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Thermographic Method for Measuring Iron Losses and Localized Loss Density

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Abstract— The knowledge of core losses in electrical machine is required for the successful design of highly efficient machines. This paper presents a thermographic technique for measuring core loss and localize loss density in an electrical machine. First, a 3D numerical solution of the stated problem was carried out in COMSOL multi-physics to study the possibility of the measurement technique. The experimental measurement process was demonstrated on a 24/12 V single-phase transformer. The excitation was supplied to the transformer by varying the applied voltage at a constant frequency of 300 Hz. IR camera was used to obtain the images of the core at the instant of supply for three different flux densities. The core losses were estimated from the initial rate of temperature rise and compared with the core loss obtained directly from the wattmeter. The results show that the developed system can accurately estimate core loss density and distribution over a wide range, with an error margin of less than 6%. However, the accuracy of the results obtained is affected by measurement condition.

Keywords— Core loss, IR camera, loss density, thermography

I. INTRODUCTION

The increasing reliance on the electrical machine in transportation systems, especially in the automotive sector, has created the need to find out new ways of producing more efficient and economical electrical machines. The demand of a highly efficient electrical machine has led more machine designers to focus on the study of losses in different parts of the machine. Hence, this research work focuses on core loss measurement in an electrical machine.

General procedures for measuring core losses in assembled electrical machines are described in international IEC and IEEE standards [1]. The iron loss is obtained from the difference between input-power, output-power, winding losses and mechanical losses when the machine is operated at several operating points which include no-load tests, load tests and short-circuit tests. However, errors in the determination of input power, output power, winding losses or mechanical losses affect the results obtained from this method. Another approach used in [2, 3] is the calorimetric method, where losses are determined directly from the heat dissipation of the machine. However, it requires several hours to complete, and measurement conditions could vary with time, which could have a considerable effect on the accuracy of results obtained.

A new promising method for determination of iron loss distribution is the temperature time technique. This approach is

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based on the principle that losses generated in the different parts of electrical machine contribute directly to the temperature rise of the machine. Hence, measuring the temperature rise at any point in a machine, the loss distribution can be directly determined. This principle has been widely applied by previous researchers [4–7] to measure localized power loss in magnetic cores. In their approach, they used thermistors and thermocouples soldered to the investigated region of the machine to obtain the localized loss distribution. However, there are some difficulties facing this approach. The probability of sensor failure is high during assembling of the core, for a more compact machine. If the sensors are not inserted before assembling, it will be difficult to insert the temperature sensor into the region of interest. Also, this approach is not suited for simultaneous measurements of multiple sampling points at a given time. Another approach used to obtain the surface temperature is the IR thermography [8, 9, 10]. This approach involves a non-contact measurement of surface temperature using an infrared camera with a thermographic detector. With IR camera, temperature measurement can be obtained over a wide area containing a massive number of sampling points. Hence, loss distribution can be determined by a large area of the sample with 2D images, unlike the sensor that gives local heat flux at a single point (or a spatial averaged one). However, the difficulty of measuring temperature rise inside the stator core of the electrical machines with IR detector is one major challenge facing this approach.

In this paper, the thermographic method of acquiring surface temperature rise was presented. The core loss and localized loss density were calculated from the measured temperature gradient using the theory developed in section II. The feasibility of the loss computation method was verified using COMSOL multi-physics simulation of the stated problem.

II. THEORY OF LOSS COMPUTATION

Core losses in electrical machines contribute directly to the temperature rise of the core. Hence, from the first law of thermodynamics, let us write the power balance equation for the heat loss in a medium.

$$q_0 = q_c + q_{hr}, \quad (1)$$

where q_0 [W/kg] is the total power supplied to the medium, q_c [W/kg] is the rate of heat generation due to conduction of the medium and q_{hr} [W/kg] is the rate of heat transfer at the boundary interface with surrounding due to convection. From (1) it can be observed that the only heat transfer mechanism

considered here is the conduction heat transfer in the solid core and the convection heat transfer at the boundary interface of the core with the surrounding. Therefore, the thermal power loss due to conduction can be obtained from the heat of conduction equation as,

$$q_c = k \frac{\partial T}{\partial t} - \lambda \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right). \quad (2)$$

From (2), if we assume that the temperature distribution at $t = 0$ is uniform in all direction, the heat loss due to conduction will be proportional to the initial rate of temperature rise as,

$$q_c = k \frac{dT}{dt}. \quad (3)$$

The thermal energy loss due to heat transfer to the surrounding per unit time is obtained from Newton's law of cooling as,

$$q_{hr} = h_{conv}(T(t) - T_0). \quad (4)$$

Therefore, substituting (3) and (4) into (1) the heat supplied per unit time to the medium is given as,

$$q_o = k \frac{dT}{dt} + h_{conv}(T(t) - T_0), \quad (5)$$

where, T [K] is the temperature, λ [W/mK] is the thermal conductivity of the material, k [J/kgK] is the specific heat capacity of the material and h_{conv} [W/m²K] is the heat transfer coefficient. However, to estimate the core loss it is assumed that the heat transfer to the surrounding is zero due to the small interval of measuring temperature rise. Hence, (5) is reduced to (3) meaning that the total power supplied to the medium is used to raise the temperature of the material.

III. MEASUREMENT SETUP

Fig. 1. Measurement setup schematics

Fig.1 shows the measurement system schematic for estimating the core loss distribution. The measurement process was demonstrated on a 24/12 V transformer. AC voltage is supplied at 300 Hz to the primary winding of the transformer with the secondary open circuited. The ammeter (A) and wattmeter (W) readings indicate the no-load current and input power of the transformer. Since the secondary is open circuited, there is no output power. Therefore, the input power consists of

the core losses and the primary winding loss due to the no-load current.

From theory, the core loss is proportional to the temperature gradient. Therefore, an IR camera positioned in front of the core is used to record the temperature rise of the core during voltage supply interval. Before recording, the camera calibration is carried out with the following parameters: emissivity, apparent reflected temperature, relative humidity, ambient temperature and measured object distance from the camera. Image acquisition speed of the IR camera used in this measurement is 30 samples per second and the total recording time of temperature rise of the core was for 30 seconds.

In order to improve the accuracy of the measured temperature, each measurement has been repeated a number of times. Then, the gradient was extracted in each step and averaged. The result is used to compute the core loss using (3).

IV. NUMERICAL SIMULATION

To verify the feasibility of the core loss calculated from the initial rate of temperature rise, a 3D time dependent heat transfer model of the transformer was implemented in COMSOL multi-physics. Fig.2 shows the geometry of the transformer model used. The simulation model directly solves Maxwell's equations in time dependent domain to obtain the current density distribution. The electromagnetic loss model based on A-V formulation is described below:

$$\nabla \times \mathbf{E} = -\frac{\delta \mathbf{B}}{\delta t} \quad (6)$$

$$\nabla \times \mathbf{H} = \mathbf{J} \quad (7)$$

$$\mathbf{B} = \mu \mathbf{H} \quad (8)$$

$$\nabla \cdot \mathbf{J} = 0 \quad (9)$$

where $\mathbf{E}$ is the electric field [V/m], $\mathbf{B}$ is the magnetic flux density [T], $\mathbf{H}$ is the magnetic field intensity [A/m], μ is the permeability of iron and $\mathbf{J}$ is the current density [A/m²]. The magnetic flux density in terms of vector potential $\mathbf{A}$ is given by :

$$\mathbf{B} = \nabla \times \mathbf{A} \quad (10)$$

therefore, from (6), and (9), it follows that,

$$\mathbf{E} = -\left(\frac{\partial \mathbf{A}}{\partial t} + \nabla V \right) \quad (11)$$

where V is a scalar potential. The current density in the transformer after excitation is given by:

$$\mathbf{J} = \sigma \mathbf{E} + \mathbf{J}^e \quad (12)$$

where σ is the electrical conductivity [S/m] and $\mathbf{J}^e$ is the external current density calculated from transformer winding excitation. Substituting (10) and (11) into (7) we have;

$$\mu^{-1} \nabla \times (\nabla \times \mathbf{A}) = -\sigma \left(\frac{\partial \mathbf{A}}{\partial t} + \nabla V \right) + \mathbf{J}^e \quad (13)$$

The boundary condition is ensured by imposing the continuity conduction as given in (9) at the boundary interface. Equation (13) is then solved using finite element method to obtain the vector potential which is used for calculating the electric field and current density induced in the core. The nonlinearity of the

material in the simulation is considered from magnetization curve which originates from the measured BH curve of the transformer core.

The core loss is derived from the current density using the equation below:

$$q_{cs} = \int_V \frac{J_c^2}{\sigma \times m_{Fe}} dV \quad (14)$$

where J_c is the current density induced in the core and q_{cs} is the simulated core loss [W/kg]. Since this loss manifests themselves through heat production in the core due to Joule effect. The electromagnetic loss model is directly coupled with heat transfer model according to (5) to obtain the temperature distribution of the transformer core.

In the study, the core loss is considered homogeneous inside the core and at the boundary interface with the air, Newton's law of cooling hold true. Hence, free convection is assumed on the surface of the core.

Fig. 2. Geometry of transformer model

V. RESULTS AND DISCUSSIONS

A. COMSOL simulation

With a sinusoidal voltage of 144 V at 300 Hz frequency applied to the primary winding of the transformer, the time-dependent solution of the stated problem was obtained for 0.05 seconds. Fig.3 shows the resulting surface temperature distribution of the core at a flux density of 1.34 T. It can be observed from the figure that the heating of the core is almost uniform, with the highest temperature rise in the middle limb. It is mainly due to the difficulty of cooling owing to the presence of the winding. However, in practical measurement, that area of the core is difficult to access with the IR camera.

Fig.4 shows the temperature rise plot obtained from one of the side limbs of the core. The linear approximation was used to estimate the initial rate of temperature rise. Finally, the core loss was calculated using (3); the solution obtained is compared with the core loss directly calculated from the electromagnetic model using the current density in the core.

TABLE I. CORE LOSS CALCULATED FROM SIMULATION

Flux Density (T)	Core Loss (W/kg)		Difference (%)
	q_c	q_{cs}	
1.34	699.29	701.87	0.368

Fig. 3. Surface temperature distribution

Fig. 4. Side limb temperature rise plot

B. Experimental Result

Table. II shows the measured boundary conditions used for calibrating the IR camera.

The transformer was excited at different voltages, 120, 136, 144, 150 V while keeping the frequency constant at 300 Hz to obtain the core loss at different flux densities. The temperature rise of the core was recorded at different flux densities by adjusting the voltage supplied at a constant frequency. Fig.5&6 shows the temperature rise plot and thermographic image of the transformer core recorded for 30 seconds duration at a flux density of 1.48 T.

TABLE II. CAMERA CALIBRATION PARAMETERS

Parameters	Values
Emissivity	0.6
Reflected temperature	24 °C
Measurement distance	0.09 m
Atmospheric temperature	20 °C
Relative humidity	50 %
Specific heat capacity	485.6 J/kg°C
Core weight	0.3636 kg

The measured core loss is obtained by subtracting the no-load winding loss from the wattmeter reading and dividing this value by the core weight. The result obtained is compared with the core loss calculated from the initial rate of temperature rise as shown in Table III.

TABLE III. CORE LOSS CALCULATED FROM MEASUREMENTS

Flux Density (T)	Core Loss (W/kg)		Difference (%)
	q_c	Wattmeter	
1.09	13.37	12.68	5.44
1.24	16.99	16.50	2.97
1.36	25.70	24.26	5.94
1.48	34.47	32.94	4.64
1.53	37.48	36.39	3.00

Fig. 5. Core temperature rise at 1.48T

Fig. 6. Thermographic image of transformer core showing the temperature distribution after 30 seconds duration of supply

VI. CONCLUSIONS

In this paper, a method for measuring iron loss distribution and core loss density in an electrical machine has been developed based on thermographic techniques. The developed method has been applied to a 24/12 V transformer.

First, a simple numerical model of the proposed measurement to check the feasibility of the loss calculation process from the initial rate of temperature rise was simulated in COMSOL. A satisfactory result was obtained when compared with the numerical solution of core loss as shown in Table I. Secondly, an experimental measurement of the core temperature rise was carried out at different flux densities. The core loss obtained from the initial rate of temperature rise was compared with the measured values from wattmeter. Results show that they are in close agreement, with highest percentage deviation of 6 %, which is probably caused by experimental conditions and measurement parameter.

Finally, based on the experimental result, it can be concluded that thermographic techniques present a faster and simpler way for measuring core loss. The method involves a contactless and nondestructive measurement of temperature rise for loss computation, unlike other techniques that require complex equipment. In addition, the results obtained from transformer core measurement demonstrate that this technique can be used to determine localized core losses. However, results are affected by factors like emissivity of the core material, material constant, and the environmental conditions.

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