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POWER LOSSES MEASUREMENTS OF NANOCRYSTALLINE AND AMORPHOUS MAGNETIC CORES

POMIARY STRAT MOCY W RDZENIACH NANOKRYSTALICZNYCH I AMORFICZNYCH

Abstract: The paper refers to the measurement of power loss in magnetic cores made of low-loss amorphous and nanocrystalline ribbons. Elaborated bridge method of power loss measurement is presented in the article. The most important issues of circuit analysis, circuit diagram and algorithm of measurement in closed magnetic specimens have been included in the content. Application of the suggested method is shown on the example of power loss measurements in toroidal, stacked amorphous core made of Metglas-2605S3A and toroidal, winding core made of Magnetec - Nanoperm ribbon. In the measurement results there are power losses determined for different maximum induction by the magnetizing frequency of 50Hz included. Achieved resolution and accuracy of the method confirm the measurement results whose values have not crossed 200mW/kg. Additionally in the paper the analysis and budget of uncertainty is presented.

Streszczenie: Artykuł dotyczy zagadnień związanych z pomiarem mocy strat w rdzeniach magnetycznych wykonanych z niskostratnych taśm nanokrystalicznych i amorficznych. W artykule zaprezentowana została opracowana metoda mostkowa pomiaru strat mocy. Metoda należy do grupy bezpośrednich metod pomiaru mocy strat w układzie mostka niezrównoważonego. W treści zamieszczono najważniejsze elementy analizy obwodowej, schematy układów pomiarowych i algorytm pomiaru stratności w próbkach magnetycznych zamkniętych. Aplikację proponowanej metody przedstawiono na przykładzie pomiaru stratności w toroidalnym pakietowanym rdzeniu amorficznym wykonanym z materiału Metglas-2605S3A i toroidalnym rdzeniu zwijanym wykonanym z taśmy Magnetec Nanoperm. W zestawieniach wyników pomiarów ujęto stratności wyznaczone w szerokim zakresie indukcji przy częstotliwości 50Hz. Osiągniętą rozdzielczość i dokładność metody potwierdzają wyniki pomiarów stratności których wartość nie przekraczała 200mW. Dodatkowo w artykule zaprezentowano budżet niepewności i analizę dokładności zaprezentowanych wyników pomiarów.

Keywords: *power loss, bridge method, low-loss magnetic materials, power measurements*
Słowa kluczowe: *strata mocy, metoda mostkowa, niskostratne materiały magnetyczne, pomiary mocy*

1. Introduction

Modern trends in designing and manufacturing of high efficiency electric devices relate to magnetic parts and soft magnetic cores as well [1]. Amorphous and nanocrystalline ribbons available on the market are characterized by appropriate magnetic parameters to adjust them as a replacement for conventional Fe-Si laminations [2, 3] . Slightly smaller saturation of induction is compensated by multiplying smaller power losses [4, 5, 6]. That is why those materials are used in cores production of distribution transformers, power transformers and other power devices more often [7, 8]. The development of material technologies did not cause any changes in measurement techniques related to determination of power loss of such cores [9, 10, 11]. Recommended measurement methods in IEC standards [12] have some disadvantages, such as a small range of power measurement (resulted in low sample weight), small range of magnetizing frequency and limited accuracy [13, 14]. In this context authors suggest the elaborated method of power loss measurement [15]. The method allows to achieve resolution at the level of 10nW and at accuracy the worst possible case at 2.5%.

2. Power losses of amorphous and nanocrystalline ribbons

Among modern, soft magnetic materials used in production of cores of power transformers two different types of materials are dominant. The first material are amorphous glasses produced on the basis of iron and iron-nickel alloy. Those materials are characterized by very low power loss at the level of 200mW in maximum induction of 1.6T/50Hz. These ribbons are applied to cores of distribution and power transformers and motors [2]. The second type of materials is the ribbon with two-phase grain structures with the crystal grain smaller then 20nm. Commercially available, this type of nanocrystalline materials have power loss at the level of 150mW in maximum induction of 1.2T/50Hz. Those cores are used in power transformers, pulse transformers, chokes and EMC components [18]. Taking into consideration small-sized cores value of measurement, dissipated power is frequently below 1mW.

3. Bridge measurement method

Proposed bridge measurement method of determining power loss of soft magnetic materials combines the advantages of balanced and semi-balanced bridges and simultaneously restrains from disadvantages of the wattmeter method. With the help of the described method one can carry out precision power loss measurements of magnetic materials in the form of low-weight samples in the range of low frequencies.

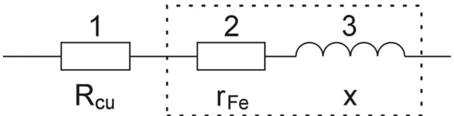

Fig. 1. Equivalent circuit of magnetic material sample with magnetizing coil

The closed sample of magnetic material with magnetizing winding can be reflected (at the first approach) by an equivalent diagram (fig. 1) showing the serial connection of three components [11]. Resistance R_{Cu} corresponds to the power dissipated in the magnetizing winding and has a value equal to the resistance of the winding. Resistance r_{Fe} represents power loss in magnetic material and X_{Fe} self-inductance of the sample. First component is a linear resistor, however the remaining two are nonlinear components, which means their values depend on instantaneous value of the current. The resistance R_{Cu} should be determined by measurement of magnetizing winding resistance under DC supply operation and the assumption that is constant in the range of low-frequencies (below 10kHz). The value of power loss in magnetic sample equals the power loss in the second component (r_{Fe}). It can be measured as an average value for the period of instantaneous power waveform in elements 2 and 3 of the diagram.

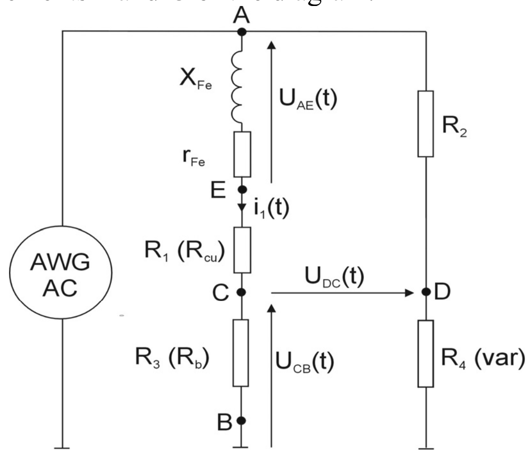

Fig. 2. Schematic diagram of the measuring circuit

In the figure 2 the diagram of measurement circuit is presented, which is the classic four-leg bridge. The first leg of the bridge is an examined magnetic sample. The sample is connected in series with the shunt resistor R_3. Remaining elements R_2 and R_4 are the second and the fourth leg. All the resistors can be considered as non-inductive in the range of frequency below 10kHz. The bridge is supplied by the generator with adjusted frequency and programmable waveform shape. Power loss measurement with the use of the described bridge has three steps:

- balancing of the bridge,
- demagnetization of the sample
- proper measurement under AC power supply

In the first stage measurement circuit together with magnetic sample is powered by DC supply. In that case the circuit reduces itself to the form shown in figure 3.

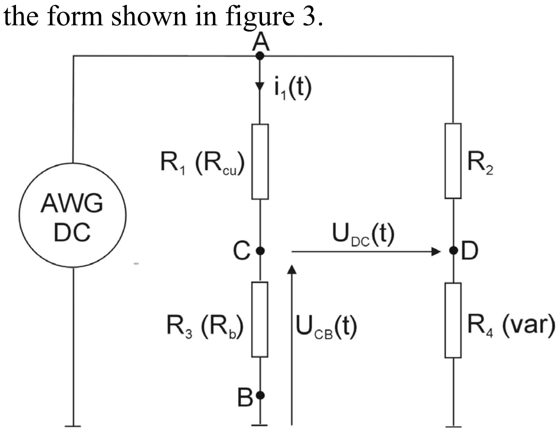

Fig. 3. Schematic diagram of the measuring circuit powered by DC

$R_1 = R_{Cu}$ – resistance of magnetizing coil
$R_3 = R_B$ – resistance of the shunt resistor
R_2 and R_4 – adjustable resistors which allow to balance the bridge powered by DC

In equilibrium state when $u_{CD} = 0$ occurs the quality (1).

$$\frac{R_2}{R_4} = \frac{R_1}{R_3} \tag{1}$$

In the next stages during the demagnetization process and proper measurement , the circuit of the bridge is configured as in the figure 2. Due to nonlinearity of the r_{Fe} an X_{Fe} of the equivalent diagram the circuit analysis has been done for instantaneous values of voltage and current. During periodical magnetization of magnetic sample dissipated power equals the average value for the period of instantaneous power dissipated on elements r_{Fe} and X_{Fe} according to relation 2.

$$P_{Fe} = \frac{1}{T}\int_0^T u_{AE}(t) \cdot i_1(t)\,dt \tag{2}$$

where:
T – period of the supply voltage waveform
u_{AE}(t) – voltage drop on the components X_{Fe} and r_{Fe},
i_1(t) – current in AC and CB legs.
Expressing the relation 2 as a function of unbalance voltage $u_{CD}(t)$ and voltage drop on the shunt resistor $u_{CB}(t)$ one can get the relation that is an equation of power loss measurement determined in the bridge configuration as presented in the figure 2.

$$P_{Fe} = \frac{1}{T}\frac{R_1+R_3}{R_3^2}\int_0^T u_{DC}(t) \cdot u_{CB}(t)\,dt \tag{3}$$

where:
P_{Fe} – dissipated power in the magnetic sample,
R_1 - resistance of the magnetizing coil (R_{Cu}),
R_3 - resistance of the shunt resistor,
T - period of the supply voltage waveform,
$u_{CD}(t)$ – instantaneous value of voltage between points CD of the bridge,
$u_{CB}(t)$ - instantaneous value of voltage between points CB of the bridge.

4. Results of measurements

Application of the method was done on the basis of 24bit AD converters and a 24bit DA converter working as the arbitrary generator which drives the hybrid power amplifier. Presented results refer to the chosen cores:

1. toroidal, stacked, amorphous core made of Metglas-2605S3A, mass of the core 0.16152kg
2. toroidal, winding core made of Magnetec - Nanoperm ribbon, mass of the core 0.225kg

The comparison of power loss measurements in the induction function for the frequency of 50Hz are presented in fig.6 and fig. 9. Power loss values determined with the bridge method (fig. 4, 7) and hysteresis method (fig. 5, 8) are considered as alternative and referential method with expanded uncertainty type B eq. 2.5%.

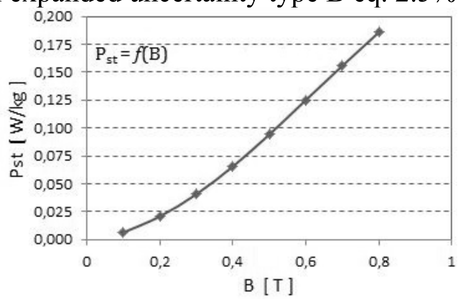

Fig. 4. Power loss measurement of the amorphous core with application the bridge method

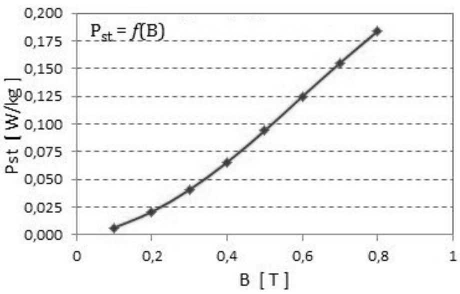

Fig. 5. Power loss measurement of the amorphous core with application the hysteresis method

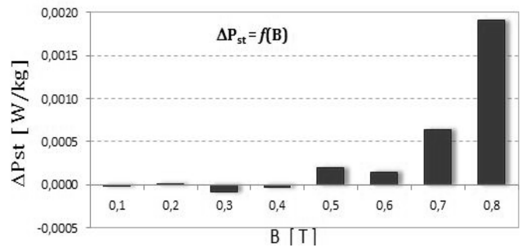

Fig. 6. Values of the differences power loss measurements between methods $\Delta P_{ST}= P_{ST\ Hist} - P_{ST\ Bridge}$

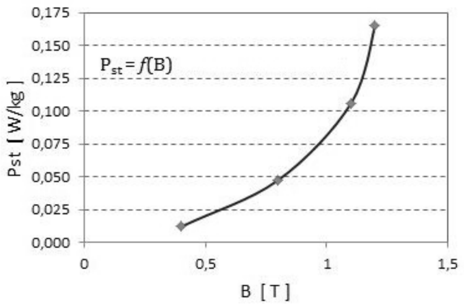

Fig. 7. Power loss measurement of the nanocrystalline core with application the bridge method

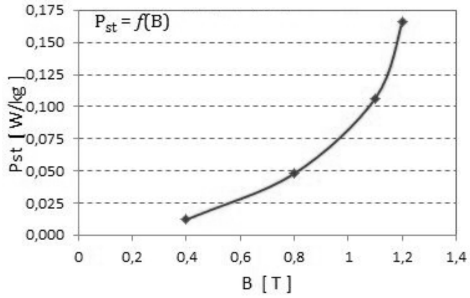

Fig. 8. Power loss measurement of the nanocrystalline core with application the hysteresis method

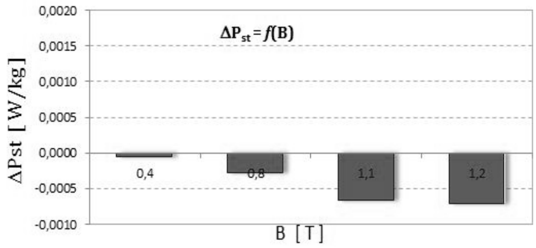

Fig. 9. Values of the differences of power loss measurements between the methods $\Delta P_{ST} = P_{ST\ Hist} - P_{ST\ Bridge}$

5. Uncertainty analysis

In the developed measurement system the determination of power losses using unbalanced bridge method and the method based on calculation of hysteresis loop area were realized. Metrological analysis presented in the form of budget uncertainty relates to unbalanced bridge method [14, 16].

The measurement function is described by the equation 3. The measurement system realized the numerical integration of measurement signals and the shaping of the form of magnetic induction [17]. The shape of the measuring signals for the induction of a smaller saturation flux density is practically sinusoidal [9]. In this case the formula (3) can be converted to the form (4):

$$P_{Fe} = \frac{R_1+R_3}{R_3^2} U_{DC} U_{CB} \cos\varphi \qquad (4)$$

where:

$_{Fe}$, R_1, R_3 - as above,

U_{CD} - RMS fundamental harmonic voltage between bridge points D and C,

U_{CB} - RMS fundamental harmonic voltage between bridge points C and B

φ-phase angle between the fundamental harmonic measurement signals.

Based on the above measurement the function expression for type B uncertainty of the measurement results of losses in the sample is as follows:

$$\frac{u_B(P_{Fe})}{P_{Fe}} = \begin{bmatrix} \left(\frac{u_B(R_1)+u_B(R_3)}{R_1+R_3}\right)^2 + \left(\frac{2u_B(R_3)}{R_3}\right)^2 + \\ + \left(\frac{u_B(U_{CD})}{U_{CD}}\right)^2 + \left(\frac{u_B(U_{CB})}{U_{CB}}\right)^2 + \\ + (\tan\varphi\, u_B(\varphi))^2 \end{bmatrix}^{\frac{1}{2}} \qquad (5)$$

where:

R_1, R_3, U_{CD}, U_{CB}, φ - as above,

u_B (φ) - the uncertainty of the phase angle resulting from the phase errors (jitter); both ADC channels of acquisition card are operating synchronously.

Table 1. Type B uncertainty budget

No	source of uncertainty (measurement function argument)	relative uncertainty
1	R_1 - resistance of the winding	0.008% for 0.5Ω
		0.04% for 1.5Ω
2	R_3 - shunt resistance	0.0042% for1Ω
3	m_{Fe} – mass of the sample	0.03%
4	$u_{CD}(t)$ – unbalance voltage of the bridge,	0.12%
5	$u_{CB}(t)$ – the voltage at the shunt,	0.12%
6	$u_B(\varphi)$ – the uncertainty of the phase angle resulting from phase errors of the channel measuring card - eq. 0.012°	0.0002* tan φ
7	φ =51° phase angle core 1	0.025%
8	φ = 89° phase angle core 2	1.15%

These values were determined based on the metrological characteristics of the following measuring instruments:

- Agilent 34420 nanovolt/microohm-meter,
- 24-bit NI PCI-4461 acquisition card,
- Radwag laboratory scale.

Table 2. Values of type B uncertainty in the measurement results of power losses of amorphous and nanocrystalline cores

Core no	Relative uncertainty type B	Cover. factor	Expanded uncertainty	
			Relative	Absolute
1	0.176%	2	0.36%	0.67mW/kg
2	1.17%	2	2.4%	4.0mW/kg

6. Summary

In the paper has been presented new measurement method and results of measurements achieved with application the bridge method. Results confirm utility and accuracy of the method. It is worth emphasizing that presented results have been made for small-size cores.

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