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Published in:
IET Electric Power Applications

DOI:
10.1049/elp2.12437

Published: 01/07/2024

Document Version
Publisher's PDF, also known as Version of record

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Core loss determination in electric machines using short-time transient thermal measurements

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Funding information
European Research Council, Grant/Award Number: 339380

Abstract
This paper introduces a novel application of the inverse modelling method, which is designed to estimate core losses in both the stator and rotor regions of an electrical machine. The technique focuses on the use of short-term transient temperature measurements obtained from the stator core of a slotless induction machine, with a focus on validating the measured temperature rise through a forward model. The measurement setup involves two primary approaches: (i) the use of thermal sensors embedded in a printed circuit board inside the stator core and (ii) surface sensors embedded on the stator yoke. Through the use of this innovative approach, the results indicate that the inverse modelling technique is highly effective in predicting core losses based on short-time transient temperature rise measurements.

KEYWORDS
AC machines, loss measurement, magnetic cores, thermal analysis

1 INTRODUCTION

The increasing attempts to achieve higher efficiency in electrical machines require accurate prediction and quantification of losses. This paper focuses on core loss estimation, which is an important aspect of electrical machine design and analysis because it provides critical information about the efficiency and performance of the machine. Core loss refers to the energy lost as heat when an alternating magnetic field is applied to the iron core of an electrical machine. This heat loss can significantly reduce the efficiency of the machine and may lead to premature failure if not properly managed [1, 2]. Hence, accurately modelling and measuring the core loss of an electrical machine is essential not only at the design stage but also in the analysis of cooling requirements during the machine operation.

Recently, the analysis of cooling requirements and the estimation of temperature rise distribution have emerged as hot topics in the field of electrical machines. Some studies [3–8] employed the lumped parameter thermal network (LPTN) combined with robust core loss estimation to investigate the impact of losses in various machines. The thermal network method is short in calculation time, but its calculation accuracy depends on the rationality of the thermal network model. Studies in refs. [9, 10] show the importance of including cooling methods in the analysis of the motor. Other studies, such as those conducted in refs. [11–15], utilised a coupled finite element (FE) and thermal model to examine the heat loss distribution. These techniques adopt a forward modelling approach where the inputs of the models are losses estimated either experimentally, numerically, or analytically, and the output of the model is the heat loss distributions.

In contrast, inverse modelling techniques based on temperature measurements have also been used extensively for estimating core losses, as demonstrated in studies by [16–20], as well as for fault monitoring, as shown in [21, 22]. However, the accuracy of the measured temperature plays a crucial role in determining the accuracy of the solution to an inverse problem. Even small errors in temperature measurements can lead to instability and prevent the possibility of obtaining a unique and reliable solution as explained in ref. [17]. Therefore, it is essential to adopt a robust methodology for temperature measurements when using inverse modelling to study electrical machines.

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The methods commonly used to measure temperature rise for inverse modelling applications can be categorised into three groups: (i) calorimetric measurements [20, 23–25], (ii) infrared thermographic measurements [18, 19, 26, 27], and (iii) thermal sensor measurements with thermistors/thermocouples [28, 29]. Each method has its advantages and disadvantages. For instance, calorimetric methods offer accurate measurements but can be time-consuming and costly to set up. Infrared thermographic measurements are simpler and faster but can be affected by the camera field of view and surface emissivity [30]. Thermal sensor measurements provide a simple way to measure temperature rise from localised regions but can be affected by contact noise and reduced accuracy due to direct contact with the measured surface.

In a previous study [31], a novel customised sensor board embedded with PT100 thermal sensors is used for the temperature rise measurements in a transformer. This reduced contact noise and increased measurement accuracy. In this paper, we explore the applicability of this method to rotating field devices, such as an induction machine topology. We also present a new methodology using short-time transient temperature rise to predict the core losses. Temperature measurement is performed with thermal sensors embedded in a printed circuit board (PCB) designed to have a similar shape as a stator core lamination and thermal sensors on the surface of the stator yoke. The core losses in the stator and rotor regions are predicted based on the two measurement approaches, and the accuracy is compared with the measured total losses. It is important to note that this study serves the purpose of validation and is conducted using a simplified laboratory setup. Future research will involve comprehensive electrical machines, incorporating rotor bars and rotation into the study.

The remainder of this is organised as follows: Section 2 describes the measurement system in detail. Section 3 presents the developed forward model consisting of electromagnetic and thermal models, which are validated against measurements. Section 4 discusses the application of the inverse modelling technique. Finally, in Section 5, the most important findings of this study are summarised.

2 | MEASUREMENT SYSTEM

This section describes the experimental setup and the performed temperature rise and electromagnetic loss measurements of the test machine. The measured temperature rise is used in the inverse model to estimate the losses, which are validated against the measured electromagnetic losses. A detailed explanation of the measurement setup and the performed measurements are given in the following subsections.

2.1 | Experimental setup

In the test setup, we utilised a 37 kW induction machine topology that operates in a standstill condition and relies on natural cooling. This machine incorporates a modified dummy rotor core design without slots and copper bars, effectively eliminating losses typically associated with rotor bars in our measurements. Additionally, this design simplifies the modelling process. The stator core of the machine is designed with customised thermal sensors embedded in a PCB placed in the middle of the stator core as shown in Figure 1a,b. The PCB is designed to perfectly replicate the geometry of a stator core lamination with a thickness of 0.5 mm as shown in Figure 1c.

PT100 temperature sensors are embedded in different sections of the board to measure temperature rise from the yoke and teeth regions. The accuracy of the thermal sensor used is 0.06°C, and the sensor has a measurement range from −50°C to 250°C [31]. To protect the PCB from getting destroyed by the compression applied during the core manufacturing process, 13 1 mm thick shims cut from the same stator core material are placed uniquely along the core welding spot. The thermal sensors are protected by covering the surface with thermally conductive tape. The final arrangement of the PCB with the shims and the thermal sensor board connectors from (a) side view and (b) front view, (c) sensor board with PT100 sensors, (d) final arrangement for sensor board with protection, and dummy rotor from (e) side view and (f) front view. The stator and rotor cores are constructed from the same material.

FIGURE 1 The parts of the experimental setup: stator core with sensor board connectors from (a) side view and (b) front view, (c) sensor board with PT100 sensors, (d) final arrangement for sensor board with protection, and dummy rotor from (e) side view and (f) front view. The stator and rotor cores are constructed from the same material.
sensors before placing it in the middle of the stator core is shown in Figure 1d. Additionally, 2 PT100 sensors are placed on the surface of the stator yoke.

The designed dummy rotor core is shown in Figure 1e,f. The designed dummy rotor core is assembled with 500 stacks of 0.5 mm thick lamination in the axial direction. This design provides a closing path for the magnetic field produced in the stator similar to the magnetic field of an actual motor at no-load. The parameters of the test machine are given in Table 1.

**2.2 | Performed measurements**

The measurements are performed with a sinusoidal supply of different voltage levels between 200 and 400 V supplied by a synchronous generator. A Fluke Norma 4000 power analyser is used to record the supply voltages, current, and power values. Temperature measurements were obtained at 5-s intervals using an Agilent 34970A data acquisition unit connected to the serial output port on the sensor board's PCB. The data collection process extended over a period of 3 h, resulting in a total of 2160 recorded data points. It is important to highlight that, given the stationary nature of the test machine, the total losses measured do not account for losses attributed to mechanical connections, rotor friction, and bearing losses present in a typical rotating machine. Consequently, the measured total power loss $P_m$ only consists of copper losses of the stator winding $P_{cu}$ and core losses $P_c$ associated with the stator $P_{c, st}$ and the slotless rotor $P_{c, rlt}$ such that

$$P_m = P_{cu} + P_{c, st} + P_{c, rlt}. \quad 1$$

The winding losses are calculated based on Ohm's law from the measured stator current $I_{st}$ and phase resistance $R_{st}$ such that

$$P_{cu} = 3I_{st}^2R_{st}. \quad 2$$

Then, the total core losses $P_c$ are calculated for each measurement by subtracting the total winding losses $P_{cu}$ from the total measured power losses $P_m$ that is stated as follows:

$$P_c = P_m - P_{cu}. \quad 3$$

**3 | FORWARD MODEL**

A forward model composed of electromagnetic and thermal modelling parts is developed using COMSOL Multi-physics. The electromagnetic model has a dual purpose: firstly, it estimates core losses in both the rotor and stator regions, and secondly, the losses are used to simulate the thermal model accuracy. The thermal model, in turn, is utilised for inverse modelling to estimate core losses in the rotor and stator regions based on the measured transient temperature rise. In the remainder of this section, the electromagnetic and thermal modelling parts of the forward model are explained. The results obtained from modelling are validated by the experimental measurements.

**3.1 | Electromagnetic model**

The main objective of the 2-D electromagnetic model of the tested machine is to achieve an accurate estimation of the flux density and core loss distribution. The model assumes that the flux distribution is constant in the axial direction, which removes the necessity of 3-D modelling. The 2-D model description of the test machine used in the simulation is shown in Figure 2a. To simulate the flux density and estimate the core losses distribution in the test machine under locked rotor conditions, a time-stepping magnetic field simulation is carried out by applying a three-phase sinusoidal voltage in the range of 200–400 V to the input terminal of the stator winding as shown in Figure 2b.

The core losses in the stator and rotor cores are computed from the fundamental and harmonic components of the flux density distribution. This calculation is performed using the generalised Bertotti approach [32] during the post-processing of FE simulations. The loss coefficients required for the Bertotti equation are derived from measurements conducted with the Epstein frame method as described in [31]. As mentioned in Section 2.1, the measured total core losses $P_c$ are a combination of stator and rotor core losses (i.e., $P_c = P_{c, st} + P_{c, rlt}$). Therefore, to validate the total core losses from the forward model against the measurements, the stator and rotor core

**Table 1** Parameters of the induction machine with dummy-rotor used in the measurements.

<table>
<thead>
<tr>
<th>Quantities</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated voltage</td>
<td>400 V</td>
</tr>
<tr>
<td>Frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Number of conductors per slot</td>
<td>12</td>
</tr>
<tr>
<td>Number of parallel paths</td>
<td>2</td>
</tr>
<tr>
<td>Number of poles</td>
<td>4</td>
</tr>
<tr>
<td>Stacking factor</td>
<td>0.95</td>
</tr>
<tr>
<td>Winding filling factor</td>
<td>0.65</td>
</tr>
<tr>
<td>Total number of stator slots</td>
<td>48</td>
</tr>
<tr>
<td>Stator outer diameter</td>
<td>310 mm</td>
</tr>
<tr>
<td>Stator inner diameter</td>
<td>200 mm</td>
</tr>
<tr>
<td>Lamination thickness</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>Air-gap length</td>
<td>0.8 mm</td>
</tr>
<tr>
<td>Axial length</td>
<td>242.5 mm</td>
</tr>
<tr>
<td>Winding resistance/phase $R_{w}$</td>
<td>0.075 Ω</td>
</tr>
<tr>
<td>End winding resistance/phase $R_{e}$</td>
<td>0.092 Ω</td>
</tr>
</tbody>
</table>
losses from the simulations are added together. In Figure 3, an example of the (a) flux density distribution and (b) core loss distribution for the 400 V supply voltage case is shown. In Figure 3c, the measured and simulated core losses are compared for all supply voltage cases.

The results of the comparison suggest that the simulation of total core losses is highly accurate in all cases, with a relative error of less than 1.1%. This finding is significant as it guarantees the reliability of the core losses distribution in thermal modelling and its ability to simulate the temperature rise. Such high accuracy in the simulation of core losses ensures the validity and credibility of the thermal modelling outputs.

3.2 | Thermal model

The main objective of the thermal model is to simulate the temperature rise for a given heat source. The core losses simulated with the electromagnetic model presented in Section 3.1 are validated against the measurements successfully. The heat sources for the thermal model are the core losses and the winding losses. 3-D time-dependent heat transfer simulation of the machine is carried out. The modelling principle is similar to the presented thermal model for a transformer geometry in ref. [31], which is based on the following heat diffusion equation:

$$\rho C_p \frac{\partial T}{\partial t} - \nabla \cdot k \nabla T = \rho_{\text{gen}}$$

where $C_p$, $k$, $T$, and $\rho_{\text{gen}}$ are specific heat capacity, thermal conductivity, temperature, and heat source, respectively.

The geometry of the machine is divided into five parts, featuring three different material properties as shown in Figure 4a. To reduce computational costs, we have modelled just $1/8$th of the geometry, applying symmetric boundary conditions to the relevant boundaries where continuity conditions are present. Each section of the geometry is homogenised by defining the specific heat capacity and mass density of each domain using Equations (5) and (6). This approach accounts for the composite nature of the material properties within the domain.

$$C_p = \lambda_1 C_{p,1} + (1 - \lambda_1) C_{p,2}$$

$$\rho = \lambda_1 \rho_1 + (1 - \lambda_1) \rho_2$$

where $\lambda_1$ is the filling factor of core/winding, $C_{p,1}$ is the constituent specific heat capacity of core/winding, $C_{p,2}$ is the constituent specific heat capacity of the insulation layer, $\rho_1$ is the mass density of core/winding, and $\rho_2$ is the mass density of insulating material. The thermal conductivity of the core and winding is modelled in two directions using the Hashin and Shtrikman approximation [33], as described by Equation (7) for the lapping direction and Equation (8) for the perpendicular to lapping direction. The interface boundary between the stator slot and winding is modelled with thin thermal contact defined in COMSOL. Multi-physics with gap conductance of 45 W/(m²K). To account for the anisotropic nature of the core and winding region, a tensor was used to specify the thermal conductivity rather than a scalar.

$$k_p = \lambda_1 k_1 + (1 - \lambda_1) k_2$$

$$k_{\text{ins}} = \frac{k_1}{1 - \lambda_1} \frac{1}{k_1} \frac{1 - \lambda_1}{k_2}$$

where $k_1$ is the thermal conductivity of the core/winding and $k_2$ is the thermal conductivity of insulating material. The empirical material properties utilised in the model are outlined in Table 2.
FIGURE 4 (a) 3-D geometry description of the machine for the thermal model. (b) Simulated temperature distribution for one slot region for 400 V supply voltage case at 3 h. Due to the symmetry, the distribution is the same for the other slots of the machine.

TABLE 2 Empirical material properties used in the thermal model.

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal conductivity $k_p$(W/mK)</th>
<th>Heat capacity $C_{pa}$(J/kg K)</th>
<th>Density $\lambda_p$(kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>385</td>
<td>392</td>
<td>8890</td>
</tr>
<tr>
<td>Electric steel sheet</td>
<td>28 (laminating direction)</td>
<td>490</td>
<td>7700</td>
</tr>
<tr>
<td>Epoxy resin</td>
<td>0.4</td>
<td>600</td>
<td>1540</td>
</tr>
<tr>
<td>Structural steel</td>
<td>44.5</td>
<td>475</td>
<td>7850</td>
</tr>
</tbody>
</table>

The losses generated in the individual parts of the machine are segregated as follows:

Stator core losses
Rotor core losses
Winding and end-winding losses

The losses are used as the heat source ($P_{gen}$ in Equation (4)) in the corresponding part. The model is simulated by applying uniform heat transfer coefficient $h_{conv}$ to the surface boundaries as described in ref. [31]. Considering the symmetry of the loss distribution in the different parts of the machine as can be seen in Figure 3b, only one slot section is used in the simulations. The model is simulated for all supply voltage cases to obtain the temperature rise. Figure 4b shows a simulated example of the temperature distribution of the tested machine after 3 h duration for the 400 V supply case. The temperature distribution is observed to be uniform over each section with the hottest region being the stator core as expected because of the heat flow direction. Furthermore, the results for each simulated case are validated with the measurements in Figure 5.

The presented results in Figure 5 show that the thermal model can accurately estimate the measured temperature rise in all simulated regions for different supply voltage cases. The observed high accuracy of the forward model makes it suitable to be used in the inverse model to predict the losses from the temperature rise, which will be the focus of the next section.

4 | INVERSE MODEL APPLICATION

This section of the paper discusses the application of an inverse modelling technique for predicting core losses in a test machine. The technique uses short-time transient measurements of temperature rise as inputs to the model. The measurement setup involves two methods, one is based on a thermal PCB placed inside the stator core and the other is based on temperature measurements from the surface of the stator core as shown in the flowchart diagram in Figure 6. Short-time transient measurement refers to the measurement of temperature rise over a short period of time, typically in the range of 50–1000 s. In the context of this study, the temperature rise in the stator core is measured over a short time period, and this data is used as input to the inverse model for predicting core losses.

The inverse model is used to predict the stator core losses $P_{p,st}$ based on the short-time transient measured temperature rise from the stator core region. An additional relationship is introduced to predict the rotor core losses $P_{p,rt}$ as a function of the predicted stator core losses $P_{p,st}$, and this relationship will be derived below using the principle of flux conservation.

The total eddy-current losses over the stator volume $V_{st}$ and rotor volume $V_{rt}$ can be expressed using the squares of the flux density amplitudes for the frequency $f$ stated as follows:

$$P_{p,st} = \int_{V_{st}} k_{eddy} B_{st}^2 f^2 dV_{st} \quad (9)$$

$$P_{p,rt} = \int_{V_{rt}} k_{eddy} B_{rt}^2 f^2 dV_{rt} \quad (10)$$
where $k_{\text{eddy}}$ is the eddy-current loss coefficient of the material, $B^2_s$ and $B^2_r$ are the squares of the flux density amplitudes of the stator and rotor cores, respectively. Assuming that the flux is equal in one pole pitch of both the stator and rotor, the following equation holds:

$$B_s S_s - B_r S_r = 0$$

where $S_s$ and $S_r$ are the area perpendicular to the flux path of the stator slots and rotor core under one pole pitch, respectively. Using Equations (5)–(7), the predicted rotor core losses $P_{p,rt}$ can be obtained by the following equation:

$$P_{p,rt} = k P_{p,rt}$$

where $k = S_r / S_s$. $2 V_n / V_d$ is a constant parameter that depends on the volumes and squares of the surface areas of the stator and rotor geometry.

To predict the core losses, the inverse model uses an iterative non-linear optimisation procedure to minimise the mean absolute error between the matrices representing the measured temperature rise $T_m$ (Equation (13)) and the predicted temperature rise $T_p$ (Equation (14)).

$$T_m = \begin{bmatrix} T^{1}_{m,1} & T^{2}_{m,1} & \cdots & T^{n}_{m,1} \\ T^{1}_{m,2} & T^{2}_{m,2} & \cdots & T^{n}_{m,2} \\ \vdots & \vdots & \ddots & \vdots \\ T^{1}_{m,n} & T^{2}_{m,n} & \cdots & T^{n}_{m,n} \end{bmatrix}$$

$$T_p = \begin{bmatrix} T^{1}_{p,1} & T^{2}_{p,1} & \cdots & T^{n}_{p,1} \\ T^{1}_{p,2} & T^{2}_{p,2} & \cdots & T^{n}_{p,2} \\ \vdots & \vdots & \ddots & \vdots \\ T^{1}_{p,n} & T^{2}_{p,n} & \cdots & T^{n}_{p,n} \end{bmatrix}$$

where $T_{m,1}$ and $T_{m,2}$ stand for the measured temperature rise in the yoke and the teeth regions. Similarly, $T_{p,1}$ and $T_{p,2}$ stand for the predicted temperature rise in the yoke and the teeth regions from the PCB measurement. “1, 2, ..., n” in the superscript represents the indices of the time instants at which the temperature rise is measured. In this case, only 500 s of the measured temperature rise is used for the prediction of the core losses. The mean absolute error between measured and predicted temperature rise is represented by the symbol $\epsilon$ and is defined as follows:

$$\epsilon = \frac{1}{n} \sum_{i=1}^{n} \left| \frac{T_p - T_m}{T_m} \right|$$

To enhance accuracy, the iterative process centres around adjusting the normalised unknown heat source $P_{p,rt}$ within the stator region.

This iterative procedure persists until the value of $\epsilon$ falls below a predefined convergence threshold, specifically $10^{-6}$, which is denoted as follows:

$$\epsilon < 10^{-6}$$

For surface measurements, the matrices for the mean absolute error are replaced with the surface temperature measurements. The core losses predicted by both measurement methods are compared to the core losses calculated by the forward electromagnetic model for the stator and rotor regions, and the results are presented in Table 3. The findings suggest that the inverse model accurately predicts the core losses in both regions using the short-time transient temperature rise measurements. However, the accuracy of the predicted loss decreases when using the surface temperature rise of the test machine, mainly due to measurement inaccuracies.

Moreover, the overall simulated and predicted core losses are calculated by summing up the stator and rotor losses in both cases and then compared with the total measured core losses as presented in Table 4. The analysis indicates that the highest margin of error in forecasting the total losses through the use of PCB and surface measurements is less than 2.6% and 8.9%, respectively. Based on these findings, we can conclude that the inverse thermal technique, combined with the short-time transient temperature measurements, can effectively and precisely predict core losses.

5 | SENSITIVITY ANALYSIS OF DATA USED

Sensitivity analysis is conducted to assess the impact of short time intervals on the accuracy of the inverse model. Different time intervals for measuring temperature rise are employed in the inverse model to estimate core losses. These time intervals denoted as $\tau_n$, are being incremented in steps of 50 s (for example, $\tau_1 = [0, 50]$, $\tau_2 = [0, 100]$). The interval $\tau_n = [0, 50n]$ represents the duration of
TABLE 3 Comparison of simulated core losses and inverse model-predicted core losses in the stator and rotor regions using the suggested measurement shown in the flowchart.

<table>
<thead>
<tr>
<th>Regions</th>
<th>Supply Voltage (V)</th>
<th>Simulated</th>
<th>PCB</th>
<th>Surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stator core</td>
<td>200</td>
<td>77.1</td>
<td>87.7</td>
<td>89.5</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>160.4</td>
<td>163.7</td>
<td>156.9</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>272.7</td>
<td>276.7</td>
<td>300.0</td>
</tr>
<tr>
<td>Rotor core</td>
<td>200</td>
<td>25.3</td>
<td>27.9</td>
<td>28.5</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>52.1</td>
<td>52.1</td>
<td>49.9</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>87.1</td>
<td>88.0</td>
<td>95.4</td>
</tr>
</tbody>
</table>

TABLE 4 Comparison of measured core losses and inverse model-predicted core losses based on thermal PCB and surface temperature measurement.

<table>
<thead>
<tr>
<th>Supply Voltage (V)</th>
<th>Measured</th>
<th>PCB</th>
<th>Surf.</th>
<th>Error</th>
<th>Predicted</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>113.5</td>
<td>115.6</td>
<td>118.0</td>
<td>1.8%</td>
<td>1.8%</td>
</tr>
<tr>
<td>300</td>
<td>214.4</td>
<td>215.8</td>
<td>206.8</td>
<td>0.7%</td>
<td>8.4%</td>
</tr>
<tr>
<td>400</td>
<td>363.2</td>
<td>364.7</td>
<td>395.4</td>
<td>0.4%</td>
<td>8.9%</td>
</tr>
</tbody>
</table>

transient measurements taken. In each interval test, the relative error between the predicted and actual stator losses is calculated. Figure 7 shows the estimated relative error for the investigated time intervals.

The results, as shown in Figure 7, demonstrate the importance of the chosen time interval on the accuracy of our estimates. We obtained an ideal time interval with the lowest relative error, indicating the highest precision and dependability in calculating core losses. This interval strikes a balance between the accuracy of the core loss estimation and the duration at which afterwards, the core loss does not change significantly. These findings not only increase our confidence in the inverse model's precision but also demonstrate that short-time transient measurements are a viable option for estimating core losses when compared to steady-state measurements, which typically take much longer to complete.

6 | CONCLUSION

In summary, this study presents an innovative approach to estimate core losses in rotating field electrical machines through inverse modelling based on short-time transient measured temperature rise. Using an induction machine topology and strategically positioning thermal sensors on a PCB within the stator core as a case study, we contribute a distinctive perspective to the existing literature. Our investigations revealed an optimal time interval, marked by the lowest relative error, signifying heightened precision and reliability in core loss calculations.

This identified interval strikes a balance between the accuracy of core loss estimation and its duration, ensuring that subsequent changes in core loss remain insignificant. These outcomes not only strengthen our confidence in the precision of the inverse model but also emphasise the viability of short-time transient measurements for core loss estimation. When contrasted with the lengthier time requirements of steady-state measurements, our findings underscore the efficiency and practicality of our proposed method for accurate core loss estimation.

In addition, the use of an electromagnetic losses model plays a crucial role in evaluating the validity of the thermal model and provides a comparative study of the estimated loss through inverse modelling. It is important to highlight that, in general, the proposed methodology does not require the inclusion of electromagnetic loss in the thermal model as the core losses can be directly obtained through the inverse model applied to an established thermal model.

AUTHOR CONTRIBUTIONS

O SARUYI OSEMWINYN: Conceptualization; Formal analysis; Investigation; Methodology; Writing – original draft; Writing – review & editing. A HDEN: Supervision; Writing – review & editing. F LRAN MRTN: Formal analysis; Supervision; Writing – review & editing. ISEM TUN GÜRBÜZ: Formal analysis; Writing – review & editing. A NOUAR B LACEN: Funding acquisition; Project administration; Supervision; Writing – review & editing.

ACKNOWLEDGEMENTS

The research work was funded by the European Research Council under the ERC Advanced Grant (A. Arkko) “Additional Losses in Electrical Machines”, grant number 339380.

CONFLICT OF INTEREST STATEMENT

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.
DATA AVAILABILITY STATEMENT
The data that support the findings of this study are available from the corresponding author upon reasonable request.

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REFERENCES

How to cite this article: Osemwinyen, O., et al.: Core loss determination in electric machines using short-time transient thermal measurements. IET Electr. Power Appl. 1–8 (2024). https://doi.org/10.1049/elp2.12437