Opportunities and Precautions in Measurement of Power Loss in Electrical Steel Laminations Using the Initial Rate of Rise of Temperature Method

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***Abstract*— A system has been developed for measuring localised power loss of electrical steel laminations based on the *initial rate of rise of temperature* method. Hardware and software components were designed and developed individually to make an accurate measuring system. Three experiments were carried out to calibrate the system and quantify its accuracy over a wide measurement range. The application of the measuring system was demonstrated in two cases of measuring localised power losses near bolt holes in laminations and near artificial lamination edge burrs in a 300 kVA, 3 phase transformer core. The experimental results show that the developed system can measure localised power loss over a wide range with uncertainty of measurement less than ±2%; but precautions are necessary when interpreting measurements in regions where the magnitude of the loss varies significantly over distances of less than a few centimetres.**

Keywords: Thermometric measurements, localised power loss, initial rate of rise of temperature, electrical steel.

1. INTRODUCTION

Electrical steels are widely used as the cores of electrical machines such as transformers, generators and motors. The energy conversion process in the electrical machine always implies magnetic core losses which have an impact on a machine's cooling requirements and efficiency. Therefore, a good knowledge of the losses dissipated in different parts of cores assembled from electrical steels or laminations of other soft magnetic materials are desired at the design and prototyping stages. Although localised core losses can be predicted from computational electromagnetic models, they are not always sufficiently accurate for complex practical core geometries or anisotropic magnetic materials, so experimental methods still need to be turned to.

The overall power loss of single strip lamination or assembled cores is measured using well established conventional systems utilising wattmeters [1-4] but they cannot be adapted to measure localised power loss. Losses in a single strip are occasionally derived from voltages induced in an embracing search coil and a surface magnetic field detector such as a Hall-effect sensor, magneto-resistive sensor or H-coil. The outputs of these B(t) and H(t) sensors are used to compute the loss over regions, in which they are located [5] and [6]. Repeatability and accuracy of such sensors is high for single strip measurements but they are difficult to use in measuring localised losses within a core. Deposition of thin film sensors for measuring localised B(t) inside a stack of laminations or a core has been successfully demonstrated [7].

Laffoon et al. [8] demonstrated the possibility of calculating localised losses by analysing temperature-time curves measured immediately after sudden application of a magnetic field to the core of a synchronous machine.

The principle of the thermal method of measuring localised losses is based on the fact that losses generated in different parts of the magnetic cores can be obtained by measuring the energy absorbed or released when operating conditions are changed. Provided that the ambient temperature remains constant for the duration of the test, the initial rate of rise of temperature is proportional to the heat input, and hence the localised power loss, at the measurement points [9]. This principle has been widely applied by previous researchers [5-23] to measure localised power loss in magnetic cores.

The application of the thermal method to loss measurement in electrical machine cores was improved by attempting to take account of heat transfer to surrounding parts of the magnetic cores as reported in detail by Gilbert [10]. Results showed that temperature changes must be accurately measured for about 5–10 Sec. However, step recording of the output voltage of the thermocouple was the main drawback of the approach which reduced the accuracy of the measurement. Ball and Lorch [11], by using a 0.0254 mm thick thermocouple wire and a DC amplifier introduced an improved method of measuring localised power loss in individual laminations in an Epstein square. In this work a thermocouple was stuck to the centre of, a strip and magnetised as part of a pack in an Epstein square for about 1 Sec. Due to time delays in the thermocouple and amplifier's response in converting and amplifying voltage to temperature, measurement did not start until about 0.5 Sec after energizing the core creating a possible large error in recording the true initial rise of temperature. The authors assumed that the surface of the sample was heated uniformly and was thermally insulated which is not the case in practice particularly in transformer joints as well as near the teeth of stator cores or near bolt holes or near edge burrs in stacked cores in general.

Albir and Moses [12] proposed using thermistor in an improved DC bridge to measure localised power loss of silicon iron. To verify that the output of the bridge was proportional to the heat transfer from the surface of the material to the surroundings, a DC current was passed through a copper strip and the I^2R loss was measured. However no details of the verification results were reported. Moses et al. [13] measured localised power loss at the T-joints of a three phase transformer core using thermocouple sensors. However twisted wire leads placed between the laminations make air gaps between the laminations and could have affected the accuracy of the measurement.

Basak et al. [14] vacuum deposited thin film sensors in the form of search coils and thermocouples in order to measure localised flux density and power loss in transformer cores. The thickness of the sensors ranged between 0.012µm and 0.05 µm so the air gap between adjacent laminations was insignificant. However, no results related to calibration and evaluations of the deposited thermocouples were reported.

Moses and Tutkun [15] investigated the localised power loss of a stator lamination made from non-oriented silicon free electrical steel at locations behind slots and teeth, under PWM and sinusoidal excitations by using thermistors in a four-arm DC voltage bridge. The localised power losses obtained by measuring the rate of rise of temperature over a 20 Sec energisation time was claimed to have a maximum error of ± 8%. However, Gilbert [10] showed that the difference between actual and measured rate of rise of temperature increases with the time over which the slope of temperature-time curve is measured and claimed that small temperature-time changes typical in silicon steel cores under normal magnetisation condition must be measured over less than the initial 5~10 Sec.

Localised power loss measurement based on the initial rate of rise of temperature method has been used by other authors to measure localised power loss in cores under sinusoidal and PWM excitations where measurement errors using **B**(t) and **H**(t) voltages are potentially high due to the high level of harmonic distortion in the measurement voltages [16-23]. But no reference could be found which has provided details of the configuration of the measuring system and the most important point, no verification and calibration of the measuring systems has been reported.

The main objective of the research presented in this paper was to develop a measuring system based on the initial rate of rise of temperature method to measure localised power loss with high accuracy verified by considering all of the required parameters of the method. Since in the previous published works, the validation of the accuracy of the measuring systems has not been reported, this paper initially covers results of experiments carried out to calibrate and quantify the accuracy of the new system for calculating local losses from initial rate of rise of temperature measurements. The basic capability of the developed system was demonstrated firstly by measuring I^2R loss of copper strip in a non-magnetic environment and secondly in a nominally uniformly magnetized Epstein square. The reliability and accuracy of the system is verified by demonstrating its use firstly in measuring localised power loss around bolt holes in a single lamination, where relatively small changes in loss occur and secondly in the case close to burred edges of a transformer core where rapid changes of localised loss occur in the region close to the burr.

2. THERMOMETRIC METHOD

The power dissipated in the steel at any part of a magnetic core may, under some conditions, be determined by measuring the initial rate of rise of temperature occurring after energizing the core. The principle of this method has been described in detail previously [11], [21] and [22] but because of the importance of this methodology in this paper, it is briefly summarised here.

In this method, within the considered regions of the power loss measurement, the condition *grad T(t)=0* should be exactly satisfied. The dynamic energy balance of thermal power loss can be defined in the simplest way by [22]:

$$p = \frac{dQ}{dt} + \frac{dQ_{ext}}{dt} \tag{1}$$

where p is thermal power loss, dQ/dt is the rate at which thermal energy Q is cumulated in the sample maintained at the temperature $T(t)$ and dQ_{ext}/dt is the rate at which the heat is transmitted to the environment. We can write:

$$\frac{dQ}{dt} = c_p \frac{dT(t)}{dt} \tag{2}$$

where c_p is the specific heat of material. The rate at which heat is transmitted to the surroundings at temperature T_0 is given approximately by:

$$\frac{dQ_{ext}}{dt} = k_{ext}[T(t) - T_0] \tag{3}$$

where k_{ext} is the heat transmission coefficient, $T(t)$ is the absolute temperature of the sample at time t after change in the operating conditions and T_0 is the initial temperature of the sample and surrounding before change in the operating condition. From (1), (2) and (3) p can be expressed as:

$$p = c_p \frac{dT(t)}{dt} + k_{ext}[T(t) - T_0] \tag{4}$$

Initially (switch-on time t_{ON}) the sample is in thermal equilibrium with the surrounding environment (i.e. $T_{ON}=T_0$). The magnetisation is switched off at switch-off time t_{OFF}, when the sample temperature is T_{OFF}. The temperature increase occurring after magnetising the sample is obtained by integrating (4) and is expressed as:

$$T(t) = T_0 + \frac{p}{k_{ext}}\left[1 - \exp(-\frac{k_{ext}}{c_p}(t - t_0))\right] \tag{5}$$

Using typical values of k_{exp}=4.4 W/kg ^oC, c_p=485.6 J/kg^{o}C and p=1 W/kg for grain oriented electrical steel and ambient temperature T_0=25 °C, the rise of temperature immediately after magnetisation was obtained by equation (5) as shown in Fig 1. Thus if a temperature-time curve is taken at a point during the period immediately before and after applying the unit function, i.e. sudden magnetization of a magnetic core, the change in slope at the instant of applying the function will be a measure of the heat generation or power dissipated at the point.

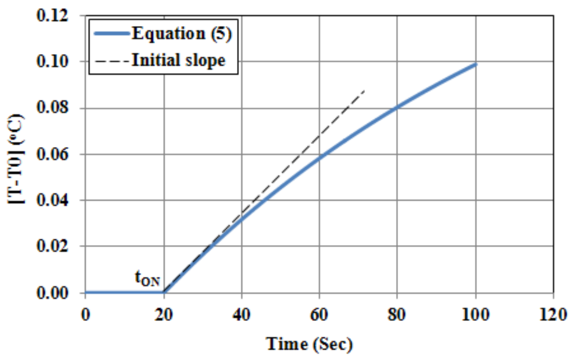


Fig. 1 Example of temperature increase versus time of electrical steel after magnetizing based on equation (5)

k_{ext}, is related to the heat transfer between the surface of the steel and surrounding air or non-magnetic transformer components. Under perfect adiabatic condition this coefficient tends to zero (k_{ext}=0) and therefore (4) reduces to [21]:

$$p = c_p \frac{dT(t)}{dt} \qquad Wkg^{-1} \tag{6}$$

Equation (6) shows that the method is essentially dependent on accurate measurement of the initial rate of rise of temperature to obtain the true value of the power loss. Therefore in order to minimise errors in measurements of the initial rate of rise of temperature and coordinate all of the measurements, Excel curve fitting function was used to obtain the initial slope of the temperature-time curves.

3. DETAIL OF THE MEASURING SYSTEM

Core losses in typical electrical machine applications incorporating electrical steels, high saturation cobalt iron alloys or energy efficient iron-based amorphous materials range from around 0.1 W/kg to 20 W/kg corresponding to initial rates of rise of temperature from 0.2 milli-deg Sec^{-1} to 40 milli-deg Sec^{-1}. Hence, this system was designed to cover this range of temperature rise to an accuracy of ± 2 %. In this section, detail of the measuring system including hardware and the flowchart is presented.

3.1. Basic block diagram of the measuring system

A basic block diagram of the measuring system is shown in Fig. 2. This block diagram comprises thermocouple, thermocouple cold junction compensator and amplifier, data acquisition card (DAC), signal processing and noise filter and a PC. A thermocouple type K was used for the temperature measurement. A cold junction compensator (CJC) was used to provide a reference temperature.

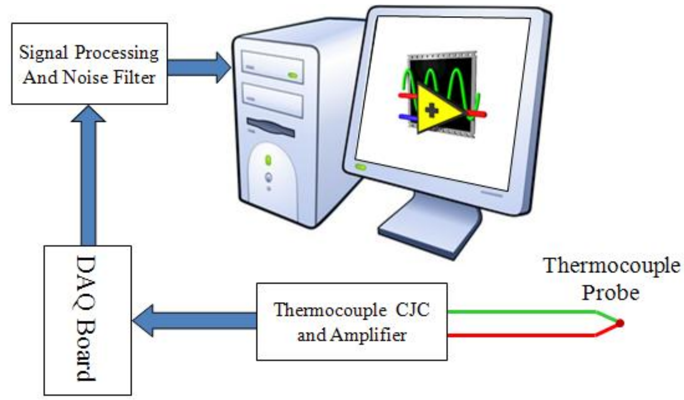


Fig. 2 Basic block diagram of the measuring system

Conversion coefficient of type K thermocouple is 40.41 µv/°C [21], i.e. by increasing 1 °C in core temperature the output voltage of the thermocouple increases by 40.41 µv, therefore a high precision amplifier was necessary for accurate measurements in the low region. A six channel electronic circuit was used to compensate the cold junction of the thermocouples and amplifying the output voltages. The amplified voltages were acquired by means of a “NI DAQPad 6259” data acquisition card then digitally integrated in “LabVIEW 10.0” and finally saved in Excel database. Before converting the signal voltage to temperature, a Fast Fourier Transform (FFT) analysis was carried out to recognize and filter the harmonics in the main voltage. The filtered voltages were finally recorded in Excel files.

3.2. Flowchart of the measurement

Fig. 3 shows a flowchart of the localised power loss measurement procedure. According to the designed flowchart the excitation voltage of the magnetising system is controlled to set the required constant flux density in the magnetic core. Prior to the start of measurements, the sample is held under adiabatic condition for appropriate time, which depends on the sample materials and geometry, flux density and magnetising frequency, to achieve a constant temperature in the core and surroundings. The temperature is then monitored for 30 seconds before energising the magnetising system to ensure it is stable to within ± 0.02 °C of the initial ambient setting. The excitation voltage is applied and the initial slope of the temperature-time curve is calculated by using linear trend-line method in Excel and consequently local power loss is calculated by using Eq. (6). A final 60 Sec interval is allocated at the end of each measurement to show the cooling curve of the specimen, as shown later in Fig 10, for example. The interval between measurements on a given sample is set to allow sufficient time for the specimen to return to its initial temperature before magnetisation, i.e. T_0 in equation (5). Finally the average value of the localised power loss is calculated and by considering uncertainty of different part of the measuring system, the combined uncertainty of measurement is calculated.

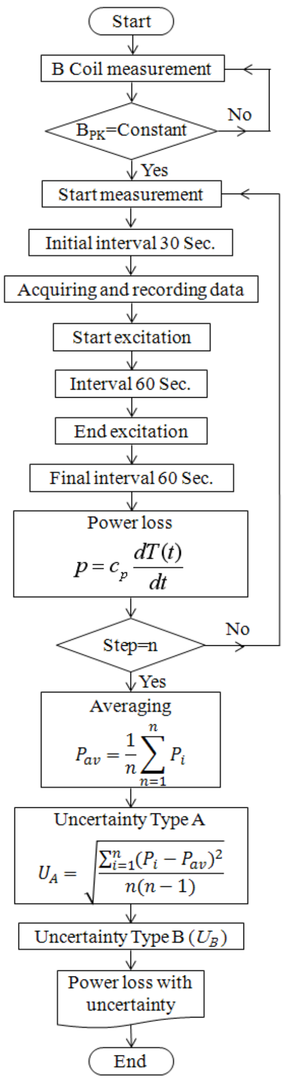


Fig. 3 Flowchart of the measurement system

4. DATA ACQUIRING AND SIGNAL PROCESSING

The main challenge of this type of measurement is dealing with the noise in the output voltage of the thermocouple circuit. Therefore one of the main tasks of this measuring system is signal processing to filter the noise. In this work, detecting and filtering the existing noise was carried out partly by MATLAB/Simulink and partly by LabVIEW. Interface software was set up to transfer data from MATLAB/Simulink to LabVIEW and vice versa.

4.1. Assessment and filtering of the noise

In order to assess the source and order of the noise existing at the output voltage of the measuring system, instead of the thermocouple voltage, a 1 mV DC constant voltage was applied to the input of the measuring system. To identify the harmonic components, the output generated voltage of the measuring system was exported from Excel to MATLAB/SIMULINK.

The analysis results demonstrated that a 50 Hz harmonic and low level high harmonic components were sometimes present at the output voltage. In order to suppress the noise two filters were used; a band-stop filter was used to remove the 50 Hz harmonic and a low-pass filter was used to remove the high frequency harmonics. The raw output voltage of the measuring system, which is converted to represent temperature by multiplying it by the conversion coefficient of the thermocouple, and the filtered waveforms obtained from each step of the filtering process are shown in Figs. 4-a. In order to compare the final output with the raw output, a zoomed-in view of this figure for 0.2 ^{o}C over 0.3 Sec. is shown in Fig 4-b.

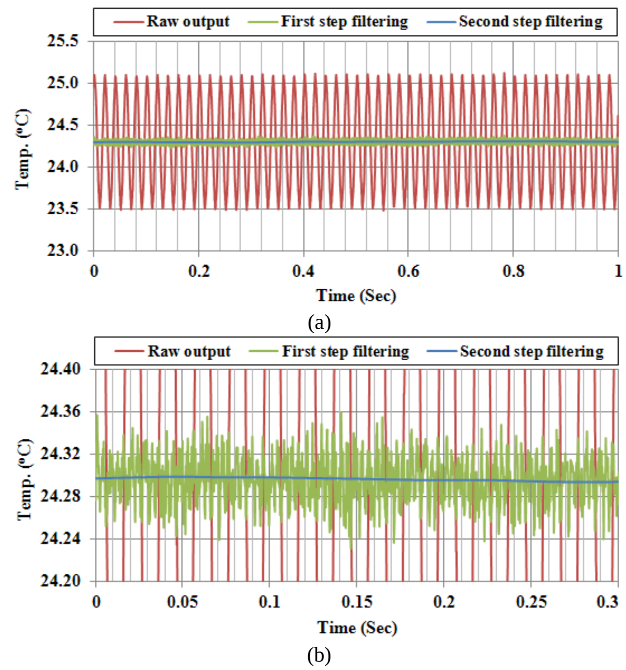


Fig. 4 Compression of raw and filtered output of ambient temperature

Fig. 4 shows that the implemented filter is sufficiently effective to filter the existing noise and it is reliable to use in the measuring system.

4.2. Effect of the filters on the initial slope of the temperature-time curve

In order to investigate the effect of the filters on the initial rise of temperature, a temperature-time curve similar to a real rise of temperature in magnetic cores with an initial slope of 0.8 ^{o}C/Sec was simulated by MATLAB and a random noise to represent the existing noise at the measure temperature was superposed onto it. The combined signal was used as the input of the measuring system. This software generated a temperature-time curve similar to the rate of rise of temperature expected in a core immediately after magnetising. The input temperature curve is shown in Fig 5-a; a zoomed-in view of this figure over 1 Sec is shown in Fig. 5-b. Obviously, the produced curve contains many harmonics with different amplitudes and frequencies, therefore it is an appropriate choice to investigate the performance of the noise filtering of the measuring system.

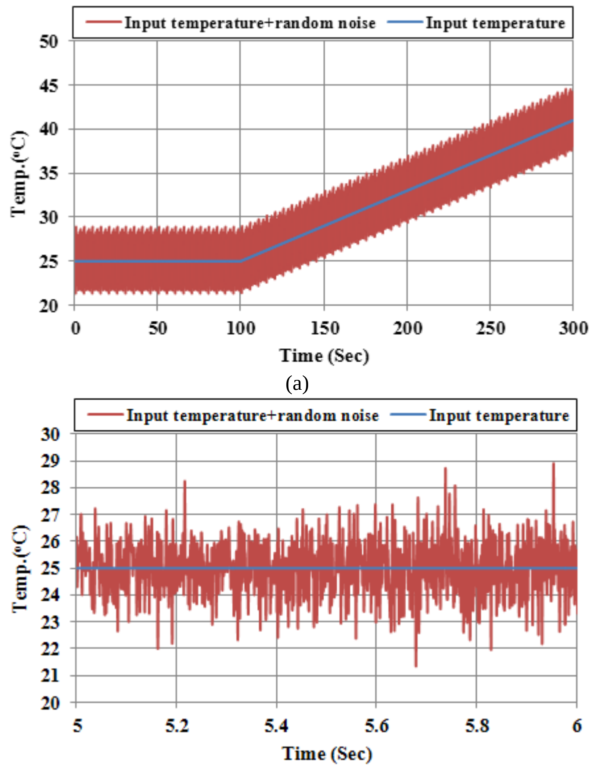


Fig. 5 (a) An ideal input signal with superposed artificial signal noise
(b) zoomed-in input signal for $5 \le t \le 6$

The output temperature which is obtained from this test showed in Fig. 6 confirms that the artificial noise is totally filtered. Since the initial slope of the graph is the most important parameter, the linear slope of the input temperature-time curve and the output filtered temperature-time curve were calculated by using the Excel curve fitting function in order to check the effect of the filter on the initial rise of the curve. The results shown in Fig. 7 confirm that the artificial noise at the input port is filtered while the main input is not affected; hence the system is reliable for measuring localised power loss of soft magnetic materials.

5. VERIFICATION OF THE MEASURING SYSTEM

5.1. Internal temperature of an adiabatic chamber

A change of ambient temperature during the measurement period can affect the localised power loss measurements. Therefore it is normally beneficial to magnetise the specimen while enclosed in an adiabatic chamber. All the measurements presented in this paper were carried out inside adiabatic enclosures.

An example of need for an adiabatic box is shown in Figs 8. Fig. 8-a shows that the maximum variation of ambient temperature without an adiabatic box is about 0.16 °C over a 60 Sec measurement; while from Fig. 8-b the maximum variation of the temperature inside the adiabatic box is less than 0.02 °C over the same duration. This temperature variation in the ambient temperature could cause a noticeable error in the measurement, e.g. if the localised power loss measured in a magnetic steel is 0.446 W/kg, the initial rate of rise of temperature is less than 10E-4 ^{o}C/Sec (see section 6.1); therefore a 0.16 °C variation in ambient temperature over a 60 Sec measurement can cause a noticeable error in the power loss measurement. This test demonstrated the need of using an adiabatic box when losses of less than 0.5 W/kg were anticipated if accuracy better than 2 % is required.

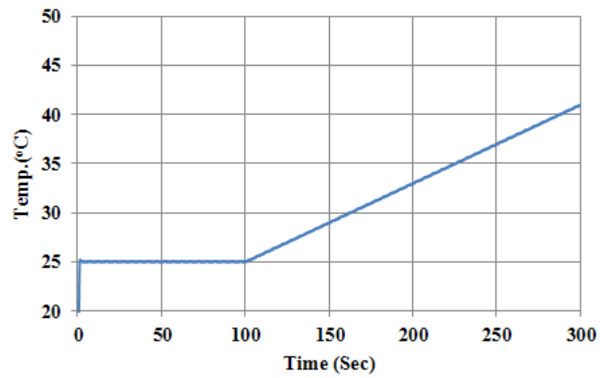


Fig. 6 Output temperature after filtering the artificial noise

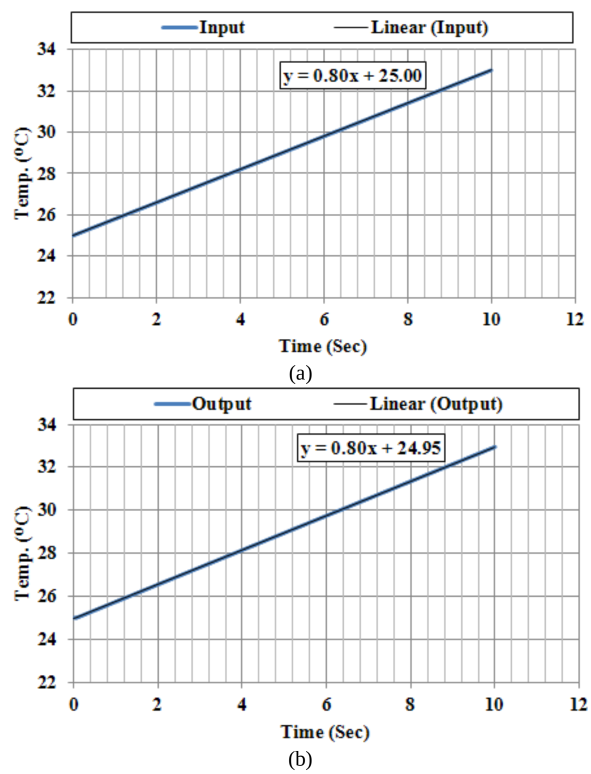
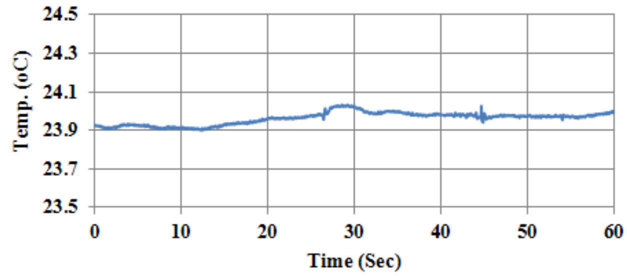


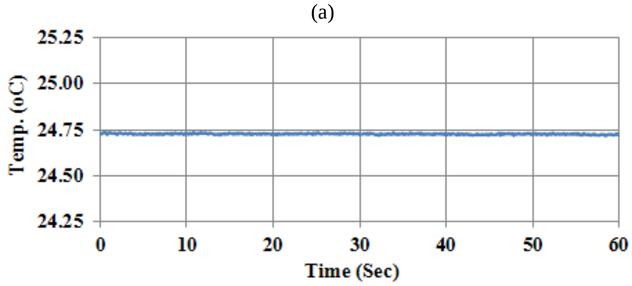
Fig. 7 Equivalent linear equation of (a) input signal (b) output signal

5.2. Power loss distribution in a copper strip heated by a DC current

The accuracy and capability of the system was verified in stages firstly by passing a known DC current through a copper strip, whose specific heat was 385 J/kg°C , and measuring the "Ohmic" losses at four positions shown in Fig 9.



(a)



(b)

Fig. 8 Ambient temperature (a) Outside of the adiabatic box (b) Inside of the adiabatic box

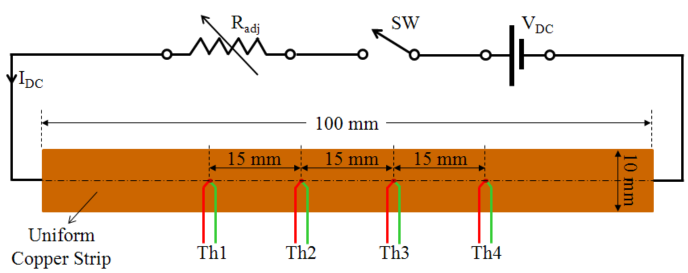


Fig. 9 Uniform copper strip as a part of a DC circuit to calibrate four thermocouples

In this way the thermocouples were calibrated and the accuracy of the complete measuring system was quantified with no effect of local material homogeneities or magnetic interference which could occur in measurement of local losses in soft magnetic materials. A similar approach has been carried out previously [13] but no experimental detail was reported. 1 amp to 5 amps DC current was passed along a 100 mm long, 10 mm high and 0.5 mm thick copper strip as indicated in Fig 9. The four thermocouples were located as shown on the pre-insulated strip surface. An example of the temperature rise versus time at point 1 is shown in Fig. 10. The initial slope of this curve (over a 30 Sec period) is 4.43E-3 ^{o}C/Sec corresponding to a localized loss of 1.71W/kg.

Measured localised power losses including repeatability or type A uncertainty U (A), and combined uncertainty or type B uncertainty U (B), are shown in table 1. The uncertainties of the measuring systems were estimated according to the recommendations given in UKAS M3003 [24]. These results as a function of thermocouple position are shown in Fig. 11. These values are average of 3 measurements at each point and each current. The calculation uncertainty took into account the uncertainties in the localised power loss measuring system, the strip resistance measurement and the uncertainty in the DC current measurement.

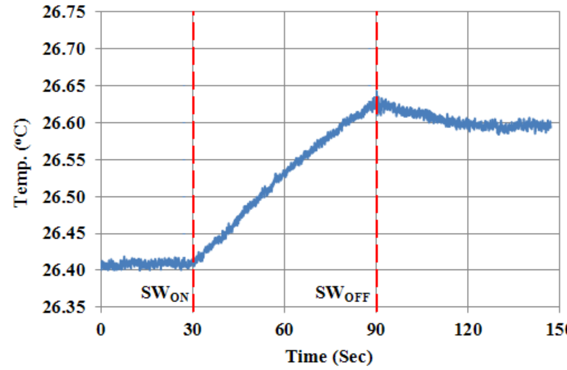


Fig. 10 Temperature rise vs. time due to heating effect at point 1 of a 5 A DC current passing along the copper strip

Table 1 Localised power loss of a uniform copper strip

Current (A)	Localised Power Loss (W/kg)				U(A)	U(B) ±%
	Point 1	Point 2	Point 3	Point 4		
1	0.0695	0.0691	0.0688	0.0698	0.00022	1.96
2	0.269	0.265	0.267	0.271	0.00129	1.96
3	0.647	0.642	0.644	0.651	0.00196	1.96
4	0.966	0.961	0.96	0.969	0.00212	1.96
5	1.706	1.692	1.695	1.71	0.00431	1.96

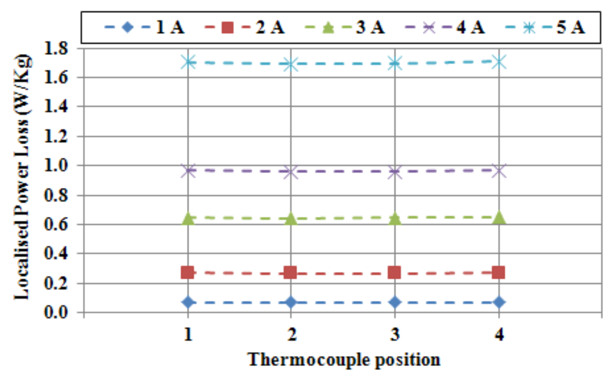


Fig. 11 Localised power loss vs. thermocouple position of a uniform copper strip at different DC current

This test shows that localized power loss measurement in homogeneous materials in a magnetic field free environment can be measured with a repeatability of better than 0.00431 and uncertainty of better than ± 1.96 %.

5.3. Localised power loss in a Epstein strip of non-oriented electrical steel

An Epstein strip of 0.5 mm thick, non-oriented (NO) electrical steel was chosen to establish the performance of the system in testing a relatively homogeneous steel since its average grain size was around 100 micron which is far lower than the region over which local loss is averaged during the rate of rise of temperature measurement technique.

Fig 12 shows the thermocouples position on the surface of the sample. The laminations were magnetised at flux densities of 1.3 T, 1.5 T and 1.7 T at 50 Hz frequency in a standard Epstein frame.

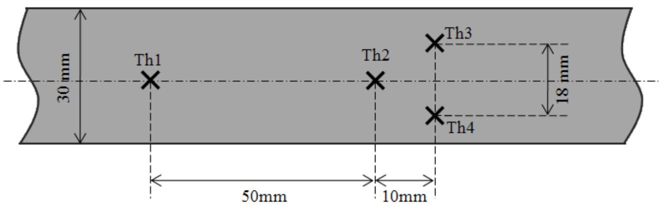


Fig. 12 Thermocouple positions on an Epstein size NO electrical steel

An example, of the temperature rise at point 1 is shown in Fig. 13.The specific heat of the NO steel is 461 J/kg°C and in this case the initial slope of this curve is 6.25E-3 °C/Sec (Over an 8 Sec period) and the calculated localised power loss at this point is 2.88 W/kg. The measured localised power loss including the uncertainty type B is shown in table 2. These results versus thermocouple position at different flux densities are also shown in Fig. 14.

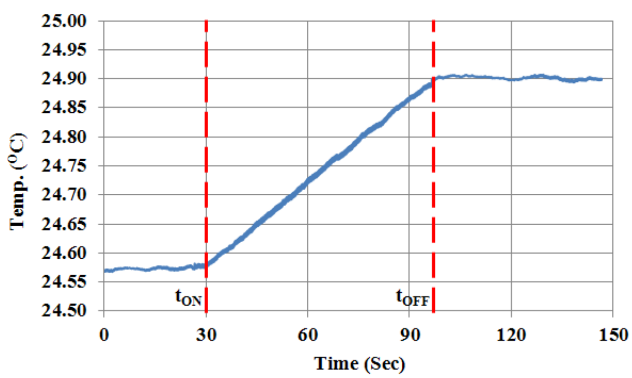


Fig. 13 Temperature rise vs. time at 1.7 T at point 1 on the surface of the NO electrical steel strip

Table 2 Localised power loss at points on the surface of the uniformly magnetised NO electrical steel strip

B (T)	Localised Power Loss (W/kg)				U(B) ±%
	Point 1	Point 2	Point 3	Point 4	
1.3	1.49	1.46	1.45	1.44	1.76
1.5	2.21	2.17	2.18	2.13	1.76
1.7	2.88	2.91	2.92	2.87	1.76

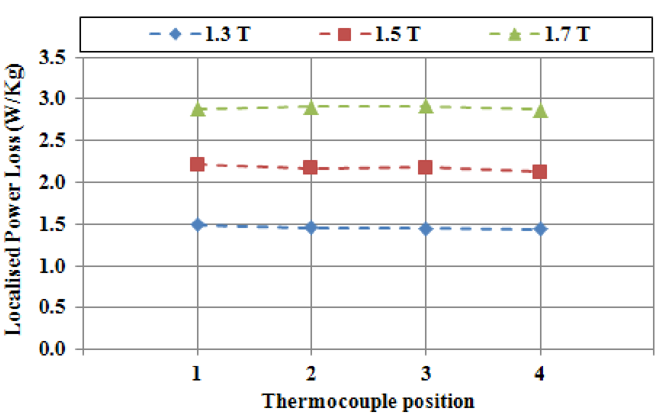


Fig. 14 Localised power loss vs. thermocouple position of NO electrical steel at different flux density

At any flux density the measured localised power loss at the four points are within ± 1.76 % of each other over the loss range from 1.44 W/kg to 2.92 W/kg. It is not surprising that the difference from point to point is a little higher than in the copper strip because the copper is more homogeneous and uniform properties are expected within the material, however in NO steels although the grains size are almost the same but slight difference between the results is expected. The test does not demonstrate the absolute accuracy of measuring localise loss in NO steel but at present there is no other method by which this can be measured or calculated.

As a final conclusion on this section, the maximum uncertainty of the developed measuring system is less than ± 2 % therefore it can demonstrate the reliability and accuracy of the system for measuring localised power loss of magnetic cores.

6. Case Study

To verify the accuracy of the measuring system two experiments with different ranges of localised power loss, effect of punched hole on localised power loss of electrical steel and the effect of artificial burrs on localised power loss of a three phase transformer core, were performed. Both experiments were carried out under adiabatic condition.

6.1. Effect of punched hole on localised power loss in a strip of grain oriented electrical steel

Power transformer cores are usually assembled from packets of laminations of different width to give an approximately circular overall core cross section. Typically in multi-step lap cores, guide pinholes are punched in each lamination to enable the core to be rapidly constructed using pins in a suitable core fabrication table. The holes cause the flux to be non-uniform in this region which leads to increases in transformer building factor. Computational FEM technique can be used to qualify and quantify this effect but they do not take account of the effect of building stress and other building parameters. In this study 24 Epstein size strips of 0.3 mm thick conventional grain oriented (CGO) electrical steels were magnetized at 1.3 T, 1.5 T and 1.7 T at 50 Hz frequency by using Epstein frame magnetising system, six strips were presented in each limb, and 4 mm diameter holes were punched at the center of the each strip in one of the limbs. The localised power loss at 5 points was measured using the initial rate of rise of temperature method. A 3-D layout of the strips in the Epstein frame and position of the thermocouple probes are shown in Fig 15.

Thermocouple Th1 was used as a reference since it was located sufficiently far from the hole and the corner joints, were the flux could be considered uniform and unaffected by the hole. The flux density at points 2 and 3 is lower than at the reference point, while flux density at points 4 and 5 is higher. So the lowest localised losses are expected at points 2 and 3 and the highest at points 4 and 5. A typical example of temperature rise versus time at flux density 1.3 T at point 3 is shown in Fig 16.

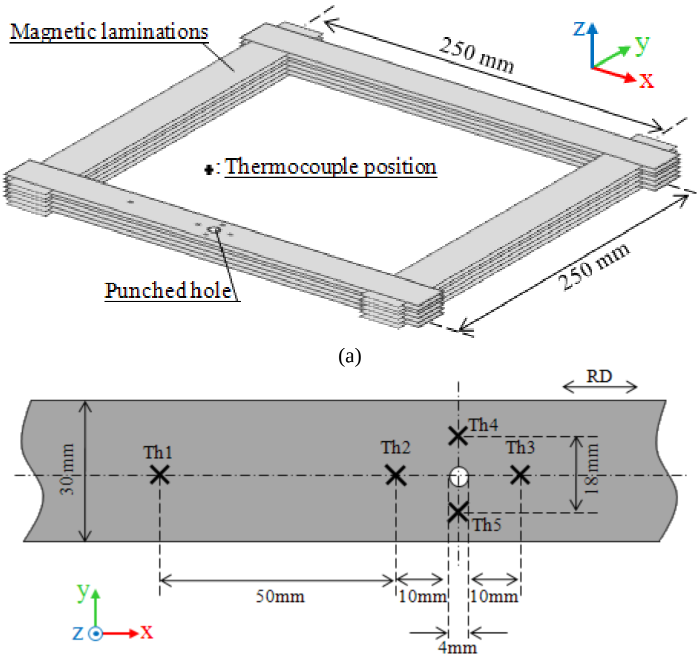


Fig. 15 (a) Location of punched strips in the Epstein frame (b) position of the thermocouples and hole in one strip

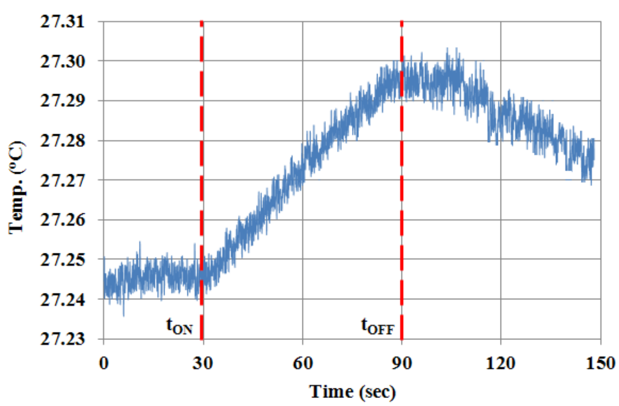


Fig. 16 Temperature rise vs. time at 1.3 T, 50 Hz at point 3 of Fig. 15

The maximum rise of temperature at this point is about 0.05 ^{o}C; it can verify the accuracy of the measuring system to monitor such a small rise of temperature. The specific heat of the GO steel is 485.6 J/kg°C and the initial slope of this curve over a 10 Sec period is 9.25E-4 ^{o}C/Sec, therefore the calculated localised power loss at this point is 0.446 W/kg. In order to observe the effect of the hole on the localise power loss at each point; this test was carried out before punching the hole as well. The results are shown in table 3. These experiments were repeated three times at each flux density and the values shown in table 3 are the average of three measurements.

Fig 17 shows localised power losses at different flux densities after punching the hole. In comparison with the reference point 1, the localised power loss at points 2 and 3 decreased 13%, 20% and 15% at 1.3 T, 1.5 T and 1.7 T respectively. While at points 4 and 5 power loss increased by 44%, 41% and 47% at the corresponding flux densities.

Table 3 Variation of localised power loss of the GO steel strip, before and after punching the hole

Thermocouple position	1.3 T		1.5 T		1.7 T	
	Before	After	Before	After	Before	After
Point 1	0.526	0.521	0.719	0.716	1.012	1.005
Point 2	0.522	0.443	0.714	0.575	1.008	0.876
Point 3	0.520	0.446	0.712	0.578	1.003	0.876
Point 4	0.528	0.738	0.726	1.019	1.018	1.523
Point 5	0.519	0.718	0.710	0.961	0.997	1.448

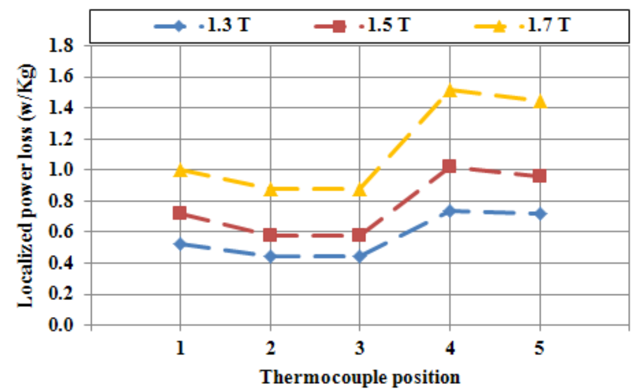


Fig. 17 Localised power loss vs. thermocouple position of the punched single strip

This study of localised power loss has been carried out on strips in which the flux density was non-uniform. Non-uniform distribution in flux density occurs not only around bolt holes but also at in transformer core T-joints and corners which leads to increased local heat and losses. The fluctuation in the local power loss caused by non-uniform flux distribution cannot be measured by conventional watt meters, but it can be measured by localised loss measurement, e.g. localised loss measurement based on the initial rate of rise of temperature method.

6.2. Measurement of localised power loss near artificial burrs in a three-phase transformer

A common phenomenon in transformer cores is the occurrence of *burr* on the edges of laminations causing inter-laminar short circuits which in turn cause high localised power loss and hence extra heating. In a perfectly assembled transformer core, eddy current paths are restricted to individual laminations due to insulated coating on the surfaces of the steel. However, poor cutting processes can create electrical edge burrs which can short circuit groups of laminations and increase eddy current loss or even cause catastrophic failure [25]. Burr size may vary from micrometers to millimeters, and they are capable of damaging the coating, burning the insulations and even melting the core [26]. Obviously, the extra localised power losses caused by the edge burrs cannot be measured by conventional watt-metric methods and a reliable localised power loss measuring system is necessary.

The effect of artificial burrs on localised power loss in a 350 kVA, 388 kg, three-phase and three-limb power transformer was investigated. The core was assembled from 0.3 mm thick laminations of Hi-B 3% Si-Fe with nominal loss of 0.97 W/kg at 1.7 T, 50 Hz in 7 step-lap configuration. The core was magnetised at flux densities from 1.5 T to 1.8 T at 50 Hz sinusoidal overall flux density. Artificial burrs made of copper tape of 25 mm long and 20 mm high were applied to either sides of packet C and thermocouples were fixed on the outer lamination of the packet C as shown in Fig. 18 at regular distances from the central axis of the burr location.

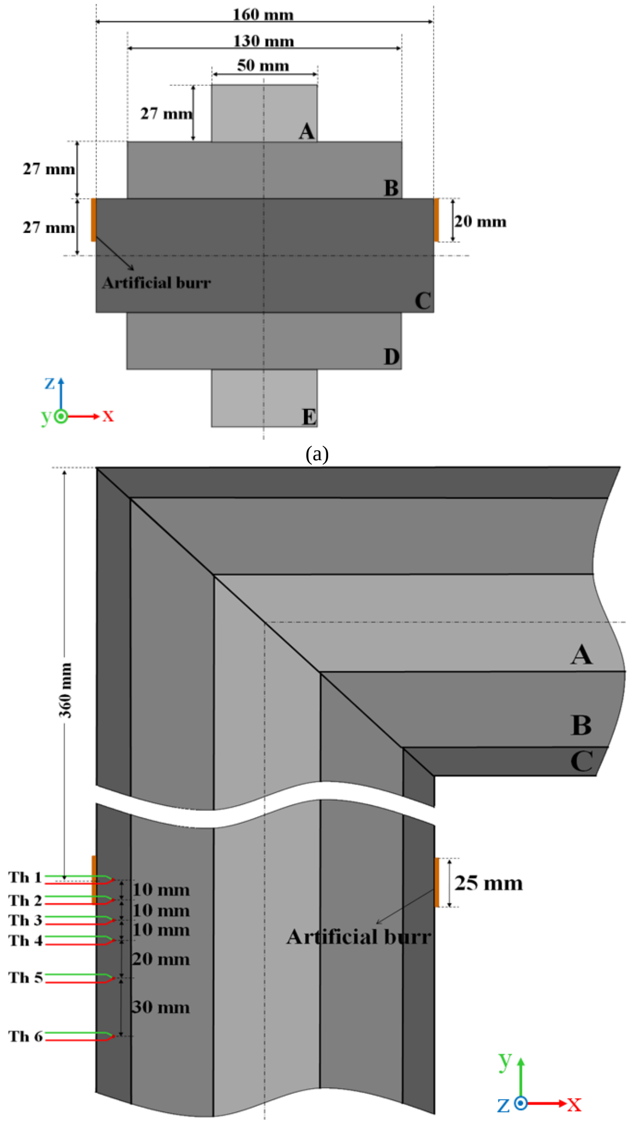


Fig. 18 (a) Cross section of the core and position of the artificial burr (b) Top view of the core and position of the thermocouples

To ensure that the transformer core has no inherent burrs, and also in order to qualify the results of the loss measurement after putting the artificial burrs, localised power loss was measured with no burrs present. All the results shown in Table 4 are the average of three measurements under different magnetisation conditions.

Table 4 Localised power loss in the core before introducing burr

Thermocouple position	1.5 T	1.6 T	1.7 T	1.8 T
Point 1	0.823	0.931	1.102	1.478
Point 2	0.819	0.932	1.112	1.482
Point 3	0.822	0.931	1.110	1.460
Point 4	0.821	0.936	1.108	1.477
Point 5	0.819	0.937	1.132	1.478
Point 6	0.822	0.934	1.115	1.456

In the presence of the artificial burrs the highest rise of temperature occurred at their centre. Fig. 19 shows the temperature rise versus time at 1.8 T at point 1. The maximum rise of temperature at this point during magnetising ($T-T_0$) was about 70 °C. The initial slope of the curve just after magnetising the core was 2.41 °C/Sec equivalents to a localised loss of 1170 W/kg at this point. Localised power loss versus thermocouple position at different values of flux density after applying the artificial burrs are presented in Table 5 and Fig. 20. The experiments were repeated three times at each flux density and the results presented here are average of three measurements. Table 5, shows that the localised power losses caused by the burr are extremely high which demonstrates the importance of avoiding significant edge burrs removal on the core losses and hence the transformer efficiency.

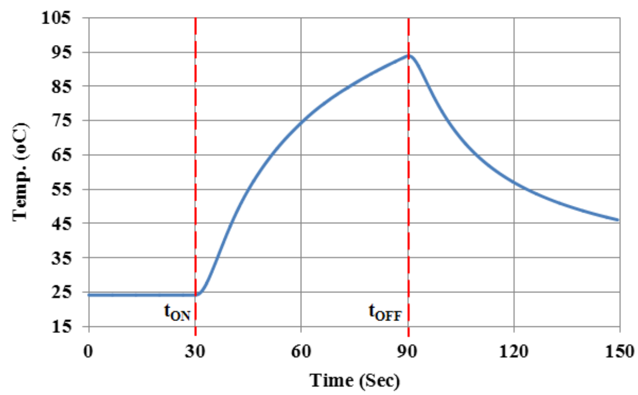


Fig. 19 Temperature rise vs. time at 1.8 T, 50 Hz at point 1 of Fig. 18

Table 5 Localised power loss of three phase transformer core after introducing burr

Thermocouple position	1.5 T	1.6 T	1.7 T	1.8 T
Point 1	31.18	114.50	493.58	1170.30
Point 2	27.53	99.40	397.60	857.77
Point 3	7.71	23.51	87.84	221.29
Point 4	5.60	16.81	55.73	115.76
Point 5	2.41	6.24	20.30	41.64
Point 6	1.79	4.69	17.37	29.95

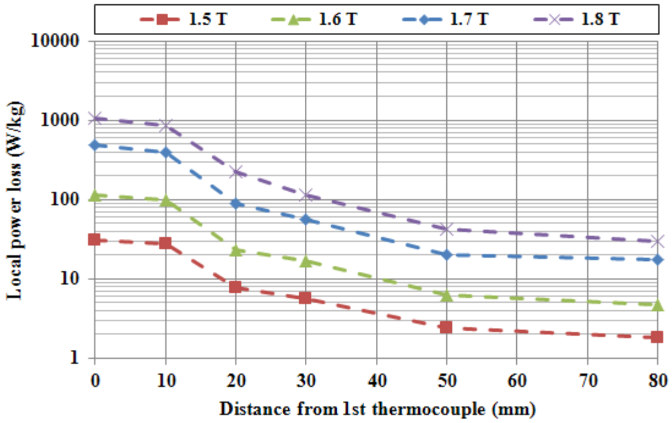


Fig. 20 Localised power loss of three phase transformer core affected by artificial burr versus position of the thermocouples

In a transformer or motor core, non-uniform localised power loss distribution and hence non-uniform heat distribution can occur due to non-uniform pressure in the core [28], rotational flux at T-joints and corners [17] and the most important inter-laminar fault [25]. Although the extra localised power loss caused by the first two factors is not noticeable [23] and [28] but these factors are unavoidable, even in a healthy transformer core. On the other hand, as it has been mentioned at the beginning of this section, inter-laminar faults in transformer core can lead to hot spots at the damaged points or areas. For example in this investigation the steady state temperature at point 1 at flux density 1.8 T before putting the artificial burr is about 26 ^{o}C, while the temperature at the same point and flux density with burrs present increased to 125 ^{o}C; such a high temperature rise could in extreme cases burn the insulation and melt the laminations [25]. Therefore localised power loss measurement after assembling the transformer core is a useful inspecting method to detect the inter-laminar fault in the transformer cores.

7. Conclusion

In the investigation of electrical machines, study on the magnetic cores from the point of power loss view is one of the main research topics. Conventional watt meters are used to measure the total power flow in a circuit, but are not usually adaptable to measure local power dissipation. They may be inaccurate at high frequencies or if the waveform is distorted; and they cannot be used to measure the loss due to rotation of flux within the plane of a sheet. The thermometric method which was used in this paper is a suitable tool to measure the localised power loss of the magnetic cores even at high frequencies, non-uniform heat distribution and distorted flux density. The accuracy of a new loss measurement system based on the initial rate of rise of temperature method was demonstrated to be adequate for measuring localised power loss of uniformly heated copper or magnetic cores with an uncertainty less than ± 2 % provided low noise conditions were maintained and suitable filtering was incorporated in the measurement procedure.

Application of the measuring system to measure localised losses around bolt holes in laminations or near burred strip edges where non -uniform loss distribution occurs demonstrated that it could be used over a range of losses from around 0.4 W/kg to 1200 W/kg with maximum uncertainty of better than ± 2 %.

The result of the experiments demonstrated that this measuring system can be applied to measure localised power loss in a wide range of local loss with uncertainty of measurement less than 2%. However, low signal to noise ratio was found at low flux density which basically was due to the small rise of temperature; so to avoid it a better adiabatic box, i.e. a vacuum chamber, is needed for applications with small rise of temperature.

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