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DETERMINATION AND SEPARATION OF MAGNETIC REVERSAL ENERGY LOSSES IN FERROMAGNETIC MATERIALS BY MEANS OF MEASUREMENT DEVICE „MAGHYST®“FOR THE PURPOSE TO DETERMINE CONDUCTIVITY OF DIFFERENT MATERIALS

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ABSTRACT

The issue of energy losses in the magnetic core of electrical machines is going to attract more and more interest. By reducing of energy losses producers can increase life cycle efficiency of electrical machines and hence improve their cost-benefit-ratio. There are many methods of determination of the energy losses. Most of them are applicable only for sinusoidal electrical excitation. The main task of this work is the theoretical und experimental determination of the magnetic reversal energy losses in magnetic drive elements for non sinusoidal electrical excitation and also of the conductivity of ferromagnetic materials.

1. INTRODUCTION

Different magnetic cores are general used in electromagnetic devices, such as inductors, transformers, actuators and rotating machines. The efficiency of a magnetic core is principally determined by the characteristics of the material and geometry. Different materials have different magnetisation curves and conductivity. Due to the nonlinearity of the soft ferromagnetic is it difficult to calculate core losses of a magnetic core.

The total energy dissipated in a magnetic core can be separated into static hysteresis loss, eddy current loss and the excess loss (the anomalous and magnetic viscosity losses). Hysteresis losses are proportional to the static hysteresis loop. The eddy current losses and magnetic viscosity losses widen the hysteresis loop at frequencies more than zero. The classical eddy current loss can be calculated under assumption of sinusoidal magnetic field and constant permeability [1] by the following formula:

$$P_W = \frac{\pi^2 \cdot d^2 \cdot B^2 \cdot f^2 \cdot}{6 \cdot \gamma \cdot \rho} \cdot 10^{-3} \qquad (1)$$

P_w	eddy current loss power
d	thickness of lamination
B	flux density
f	frequency
ρ	specific resistance
γ	density

However, according to the classical calculation the current losses amount to 1/3 or 2/3 of measured eddy current losses. The reason of this difference is the domain wall motion effect, which is known as anomalous loss [2]. For anomalous and magnetic viscosity losses calculation it is necessary to consider the domain wall motion effects and microstructure of metals [3].

In this paper, the determination of core losses under non sinusoidal excitation, such as the eddy current losses, was examined. Furthermore the conductivity of ferromagnetic materials is determined using results of magnetic measurements.

2. PRACTICAL APPLICATION

2.1. Measuring magnetic values and parameters

The results of two experiments are presented in this paper. Each of the experiments represents measurements of *B-H*-curves of ring core samples. The measurements were realized with the testing device MagHyst® (Fig.1) produced by the STZ Mechatronik [4].

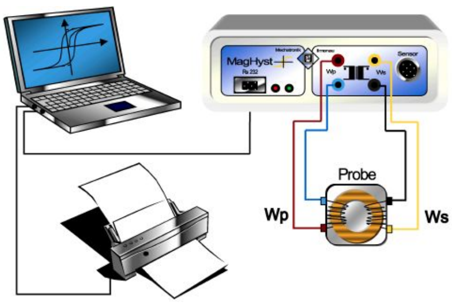
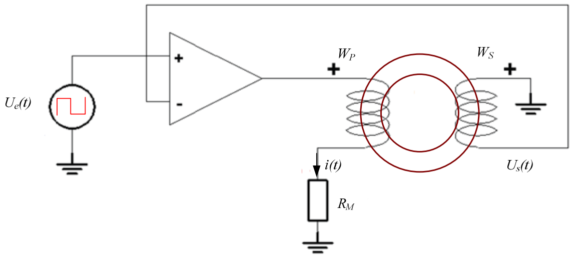
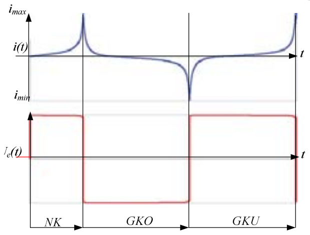


Figure 1 Testing device MagHyst®

The testing device works based on a feedback process. The distinctiveness of this device lies in the fact that the excitation current is not sinusoidal [5]. But it is controlled by given slope of measured current edge. Figure 2 illustrates the circuit for the measuring magnetic values of a ring core.





Secondary coils:

$U_s(t)=d\Psi/dt$

$\Psi_s(t)=\int U_s \cdot dt+\Psi_0$

For $U_s(t)=U_e(t)=const$:

$\Psi_s(t)=U_s \cdot t+\Psi_0=U_e \cdot t+\Psi_0$

Primary coils:

$i(t)=f(\Psi_s(t))$

Figure 2 Circuit for the measuring magnetic values

The measurements of the B-H-curve were realized for three ring core samples whose parameters are shown in table 1.

Table 1: Experimental conditions and parametrs and dimensions of ring core samples

No	Quantity	Ring1	Ring2	Ring3
1	Material	C45	C45	9SMnPb28
2	Inner diameter	40mm	50mm	40mm
3	Outer diameter	60mm	60mm	60mm
4	Number of turns of winding, W_p; W_s	212		
5	Excitation current, i_{max}.	2A, 4A, 8A		
6	Flux change rate $d\Psi/dt$	0,05V; 0,1V; 0,15V; 0,2V; 0,25V; 0,3V; 0,35V; 0,4V; 0,45V; 0,5V ; 0,55V; 0,6V; 0,65V		
7	Cross-section, A_{Fe}	100mm^2	50mm^2	100mm^2

In the first experiment *B-H*-curves for Ring1 and Ring2 were measured. All the experimental conditions except geometrical dimensions were equal for each ring core sample. In the second experiment *B-H*-curves for Ring1 and Ring3 were measured. The measurement conditions were the same as in the first experiment, except the fact, that the samples were produced from different materials with equal geometrical dimensions.

2.2. Analysis of measurements results

It is well known that the total energy dissipated in a magnetic core is proportional to the area of the hysteresis loop [1]

$$W_V = V_{Fe} \cdot \oint HdB \tag{2}$$

Consequently, the measured B-H-curves area must be calculated in order to estimate energy losses for every ring core sample.

2.2.1. Hysteresis loop area calculation

The hysteresis loop area is usually calculated by numerical integration. The new method for integrating is described in this paper [6].

The triangle method works by dividing hysteresis loop in triangles (Fig.3).

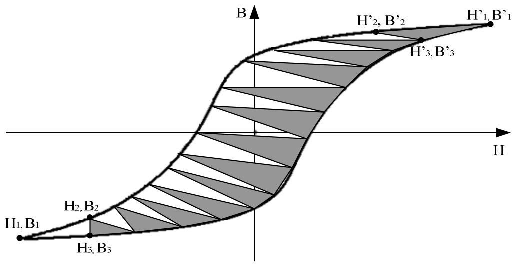


Figure 3: Dividing hysteresis loop in triangles

Firstly the areas of white triangles and then the areas of grey triangles must be stated for the hysteresis loop area calculation. The result is added up. This method can be mathematically described by the Heron's formula. For white triangles:

$$a = \sqrt{(H_1 - H_2)^2 + (B_1 - B_2)^2} \tag{3}$$

$$b = \sqrt{(H_3 - H_1)^2 + (B_3 - B_1)^2} \tag{4}$$

$$c = \sqrt{(H_3 - H_2)^2 + (B_3 - B_2)^2} \tag{5}$$

$$S = \frac{(a + b + c)}{2} \tag{6}$$

$$A = \sqrt{S \cdot (S - a) \cdot (S - b) \cdot (S - c)} \tag{7}$$

H_1, H_2, H_3 coordinates of triangle vertices (magnetic field intensity);
B_1, B_2, B_3 coordinates of triangle vertices (flux density);
a, b, c side lengths of white triangles;
S semi perimeter of white triangles;
A area of white triangles;

For grey triangles:

$$a' = \sqrt{(H'_1 - H'_2)^2 + (B'_1 - B'_2)^2} \tag{8}$$

$$b' = \sqrt{(H'_3 - H'_1)^2 + (B'_3 - B'_1)^2} \tag{9}$$

$$c' = \sqrt{(H'_3 - H'_2)^2 + (B'_3 - B'_2)^2} \tag{10}$$

$$S' = \frac{(a' + b' + c')}{2} \tag{11}$$

$$A' = \sqrt{S' \cdot (S' - a') \cdot (S' - b') \cdot (S' - c')} \tag{12}$$

H'_1, H'_2, H'_3 coordinates of triangle vertices (magnetic field intensity);
B'_1, B'_2, B'_3 coordinates of triangle vertices (flux density);
a', b', c' side lengths of grey triangles;
S' semi perimeter of gray triangles;
A' area of grey triangles;

$$A_h = \sum A + \sum A' \tag{13}$$

A_h area of the hysteresis loop;
$\sum A$ sum of areas of white triangles;
$\sum A'$ sum of areas of grey triangles;

2.2.2 Evaluation of measured data

The hysteresis loop areas are pictured in dependence of the flux change rate. The resalts are shown in Figures 4 and 5.

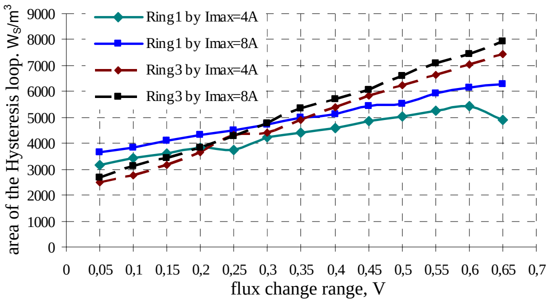


Figure 4 Dependence of the hysteresis loop area A_h on the flux change rate $d\Psi/dt$ for the first experiment

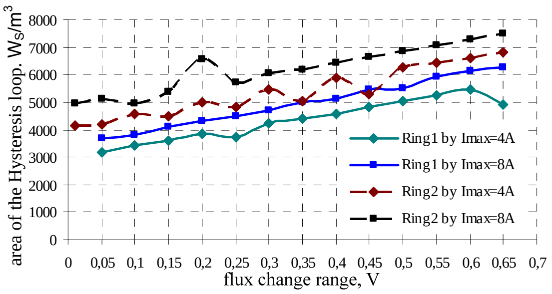


Figure 5 Dependence of the hysteresis loop area Ah on the flux change rate $d\Psi/dt$ for the second experiment

Trendlines are determinate using a linear approximation for dependence A_h $(d\Psi/dt)$. Figure 6 shows that the angle of slope trendlines is equal for every material and independent from geometrical dimensions of ring core samples. The eddy current losses are characterized by the gradient. Their value depends on excitation frequency, geometrical dimensions of sample and conductivity [1].

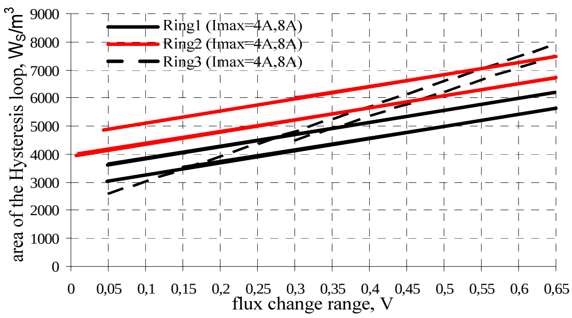


Figure 6 Trendlines of dependences A_h $(d\Psi/dt)$ for first and sekond experimentes

Because one parameter in the sample measuring is unequal, we can suppose that the conductivity is determinate by the gradient.

Differences in geometrical dimensions of samples only have influence on hysteresis losses and not on the gradient.

3. THEORETICAL MODEL

The classical method of eddy current losses calculation may not be used, since the flux density is nonsinusoidal. Instead of this the following model is proposed. For a simplified calculation it is assumed that the energy current losses only consist of hysteresis losses and eddy current losses (Fig.6) [1].

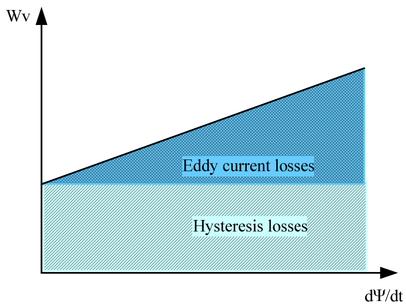


Figure 7 Assumption for separation of magnetic reversal energy losses

Hysteresis losses are proportional to the area of static hysteresis loops under magnetic reversal rate $d\Psi/dt=0$. It is possible to calculate the eddy current losses with Joule's law:

$$W_{Vw} = R_{el} \cdot I_w^2 \cdot T = \frac{U_{ind}^2}{R_{el}} \cdot T \cdot \qquad (14)$$

According to the Faraday's law, the voltage induced in the secondary winding is proportional to $d\Psi/dt$.

$$U_{ind} = -N \cdot \frac{d\Phi}{dt} = -\frac{d\psi}{dt} = -U_S \Rightarrow W_{Vw} = \frac{\left(\frac{d\psi}{dt}\right)^2}{R_{el}} \cdot T \qquad (15)$$

W_{Vw}	eddy current losses
R_{el}	resistance of ring core
I_w	eddy current
U_{ind}	generated voltage
N	number of turns
U_S	voltage across the primary coil
ψ	flux linkage
Φ	magnetic flux
T	magnetization cycle

For simplify the calculation of electrical resistance it is assumed that the cross-section of the ring core is round and magnetic field is homogenous.

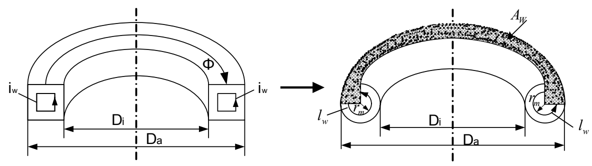


Figure 8 Assumption for geometrical dimensions of ring core samples

$$R_{el} = \frac{1}{k} \cdot \frac{l_W}{A_W} \qquad (16)$$

$$l_w = 2 \cdot \pi \cdot r_m \qquad (17)$$

$$A_W = \frac{\pi}{8} \cdot \left(D_a^2 - D_i^2 \right) \qquad (18)$$

l_w length of the eddy current

A_w cross-section of the eddy current

$æ$ conductivity

r_m mean radius

Hence the hysteresis losses can be determined as follows:

$$W_{Vw} = V_{Fe} \cdot B \cdot H = \frac{\left(\frac{d\psi}{dt}\right)^2 \cdot k \cdot A_W \cdot T}{2 \cdot \pi \cdot r_m} \qquad (19)$$

T magnetization cycle (Fig.9)

$\frac{d\Psi}{dt}$ „MagHyst®” - parameters

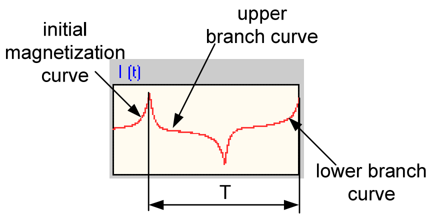


Figure 9 Excitation current characteristic

3.1.1. Comparison of the with the calculated eddy current losses

The dependence of eddy current losses on the flux change rate *dΨ/dt* measured by the MagHyst® device (solid curves) and calculated by equation (19) (dashed curves) are presented in Figures 10 and 11.

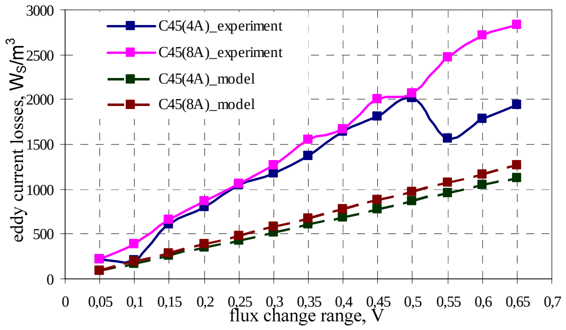


Figure 10 Comparison of the measured with the calculated eddy current losses for material C45

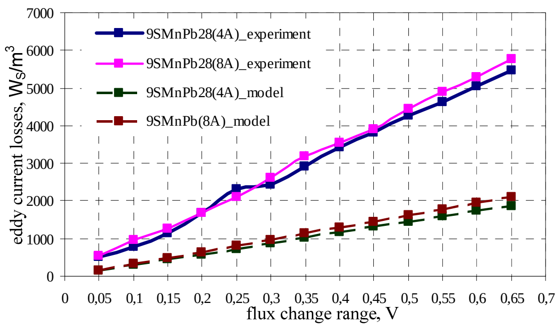


Figure 11 Comparison of the measured with the calculated eddy current losses for material 9SMnPb28

The Figures 10 and 11 show that the measured eddy current losses for C45 and 9SMnPb28 are bigger than calculated.

The electrical conductivity can be calculated using the measurement data ($B \cdot H$) and equation (19).

$$æ = \frac{2 \cdot \pi \cdot r_m \cdot V_{Fe} \cdot B \cdot H}{\left(\frac{d\psi}{dt}\right)^2 \cdot A_W \cdot T} \qquad (20)$$

$B \cdot H$ hysteresis loop area without static hysteresis

V_{Fe} volume of the ring core sample

The results of the calculation are presented in Figure 12

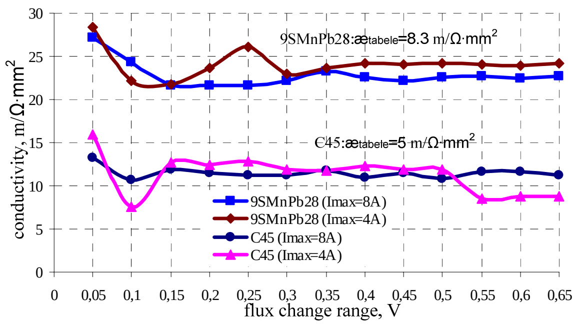


Figure 12 calculated conductivity for ring core samples of steel C45 and 9SMnPb28

The figure 12 shows that the calculated conductivity is constant for different *dΨ/dt* but higher than commonly used values [7, 8].

4. CONCLUSION

In this paper measurements of B-H-curves of ring core samples were discussed. This measured data was presented as dependencies of the hysteresis loop area on the flux change rate. By investigating the behaviour of magnetic characteristics under different flux change rates it is determined that the gradient of these dependencies is influenced by sort of material and not by sample's geometry.

The calculated eddy current losses and conductivity by the theoretical model significantly differ from the measured ones. This could be explained by the fact that the model is simplified and disregard such effects as material nonlinearity, skin-effect, excess losses and real sample geometry.
Therefore, the main aspect of the subsequent work is to develop a model which can help to calculate the conductivity and the eddy current losses more exactly.

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