructed for experimental testing of a 31.5 MVA/110 kV naturally cooled transformer. Simulation results match well with experiments, making it suitable for optimizing design and load scheduling. The FVM was utilized in [6] too, which transforms a simplified fluid-thermal coupled, continuous models into discrete ones. To more accurately reflect reality, the proposed solution used two approaches: (1) Replace the original oil temperature calculation formula with an industry's latest oil temperature formula to

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improve internal heat generation and cooling process calculations, thereby enhancing top oil temperature and hot spot temperature calculations; (2) Solve the differential equation for winding hotspot temperatures using a more advanced variable-step-length Runge-Kutta method to improve calculation accuracy. As a more recent contribution to this domain, the authors of [7] developed a thermal model that utilizes basic operator information; the model aims to enhance the understanding of transformer hotspot temperatures, which are critical for assessing the aging process and ensuring the reliability of power transformers.

In this paper, a thermal network methodology for modelling the internal temperature distribution of a transformer winding, enabling the identification of hot spots is proposed. The methodology discretizes the transformer into a network of interconnected nodes, each representing a specific conductor and its insulation. The thermal interactions between the nodes are modelled using a set of equations, accounting for heat transfer mechanisms such as conduction and convection. The resulting model is then capable of simulating the three-dimensional effect inside a transformer to capture the effect of the increase of the mean turn length from the inner to outer winding layers. While standard IEEE/IEC models rely on simplified top-oil temperature empirical curves, this proposed approach utilizes a discretized thermal network to map internal heat flow at the component level, which allows to account for specific material properties and geometry, capturing local temperature gradients that lumped-parameter models often miss.

To verify the accuracy of the proposed network modelling, its results are compared to those obtained from experimental tests. The validated model can be used to predict hotspot locations, optimize transformer design and develop more efficient cooling strategies, ultimately enhancing transformer performance and reliability. By providing an efficient and reliable tool for hot-spot identification, this research contributes towards the development of more resilient and efficient power systems.

II. Non-Linear Loss Distribution

Because of skin and proximity effects, the current distribution in transformer windings is inherently non-uniform. Consequently, the resulting copper loss distribution is also spatially non-uniform and depends on multiple factors, including the physical and electrical arrangement of the windings, conductor geometry, winding material, and operating conditions such as load level and frequency. Accurately accounting for these effects using analytical formulations is cumbersome, as it requires numerous simplifying assumptions that can significantly reduce accuracy, particularly for modern transformer designs with compact windings and high current densities. Since the local temperature rise in windings is directly governed by the local loss density, the use of averaged or uniformly distributed losses can lead to substantial errors in thermal calculations and hot-spot temperature prediction. Therefore, an accurate thermal assessment requires non-linear, spatially resolved loss distributions as input rather than lumped or homogenized loss values.

To address this, the current and loss distributions in the windings are calculated using a finite-element-method (FEM)–based commercial software, Ansys Maxwell. The primary and secondary windings are modeled using a 2D axisymmetric approach, which significantly reduces simulation time while still capturing skin and proximity effects, as well as the influence of winding geometry, spacing, and material properties. The low-voltage (LV) winding is modeled turn by turn due to its relatively small number of turns, enabling direct resolution of local current crowding and loss concentration. In contrast, the high-voltage (HV) winding, which consists of a large number of turns, is modeled as a bulk conductor using the Litz wire equivalent model available in Ansys Maxwell. This approach is justified because the individual conductor dimensions are sufficiently small for skin effects within single turns to be neglected, while collective proximity effects are still accurately represented. Results of non-linear loss distribution are shown in Fig. 1.

Using these two modeling strategies, detailed spatial loss distributions are obtained for both the LV and HV windings, as illustrated qualitatively below (LV winding at the bottom, HV winding at the top). These non-uniform loss distributions are then mapped directly onto the thermal network model (TNM) and used as distributed heat sources. This coupling ensures that local thermal gradients and winding hot-spots are captured with significantly higher fidelity compared to approaches based on uniform or averaged loss inputs, resulting in a more accurate prediction of winding temperature distribution under load.



Fig. 1. Non-linear loss distribution.

III. Thermal Hydraulic Model

The thermal hydraulic model (THM) handles the integral liquid flow loops. It represents each winding (or winding block) as a closed oil flow loop where heat generated by ohmic and eddy current losses is transferred to the cooling oil and ultimately dissipated to the environment via the radiators or corrugated ribs [8], [9].

The heat transferred to oil in each winding segment is governed by:

$$P_{\text{diss},j} = \dot{m}_j C_{p,j}(\theta_{o,j} - \theta_b) \tag{1}$$

where, $\dot{m}_j$ is the oil mass flow rate through winding j, $C_{p,j}$ is the specific heat capacity of the oil, $\theta_{o,j}$ and θ_b are the top and bottom oil temperature rises, respectively.

This correlation links the winding losses to the thermal rises of the oil and forms the basis for the heat balance in each loop. Heat dissipated through each corrugated rib is computed using the integrated differential energy equilibrium equation:

$$P_{cool,rad} = \dot{m}_{rad}\, C_{p,rad}\, \theta_{om} \left[1 - exp\left(-\frac{h_a\, A_{rad}}{\dot{m}_{rad}\, C_{p,rad}}\right)\right] \tag{2}$$

where, h_a is the mean air-side heat transfer coefficient, A_{fin} is the cooling surface area, and θ_{om} is the mean oil temperature rise inside the radiator.

Applying steady-state energy balance condition between the thermal energy entering the ribs and the energy dissipated to ambient then yields:

$$\dot{m}_{\text{fin}} C_{p,\text{fin}}(\theta_{o,j} - \theta_b) = h_a A_{\text{fin}} \theta_{om} \tag{3}$$

Oil circulation is driven by buoyancy forces generated by temperature-dependent density variations. The pressure gain in each loop is calculated through the hydrostatic integration:

$$\Delta p_{\text{gain}} = \int \rho \vec{g} \cdot d\vec{H} \tag{4}$$

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which simplifies using the Boussinesq approximation to:

$$\Delta p_{\text{gain}} = \rho g \beta (\theta_o - \theta_b) \Delta H \tag{5}$$

where β is the thermal expansion coefficient and ΔH is the hydraulic height difference between the winding and ribs centers.

Pressure drops along each loop include both major (frictional) and minor (directional change) losses:

$$\begin{aligned} \Delta p_{\text{drop}} &= \frac{1}{2} \rho f \frac{L}{D_h} V^2 \\ \Delta p'_{\text{drop}} &= K \frac{1}{2} \rho V^2 \end{aligned} \tag{6}$$

The total loop pressure drop is the sum of contributions from all winding ducts and the channels. Steady-state oil flow is obtained when:

$$\Delta p_{\text{gain}} = \Delta p_{\text{drop}} \tag{7}$$

This hydraulic balance is solved iteratively for all loops. The methodology follows the analogy of parallel electrical resistive circuits, each winding branch must exhibit equal pressure drop for convergence. CFD simulations confirm that the LV and HV windings indeed exhibit identical pressure drops, validating the THM assumption [8], [9].

The convection coefficient (for oil or air) is not measured directly. It is computed through the Nusselt number using:

$$h = Nu \cdot \frac{\kappa}{L_c} \tag{8}$$

where, k is the thermal conductivity of the fluid (oil or air), L_c is the characteristic length (e.g., duct hydraulic diameter or ribs height).

While oil motion inside the transformer is driven by buoyancy forces, the THM uses natural convection correlations, consistent with transformer literatures and CFD-validated behavior [9]. For laminar natural convection in vertical channels (typical in oil natural or ON cooling) Nusselt number is calculated as

$$Nu = 0.59\, Ra^{1/4} \quad (10^4 < Ra < 10^9) \tag{9}$$

The Rayleigh number (Ra) is defined as the product of the Grashof (Gr) and Prandtl (Pr) numbers, defined as follows:

$$\begin{aligned} Ra &= Gr \cdot Pr \\ Gr &= \frac{g\, \beta\, \Delta T\, L_c^3}{\nu^2} \\ Pr &= \frac{\nu}{\alpha} \end{aligned} \tag{10}$$

Thus, the oil-side convection coefficient becomes:

$$h_{\text{oil}} = 0.59\, Ra^{1/4} \frac{k_{\text{oil}}}{L_c} \tag{11}$$

On the other hand, the heat dissipation from the ribs to the ambient air also occurs by natural convection. Suitable correlations for vertical ribs surfaces are:

$$Nu = 0.10\, Ra^{1/3} \tag{12}$$

Therefore, the ribs' air-side convection coefficient becomes:

$$h_a = 0.10\, Ra^{1/3} \frac{k_{\text{air}}}{L_c} \tag{13}$$

IV. Thermal Network Model

The proposed thermal network model (TNM) is based on using the FVM where the heat is transferred by conduction through the winding conductors and by convection through fluid mass flow. Each node is set up as a finite volume, and the equation system is solved iteratively to obtain the temperature distribution within each node. The TNM is coupled to the overall thermal hydraulic model (THM) that handles the integral liquid flow loops.

The THM solves the liquid temperature distribution and the corresponding heat transfer convection coefficient which are delivered to the TNM for each iteration to allow accurate calculation of the winding-liquid gradients. The output of the TNM is used to update the liquid properties within the THM, which in turn affects the heat transfer between the winding conductors and the liquid. The coupling between the TNM and THM allows for a comprehensive analysis of the thermal behavior of the transformer winding, accounting for both the internal and external heat transfer processes. The nested iteration process ensures that the results from each model are accurate and consistent with each other, leading to more reliable predictions of the temperature distribution within the transformer winding.

A. Modeling a single turn

To accurately calculate temperature distribution inside windings, a mathematical model is required. The most critical aspect of this modelling is preparing the coefficient matrices for the equation. As a starting point, a single conductor model can be used as a simple example for demonstration purposes Fig. 2.

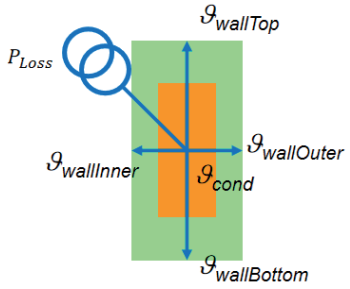

Fig. 2. Heat transfer modelling of a single conductor element.

In this context, current-carrying conductors are subject to heat loss due to electrical resistance, and temperature boundaries exist at each of four different directions (bottom, top, inner and outer face directions). Within three-dimensional modelling, there are six such directions. Considering the principles of thermal energy conservation, a thermal balance equation can be formulated. Equation (14) accounts for heat transfer between locations with varying material properties and the heat flux due to the spatial gradients in the temperature distribution balance the heat generated by electrical resistance of a conductor.

$$\begin{aligned} P_{\text{Loss}} = {} & \frac{\theta_{\text{cond}} - \theta_{\text{wallInner}}}{R_{\text{inner}}} + \frac{\theta_{\text{cond}} - \theta_{\text{wallOuter}}}{R_{\text{outer}}} \\ & + \frac{\theta_{\text{cond}} - \theta_{\text{wallBottom}}}{R_{\text{bottom}}} \\ & + \frac{\theta_{\text{cond}} - \theta_{\text{wallTop}}}{R_{\text{top}}} \end{aligned} \tag{14}$$

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Equation (14) can be applied for insulation layers in which the generated heat P_{Loss}=0. The adjacent conductors are thermally linked through the conduction resistance of the solid insulation separating them. This insulation forms a stationary heat-transfer path, allowing temperature gradients in one conductor to influence the neighboring conductors through purely conductive mechanisms.

For conductors that interface with the cooling oil, the thermal connection to the liquid occurs through a series combination of resistances. Heat must first conduct through the solid insulation layer that surrounds the conductor, after which it is transferred into the oil by natural convection at the insulation-oil interface. Thus, the overall thermal linkage between the conductor and the oil is governed by the combined resistances of (i) conduction through the solid insulation and (ii) convection from the insulation surface to the liquid.

The extended heat-flow equation with insulation resistances,

$$P_{\text{Loss}} = \frac{\theta_{\text{cond}} - \theta_{\text{wallInner}}}{R_{\text{ins,inner}} + R_{\text{inner}}} + \frac{\theta_{\text{cond}} - \theta_{\text{wallOuter}}}{R_{\text{ins,outer}} + R_{\text{outer}}} + \frac{\theta_{\text{cond}} - \theta_{\text{wallBottom}}}{R_{\text{ins,bottom}} + R_{\text{bottom}}} + \frac{\theta_{\text{cond}} - \theta_{\text{wallTop}}}{R_{\text{ins,top}} + R_{\text{top}}} \quad (15)$$

where, θ_{cond} is the conductor temperature, $\theta_{\text{wallInner}}$, $\theta_{\text{wallOuter}}$, $\theta_{\text{wallBottom}}$, θ_{wallTop} are the boundary temperatures around the conductor (inner duct, outer duct, bottom spacer, top duct), $R_{\text{ins},i}$ is the insulation conduction resistance in direction i, R_i is the thermal resistance beyond insulation which may include: conduction through remaining solid layers or convection to oil (for duct-facing surfaces).

For a conductor facing an oil duct, the post-insulation resistance becomes,

$$R_i = \frac{1}{h_i A_i} \quad (16)$$

so the total path becomes,

$$R_{\text{total},i} = \frac{t_{\text{ins},i}}{k_{\text{ins}} A_i} + \frac{1}{h_i A_i} \quad (17)$$

The geometry of conductors is cylindrical, as shown in Fig. 3,

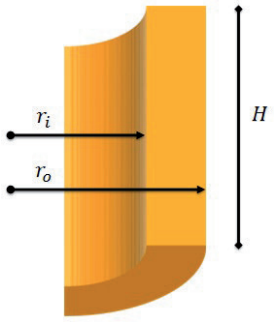

Fig. 3. Three-dimensional geometry of a conductor.

The thermal resistance of a cylindrical conductor along the axial direction is calculated as

$$R_a = \frac{H}{\pi(r_o^2 - r_i^2) \times k} \quad (18)$$

and the resistance along the radial direction is

$$R_r = \frac{\ln\left(\frac{r_o}{r_i}\right)}{2\pi H \times k} \quad (19)$$

In the proposed network model, the axial and radial resistances for each conductor element are calculated respectively.

B. Modeling a Winding

In a winding there are multiple conductors grouped in columns and rows, so the conductor elements are connected together sharing boundary conditions, as Fig. 4 shows. Foil conductors can be split axially to provide greater discretization within the model; in this scenario, the insulation between adjacent conductors is disregarded.

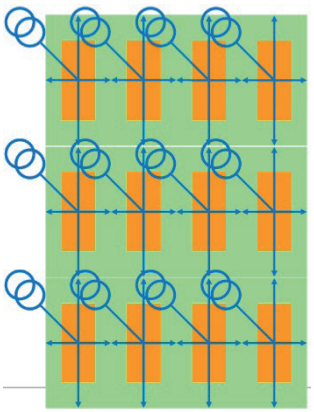

Fig. 4. Winding element comprising groups of conductors arranged horizontally and vertically.

Once the coefficient matrices have been thoroughly prepared, the solution to the thermal balance equation can be obtained through a straightforward process. By utilizing matrix operations, specifically the inversion function provided by the platform, the left-hand side coefficient matrix can be inverted to solve for the temperature distribution. The equation can be solved using the following formula.

$$T = A \backslash b \quad (20)$$

The solution to the thermal balance equation yields a vector of temperature rises for all conductor elements. This result serves as the foundation for delivering detailed temperature distributions across winding sections, including both axial and radial windings sections. By visualizing these temperature distributions, transformer designers can identify critical locations with high temperatures, such as hot spots, which indicate potential insulation aging issues.

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V. Guidelines for Graphics Preparation and Submission

To validate the accuracy of the proposed network modelling, its results are compared to those obtained from experimental tests. The comparison shows that the proposed model accurately predicts the temperature distribution within the transformer winding, with good agreement between the simulated and experimental results.

A. Experimental Setup

This section details the experimental set-up and how measured values from a special heat run test can be used to validate a proposed thermal network methodology. The goal is to ensure that the network model accurately reflects the real-world performance characteristics of the transformer under various loading conditions. The experiment involved conducting a series of heat run tests on a 630 kVA distribution transformer filled with synthetic ester insulating liquid. The voltage is 30/0.4 kV. The low-voltage (LV) winding consists of an aluminum foil winding with two cooling ducts, while the high-voltage (HV) winding is an aluminum layer-type (rectangular wires) winding. Both windings are designed with one axial cooling duct with a high percentage of collapse as shown in Fig. 5.

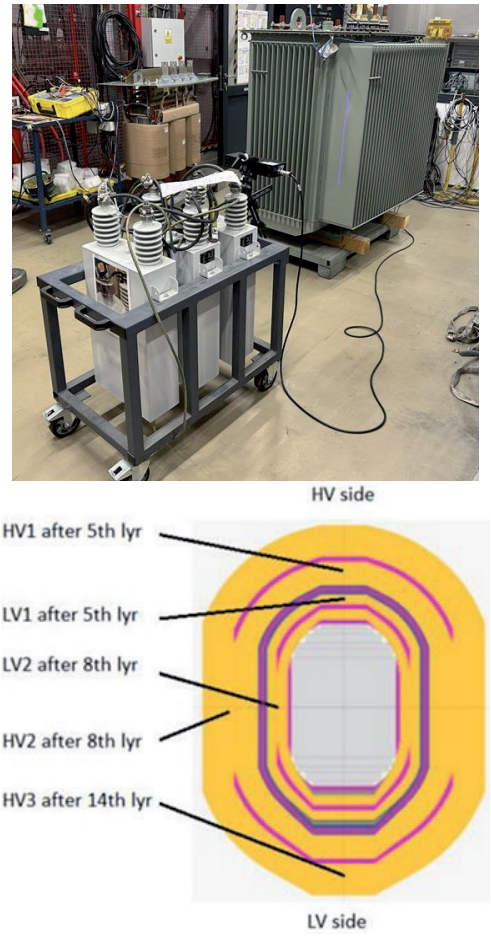


Fig. 5. (upper) Tested unit (lower) FOS locations.

This unit was equipped with FOS temperature gauges, a top-oil temperature thermometer pocket, and an external apparatus to measure the deformation of the fins during loading. Besides, a data acquisition unit and a laptop were equipped and used as well. During the setup, it was ensured that there was no debris within the FOS connectors. A dedicated pencil cleaner was used to clean all connectors. The test procedure included four loading stages completed until steady state: 100%, 125%, 86%, and 143%. After each loading stage, the transformer was left to cool down, allowing for recording cooling curves between measured loading stages. During the test, temperature rises in the high-voltage (HV) and low-voltage (LV) windings as well as the top-oil temperature rises were measured. With FOS measurements, detailed data on the temperature distribution within the transformer was successfully obtained. Overall, the test successfully met its objectives, providing data for the validation of TNM. This information will contribute significantly to the development of more efficient and reliable distribution transformers. The entire heat run test is shown in Fig. 6.

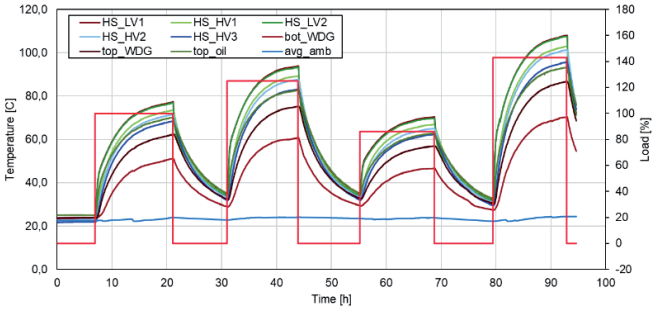


Fig. 6. Entire heat run test.

B. Result Comparison

The result of the TNM is shown in Fig. 7. The comparison between experimental data that are taken only from the end of each loading stage once stability was reached and the TNM results is shown in Fig. 8. The calculated hotspot results are obtained at the specific locations where the sensors are positioned, allowing for direct comparison of their values. The discrepancy between the calculations and the experiments is within 6% for the low voltage winding and 2% for the high voltage winding, respectively.

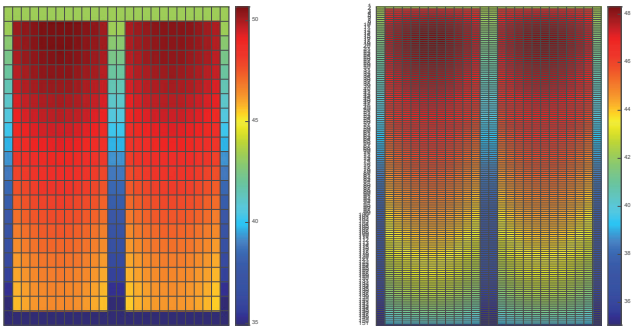
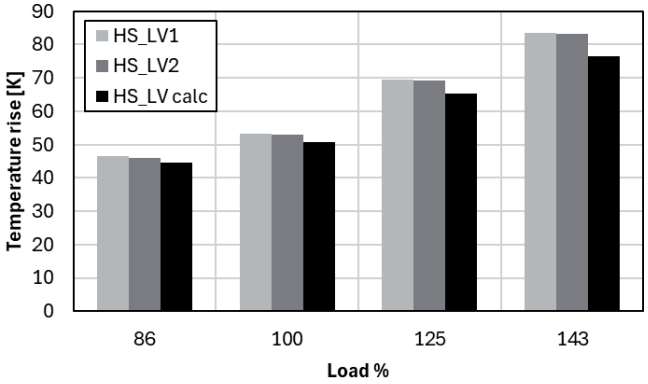


Fig. 7. Temperature distribution in the LV and HV windings using the TNM corresponding to 100% load.



(a) Hotspot result comparison of low voltage windings.

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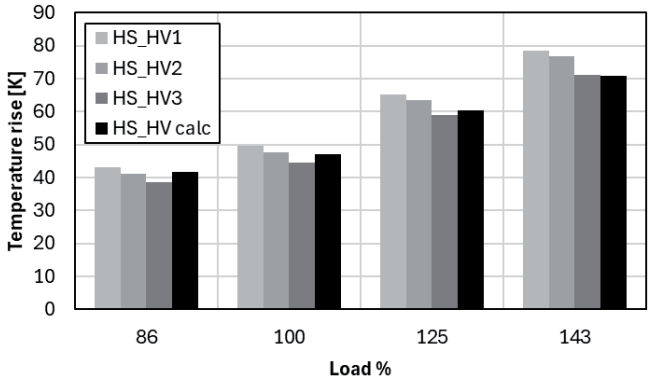

(b) Hotspot result omparison of high voltage windings.

Fig. 8. Hotspot result comparison of windings.

This comparison of results indicates that the developed TNM has high accuracy in predicting transformer behavior, making it a valuable tool for network analysis and design. At a load percentage of 143%, the numerical model prediction was lower than the experimental results. However, the deviations between them remained within an acceptable tolerance. Therefore, by following the detailed experimental setup and data analysis process, the TNM is successfully validated, and the proposed network methodology demonstrates its utility in accurately modelling transformer performance under various loading conditions.

VI. Conclusion

The results from the special heat run test have unequivocally demonstrated that the proposed network methodology is highly accurate and reliable for validating the behavior of transformers under various loading conditions. The extensive comparison between simulated and experimental data, including temperature rises, revealed significant correlation and minimal deviation. These results highlight that the model effectively predicts temperature changes due to varying loads, providing a robust framework for thermal analysis. Accurate predictions of transformer winding hotspots enable early detection and maintenance, reducing downtime and extending the lifespan of transformers and the predictions will be practically applicable for various operational load scenarios. In conclusion, the validation of the proposed network methodology has demonstrated its effectiveness in accurately modelling transformer behaviour under different loading conditions. This work not only enhances our understanding of transformer performance but also provides a valuable tool for optimizing network design and improving operational efficiency in power systems.

VII. Future Directions

While the current study has provided promising results, there is still room for improvement and expansion. Future work should include a wider range of operating conditions to ensure the model's robustness across different scenarios. The performance of transformers with various insulating liquids should be studied to assess the model's versatility. The TNM can also be considered to integrate with other numerical models for more comprehensive analysis, providing insights into system-wide behavior under transformer thermal stress.

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