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APPLICATION OF THE TEMPERATURE-TIME METHOD FOR MEASUREMENT OF LOCAL POWER LOSSES IN TRANSFORMER STEEL PARTS

SUMMARY

Paper presents an application of temperature-time method for measurement of local losses in magnetic steel. Developed measurement system is described with focus on design of sensors and choice of instruments. Chosen equipment is tested on a DC circuit designed for measurement of losses in aluminum and copper conductors. Same measurement system is used for local loss measurement on magnetic steel rings. Measurement errors due to non-uniform loss distribution inside magnetic steel and heat dissipation to surrounding medium are analyzed and estimated.

Key words: local power loss, temperature-time method, magnetic steel, thermocouple, coupled calculation

1. INTRODUCTION

Stray losses in constructional steel parts are an important topic in transformer design process. High values of local loss densities in constructional elements can lead to temperature rises that can endanger transformer operation and lead to its failure. In order to determine local loss values, system with sensors for local measurement has to be used. One of appropriate methods for such measurements is the temperature-time method. The method relies on the fact that after a body has settled at a steady state temperature and internal heat source is suddenly removed or applied, initial rate of temperature change at any point is proportional to heat input (loss density) at that point. Correct application of this method thus allows both losses and their spatial distribution to be determined. So far method has found its application in measurement of losses in silicon-steel strips usually used for transformer cores [1] – [3]. Similar system has been used for measurement of stray losses in transformer tanks [4] and iron losses in induction motors [5].

2. TEMPERATURE-TIME METHOD

A possibility for determining local loss in constructional steel parts is to measure transient temperature-time curve and determine its initial slope. Example of determining the initial slope of a heated body is shown in Figure 1.

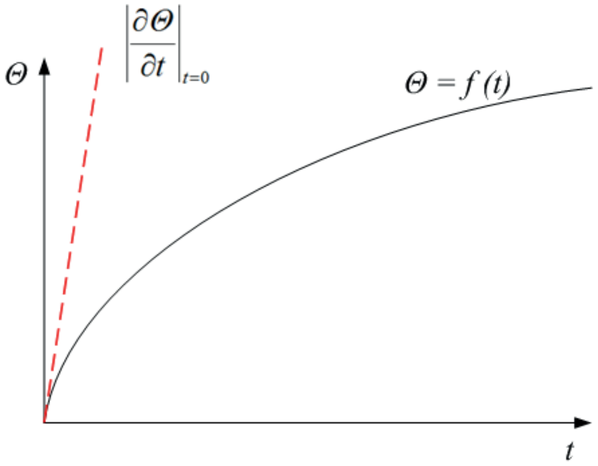


Figure 1 – Principle of determining initial slope of a heating curve

The curve shown in Figure 1 can be mathematically expressed by the heat diffusion equation in a simplified form

$$p = c\rho \frac{\partial \Theta}{\partial t} + q \tag{1}$$

where p is generated heat (power loss), Θ body temperature, c thermal capacitance, ρ mass density and q heat dissipated to surrounding regions. Surrounding regions to which heat dissipates are cold metal bodies (where generated heat is much lower than at the measurement point) and surrounding fluids (which cool the heated body by convection or radiation). Dissipated heat highly depends on temperature differences between the measurement point and surrounding regions. As temperatures of heated bodies grow dissipated heat from measurement points become higher and cause the initial straight line to turn into an exponential curve. So, if initial conditions consider all metal parts and the surrounding fluid at equal temperatures, for $t = 0$ it can be stated $q = 0$, and expression (1) can be written as

$$p = c\rho \left|\frac{\partial \Theta}{\partial t}\right|_{t=0} \tag{2}$$

Therefore, heat loss at any point can be obtained by multiplying the initial temperature gradient, mass density and thermal capacitance of the material under test. However, it is important to determine initial section where temperature-time curve can be considered as a straight line because of negligible heat dissipation. This will highly depend on type of convection cooling the heated parts are exposed to and how non-uniform power losses are in the body observed. The easiest solution would be to thermally isolate the observed body and to use the method only in cases of uniform heat sources inside the body. However, this is not easy to achieve in practice, such as in cases of power transformer.

3. DETAILS AND VERIFICATION OF THE MEASUREMENT SYSTEM

The first step when making a measurement system for the temperature-time method for loss measurement is to choose sensors for temperature measurements. The probes should be robust and have good thermal connection with the measurement point. Another important requirement is to be able to measure temperature instantly. Thus, sensors should have negligible heat capacity as recommended in [1] and [2]. To meet all of these requirements thermocouples were made from 0,08 mm thick constantan and copper wires. When working with AC power sources it is obligatory to twist the two wires together, so that AC pick-up in inductive loops of sensor leads is minimized. The measurement junction was placed and fixed on a point where losses are to be measured, while the reference junction was inserted in a water bath at a stable and known temperature. The main disadvantage of thermocouples is that they have relatively weak signal. For example, copper-constantan (T-type) thermocouples have sensitivity of about 43 μV/°C. In order to detect temperature changes of 0,001 °C, a so-called nanovoltmeter with resolution of 1 nV was used. Thermocouple voltage was recorded every 0,2 s and processed by a LABVIEW [6] application on a computer. Full developed measurement system is shown in Figure 2.

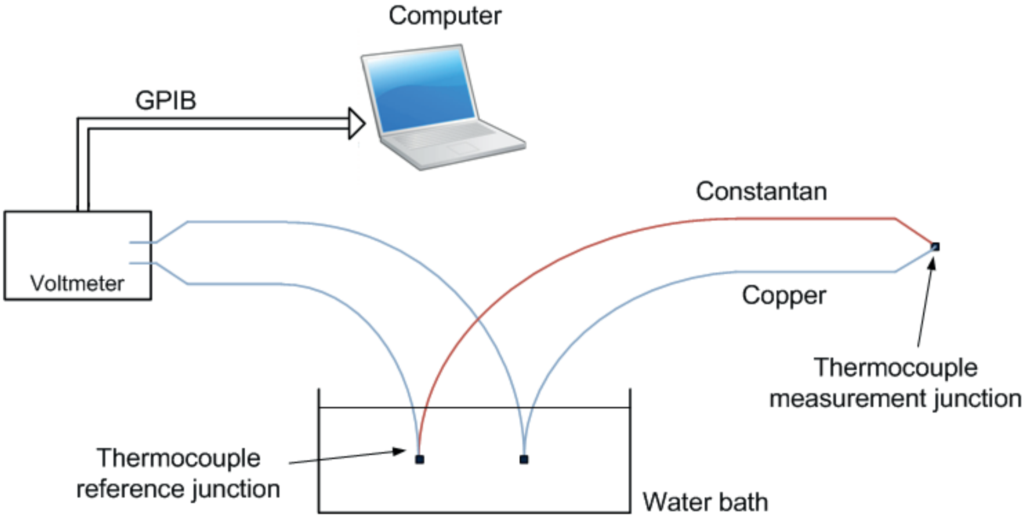


Figure 2 – Measurement system

In order to test applicability of chosen sensors and instrument for the loss measurement method, measurement system was first tested on aluminium and copper strips. Thermocouple measurement junction was fixed in the middle of 1000 mm long copper and aluminium strips, as shown in Figure 3. Circuit breaker was used to apply a DC voltage source suddenly to the strips, while resistors were used to change current in the circuit.

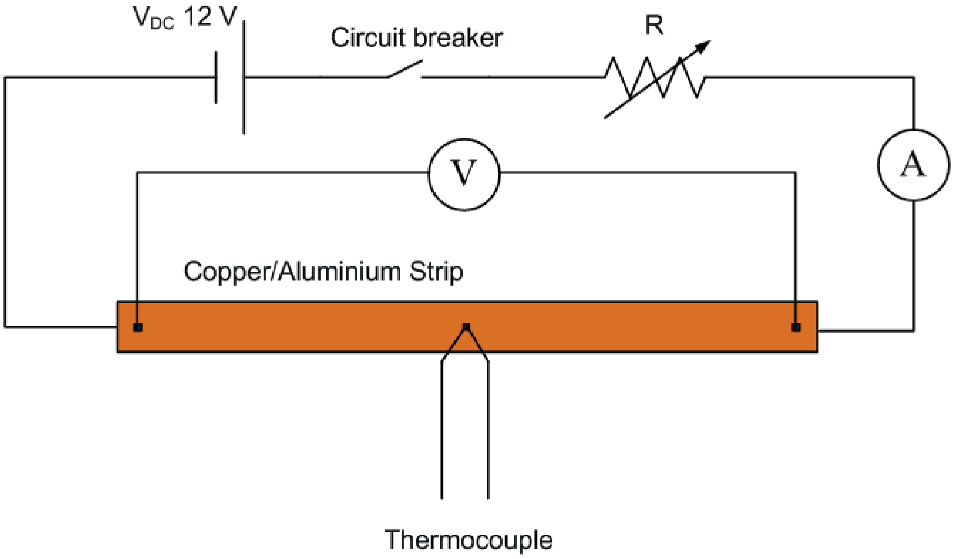


Figure 3 – Measurement of losses on copper and aluminium strips

An example of a recorder temperature-time curve is shown in Figure 4. Initial gradient for the curves was calculated from the temperature change in Δt = 1 s after the voltage source was applied. From the measured temperature gradient and expression (2) value of local losses in W/m^3 were evaluated. Specific heat capacity of copper was 385 J/kgK and of aluminium 890 J/kgK. Mass density of copper was 8940 kg/m^3 and of aluminium 2700 kg/m^3. At the same time current and voltage of tested conductors were measured. Total losses of conductors were evaluated by wattmeter and compared with results from the temperature – time method in Table I.

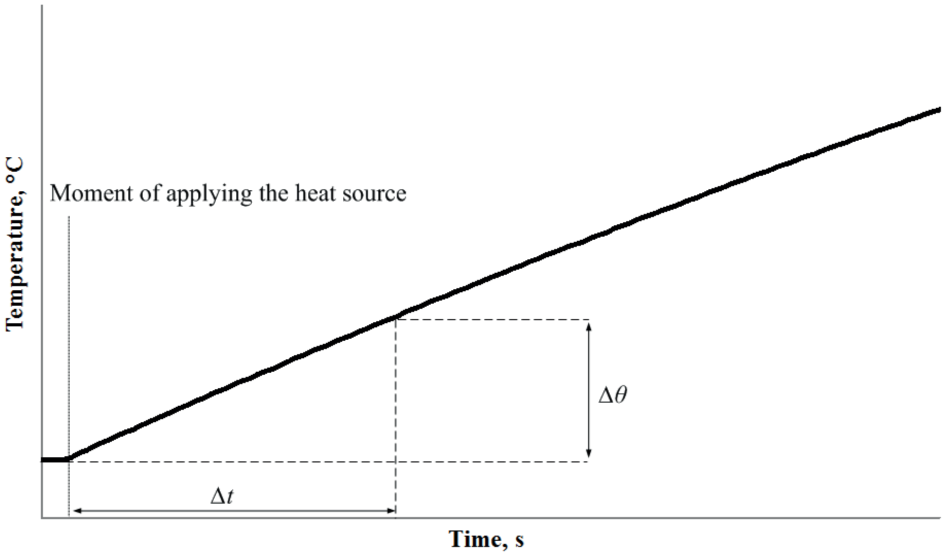


Figure 4 – Principle of determining temperature-time gradient

Table I –Measured losses in aluminium and copper conductors

Conductor	Current, A	Measured gradient, °C/s	Total losses, W		Ratio (1)/(2)
			Temperature-time method (1)	Wattmeter (2)	
Copper 1,0 x 15 mm^2	81,5	0,143	6,64	6,83	0,97
Copper 5,6 x 4,0 mm^2	98,3	0,098	6,80	6,80	1,00
Aluminium 2,0 x 15 mm^2	80,8	0,088	5,71	5,51	1,04
Aluminium 9,0 x 2,5 mm^2	95,0	0,230	12,43	11,30	1,10

Results from both measurement methods showed good agreement. Experiment has confirmed the suitability of thermocouples as sensors and nanovoltmeter as an instrument for local power loss measurement by the temperature-time method.

Here it should be emphasized that losses that were measured were distributed uniformly inside the heated object (copper/aluminium conductors). This is not the case when losses are caused by eddy currents in thick magnetic materials. Due to small skin depth (from 1 to 3 mm) of magnetic steel parts, losses are localized in a thin layer at surface of a magnetic part. Cold metal interior cools the surface layer, making value of the dissipated heat from equation (1) substantial.

Experiments with conductors were done in air. In case of transformers, metal parts are in most cases in contact with oil. Convection cooling by oil is much more efficient than convection by air. This can have additional influence on measurement results of the temperature-time method.

4. MEASUREMENT AND CALCULATION OF LOSSES IN MAGNETIC STEEL

When heat sources are non-uniform, errors in measured losses will occur if the temperature rise being measured is not completed before appreciable heat diffuses to or from other parts of different temperatures. The errors in these cases can be estimated by analysis of heat transfer on a simple geometry.

An experimental ring made of magnetic steel wound throughout its circumference with a copper conductor was considered as a model for evaluating possible measurement errors. Configuration is shown in Figure 4. Inner ring diameter D_i was 325 mm, outer diameter D_o 385 mm. By changing the thickness of the ring b, it was possible to better understand the influence of dissipation of heat to cold metal interior on the error of measurement. Coil wound around the ring was excited by a sinusoidal current source of frequency 50 Hz. Magnetic permeability of magnetic steel was modeled as a single-valued B-H curve, while electrical conductivity was 6,56 MS/m.

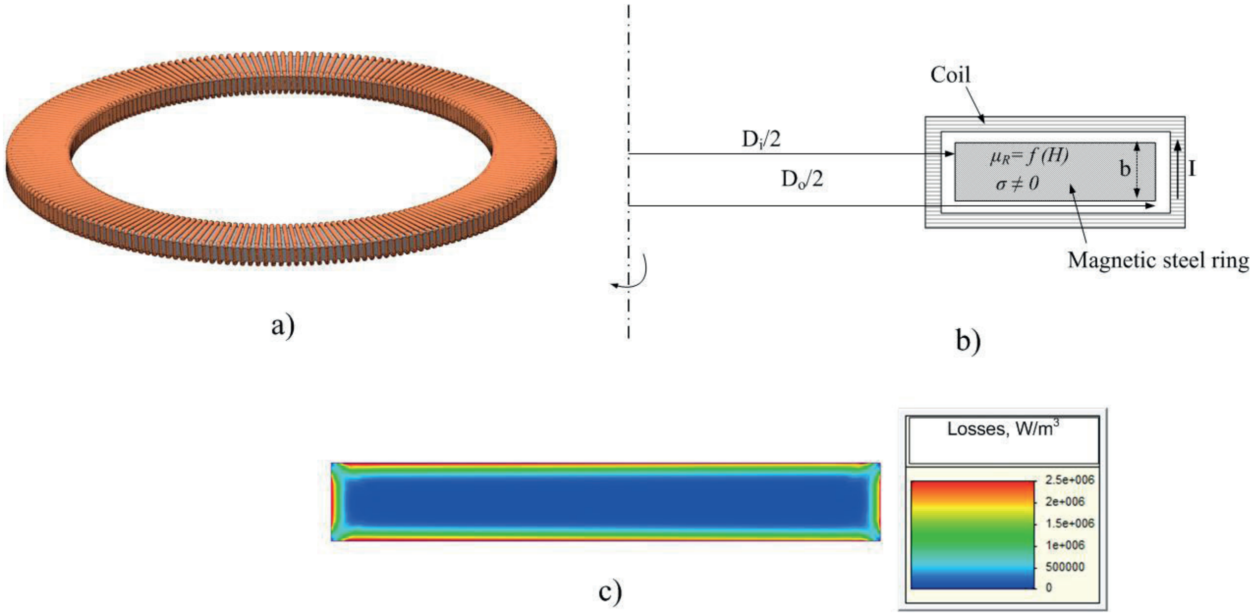
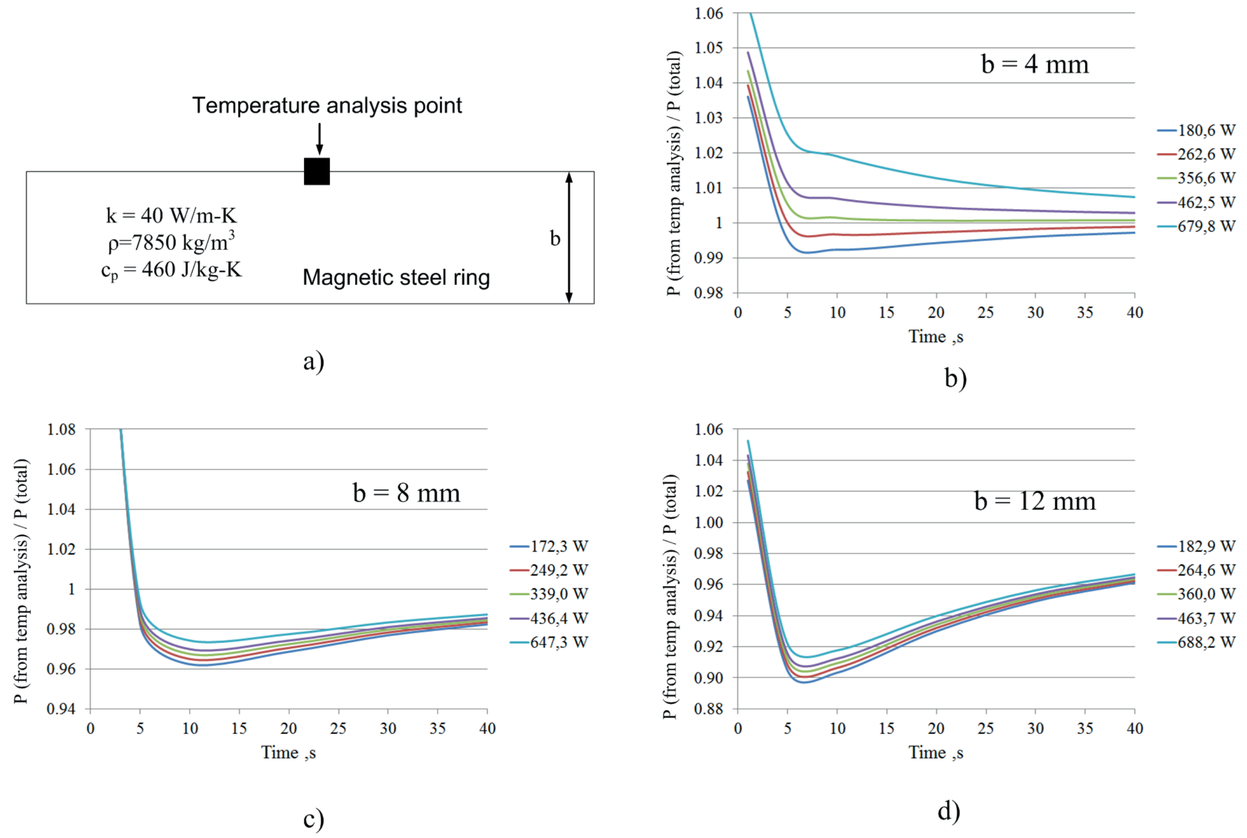


Figure 4 – a) Experimental magnetic steel ring, b) 2D model in MagNet, c) Loss distribution inside the ring (MagNet)

The model from figure 4 b) was also analyzed in thermal finite element method (FEM) software ThermNet [7]. Losses calculated in MagNet represented heat sources in ThermNet. Using a time “step-by step” (Transient) calculation in ThermNet it was possible to calculate temperature-time curves for different losses induced inside the ring. Heat dissipation to ambient was neglected in order to solely observe influence of non-uniform distribution of losses inside steel to the measured gradient. Since the losses were distributed non-uniformly it was necessary to analyze temperature-time curves on various positions inside the ring. The most interesting temperature-time curves were on the surfaces of the ring (where measurements with thermocouples can be made). Figure 5 a) shows the position where temperature-time curves were analyzed. In Figure 5 b)-c) calculation results are shown for 4, 8 and 12 mm thickness of steel ring. Curves show ratio of total ring losses determined from the initial slope of temperature-time curve after time Δt to total losses calculated by MagNet. Losses from temperature-time curves were evaluated by using expression (2) and considering temperature gradient as uniform inside the ring volume. Density of steel was 7850 kg/m^3 and specific heat capacity 460 J/kgK. Curves are shown for various total losses inside the ring. Losses in the ring were regulated by changing the current through the coil wound around the ring.

For three different thicknesses of the ring it is quite clear that after 5 to 10 seconds total losses determined from temperature gradient of the ring will not differ more than 10 % from calculated losses by MagNet. This is an interesting result from the practical point of view. Measurements can be made after couple of seconds when temperature rise becomes significant (from 0,1 to 1,0 °C) and enables a more accurate estimation of the initial temperature gradient.



a) b) c) d)

Figure 5 – Ratio of losses determined from temperature-time curves at different time instants to total losses

Model used for numerical calculation has been built and tested in laboratory. Basic idea was to measure total losses inside the ring (similarly as shown for copper and aluminium conductors) and compare with measurement from the temperature-time method. Experimental setup is shown in Figure 6.

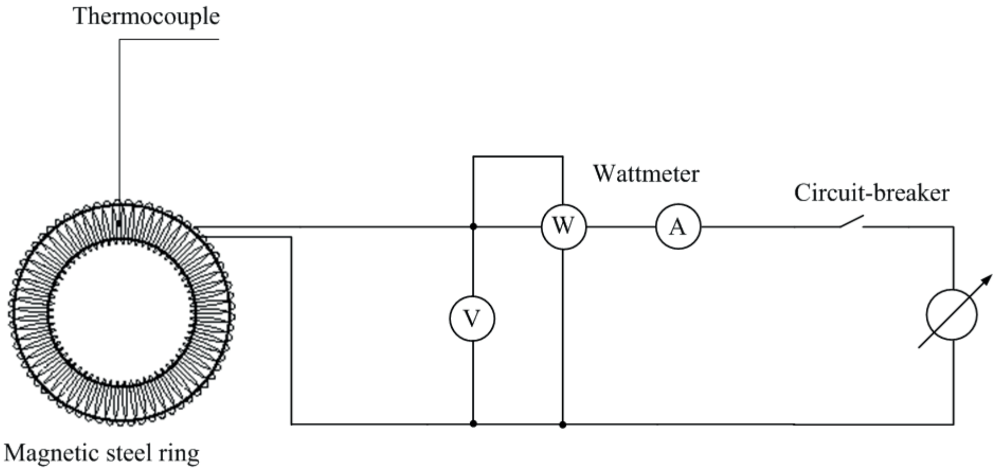


Figure 6 – Experimental setup for application of temperature-time method on magnetic steel ring

Total losses in the model were measured by a wattmeter and compared to measured losses by the temperature-time method. Measurements were made with steel ring in air and immersed in transformer oil. Usually transformer steel parts are in contact with oil, so influence of cooling conditions that are usually present in practice were observed. Steel ring in laboratory with thermocouples fixed on its surface is shown in Figure 7. The ring had the same inner and outer diameter as the numerical model, while the thickness was 8 mm. Coil wound on the steel ring had 100 turns. Clearances between adjacent turns of the coil were made in order to enable easier fixing of thermocouples on steel surface.

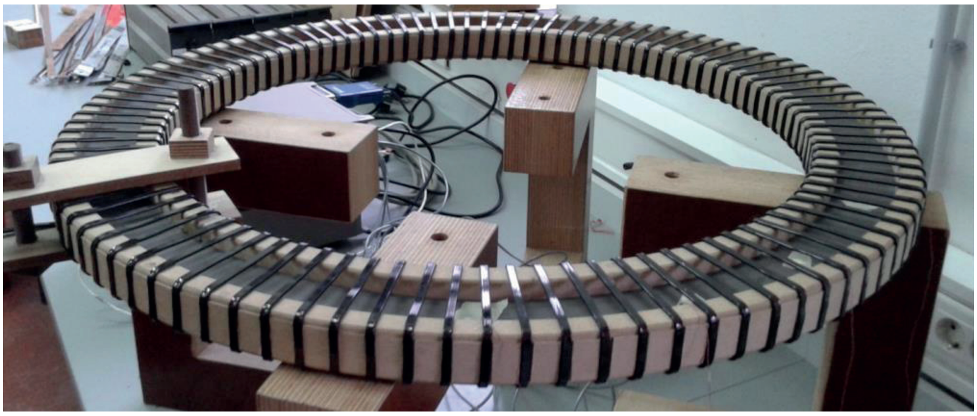


Figure 7 – Magnetic steel ring used for experiment

Results of temperature rise measurements in air and oil are shown in Table II. Results are presented for different values of magnetic field in the middle of the ring. Initial gradient of temperature-time curves was calculated from the temperature change Δt = 10 s after the voltage source was applied

Table II – Measurement results on magnetic steel

Magnetic field, A/m	Wattmeter losses (1), W	Air		Oil	
		Temperature-time method (2), W	Ratio (2)/(1)	Temperature-time method (2), W	Ratio (2)/(1)
2764	191,0	181,7	0,951	167,5	0,877
3430	272,6	261,6	0,960	244,9	0,898
4121	365,5	351,8	0,963	326,0	0,892
4825	465,4	452,3	0,972	425,3	0,914
6150	673,1	671,4	0,997	625,0	0,929

Results of the temperature-time method in air agree within 5% of measured wattmeter losses. Experiment has shown that when magnetic steel is immersed in oil, due to heat dissipation from magnetic steel to oil, measured temperature gradient decreases up to 8%. From practical point of view, this is an important result, since it is hard to evaluate heat transfer coefficients at positions where thermocouples are to be placed, especially in cases of small temperature differences between heated object and surrounding fluid.

5. CONCLUSION

Temperature-time method has found its application in various materials that are used in electrical machine and transformers. The paper has shown the potential of its application for determining local losses in magnetic steel usually used for constructional metal parts of transformers. Although losses in steel are mostly non-uniform and hard to measure locally, a simplification of the measurement method was proposed which solves this practical constraint. From results of electromagnetic and thermal FEM calculations it was possible to determine appropriate time instant at which temperature gradient can be calculated. From measured temperature gradient it was possible to determine total losses in the geometry and compare with wattmeter measurement. Difference between two measurement methods was not higher that 5 %.

Additionally, difference between measurement in air and oil was pointed out. Convection cooling by oil had additional influence on measured temperature when sensors were fixed on steel surfaces. Differences between measured temperature gradient in air and oil were not higher than 8 %.

Future research will be focused on application of the temperature-time method on transformer steel parts exposed to air and oil cooling (e.g. tanks) and comparison with FEM magnetic and thermal calculation.

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