Jerzy BAJOREKI[1], Dominika GAWORSKA - KONIAREK[2]

Politechnika Wrocławska (1), Instytut Elektrotechniki (2)

Measurement of the losses of electrical steel sheet samples at high magnetic flux density

Abstract. *The paper presents an integral sampling method which enables one to determine not only magnetization characteristics, but also loss at deep saturation magnetization. The peculiarities of the method, the obtained typical hysteresis loops and the calculated loss values are discussed..*

Streszczenie. *W artykule przedstawiono metodę próbkowania całkowego pozwalającą wyznaczyć nie tylko charakterystyki magnesowania ale również stratności w obszarze nasycenia magnetycznego. Przedyskutowano właściwości metody, otrzymane przykładowe przebiegi pętli histerezy oraz wyniki obliczonych wartości stratności. (**Pomiar stratności próbek blach elektrotechnicznych w obszarze nasycenia magnetycznego**).*

Słowa kluczowe: blacha elektrotechniczna, pomiar stratności, pętla histerezy, duża gęstość strumienia magnetycznego
Keywords: electrical steel sheet, loss measurement, hysteresis loop area, high magnetic flux density

Introduction

Magnetic flux density in the cores of electrical machines can reach a significant level, since the magnetic induction in tooth material is often close to saturation one [1, 2]. The calculation of the behavior of the machine's core in such conditions is usually impossible due to lack of relevant data. Magnetic properties (especially total energy loss) of electrical steel sheets are usually measured up to a peak polarization of J_p = 1.5 T - in the case of nonoriented electrical steel sheets and J_p=1.7 T - for oriented ones – according with requirements of the standards.

One of the main causes of such situations are the problems which are encountered when measuring the losses at area saturation. The measurement of loss poses a great challenge for the measuring systems used to determine the electromagnetic properties of electrical steel sheets since adequately deep magnetization of the tested sheet specimen needs to be obtained while maintaining the sinusoidal waveform of induction. The maintenance of the sinusoidal waveform of induction at deep saturations is very difficult and even impossible. In the Epstein frame the problem occurs already at a field strength close to 10 kA/m – Figure 1.

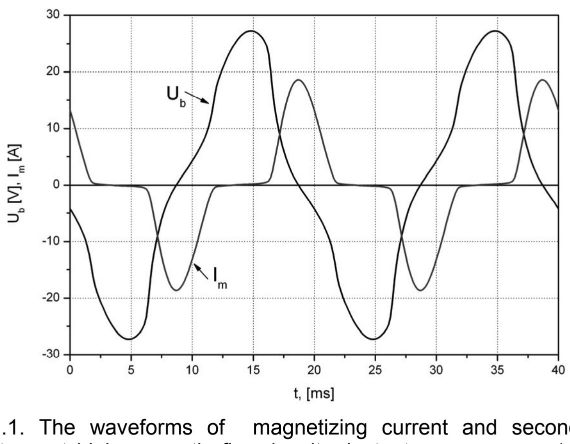

Fig.1. The waveforms of magnetizing current and secondary voltage at high magnetic flux density, instantaneous power (H_m = 13 800 A/m, J_p = 1.8T)

But in many cases, the magnetic properties of electrical steel sheets need to be tested at the frequency in a field with a strength of 30 kA/m or even higher. At field strengths up to 30 kA/m a special Epstein frames is used for this purpose [1]. At such deep saturations only the magnetization characteristic is measured. Total energy loss cannot be correctly determined by commonly used dot products of magnetizing current and secondary voltage not only because of the nonsinusoidal waveform of induction in the specimen, but also due to the very high percentage of reactive power relative to that of active power. Apart from that, dot product calculations do not yield a correct loss value at high magnetic flux densities since the magnetizing current waveform and the secondary voltage waveform are nearly in quadrature (the power factor drops to very low value – even up to 0.01) – Fig. 2 [2 - 4]. In addition to that, the sampling frequency is not synchronized with the frequency of the quantities being sampled. For this reason, in order to avoid the large errors associated with the assignment of total energy loss of magnetic materials at the range of high magnetic flux densities by means of standard methods, the application of thermometric techniques is recommended where measurements accuracy is not dependent on low power factor [2,5]. The disadvantages of these techniques are their time-consuming and cost effectiveness.

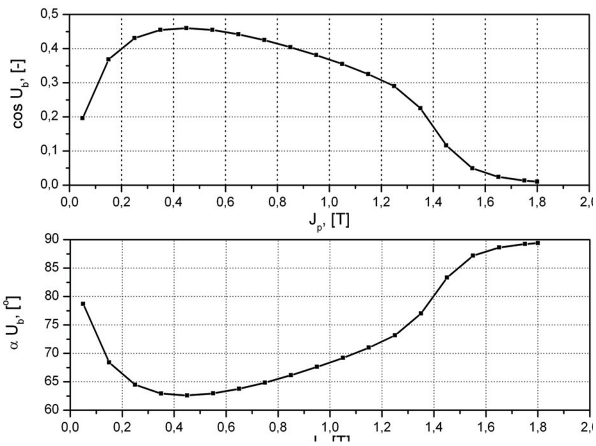

Fig.2. The change of phase shift φ between waveform of measuring voltage and magnetizing current and its cosinus (power factor) in function of polarization peak value J_p

This paper presents an integral sampling method which enables one to determine not only magnetization characteristics, but also loss at high magnetic field strengths. The peculiarities of the method, the obtained typical hysteresis loops and the calculated loss values are discussed.

Integral method of measuring flux

The integral method is a natural method of measuring instantaneous flux values [6]. It consists in averaging the excised fragments of the signal induced at the output of the winding linked with magnetic flux ψ (1).

$$e_2 = -\frac{d\psi}{dt} \tag{1}$$

Because of differential relation (1) the waveform of signal e_2 does not include all the information about the flux. The initial condition still needs to be taken into account.

The loss, hysteresis loop and magnetizing characteristic of specimens of magnetic materials are determined at symmetric magnetization. It is even required that induction waveform be sinusoidal. At symmetric magnetization instantaneous values of magnetic flux satisfy the condition of asymmetry:

$$\psi(t) = -\psi(t + T/2) \tag{2}$$

This information is sufficient for taking into account the initial condition for determination of definite Riemann integral. Other quantities linearly dependent on the flux also recur after the half-period with an opposite sign.

If half-period fragments are averaged, then, taking into consideration (1) and (2), one gets

$$\left\langle e_{2(t,\, t+T/2)} \right\rangle = \frac{1}{T_i}\int_t^{t+T/2} e_2 dt = -\frac{2}{T_i}\psi(t) \tag{3}$$

where $T_i \geq T$ – integration time. Instantaneous values of magnetic flux, measured by integral method, are accurate. In fact, they are determined by the average value of cut half-period fragments of signal and correspond to the time of closing the key.

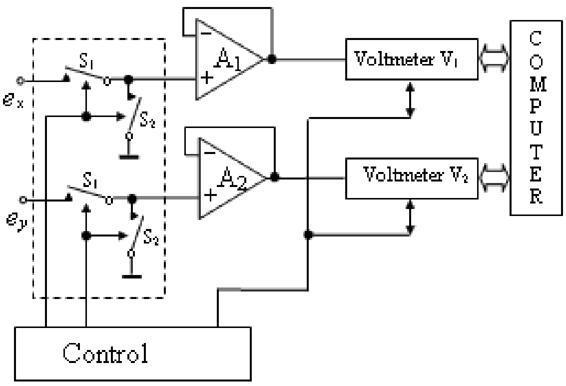

Fig.3. Two-channel system for simultaneous measuring of instant magnetic flux values in coil H (signal e_x) and in coil B (signal e_y).

Figure 3 shows a two-channel system applied for this method which enables one to simultaneously measure (at the same instants) the instantaneous values of induction in the specimen and the instantaneous values of the tangent field strength component. Input signals e_x and e_y depend on the measured quantities in accordance with the basic equations of electrodynamics.

The main components of the system are keys S_1 and S_2. By means of keys S_1 signals e_x and e_y are switched on to the inputs of the voltmeters at selected instants t and switched off after a half-period. In the remaining measurement cycle time a zero potential is forced at the voltmeters' inputs by closing keys S_2 at the instant at which keys S_1 are opened. The simultaneous measurement of the mutually corresponding instantaneous values of induction and the tangent magnetic field strength component is absolutely necessary in order to correctly determine loss, particularly at high field strengths. The simultaneity of measurements in the system is determined by the simultaneous closing of keys S1. But the required simultaneity cannot be achieved merely by controlling the keys by the same pulses because the particular keys slightly differ in their characteristics. Thus the phases of control pulses should be corrected so that for the same input signals $e_x = e_y$ a sequence of pairs of instantaneous flux values which do not form a loop on plane x, y is obtained.

Determination of loss

A sequence of pairs of instantaneous values $\{H_k, B_k\}$ forming a closed hysteresis loop can be determined from the synchronously measured instantaneous values of the flux associated with coil *H* and the flux associated with coil *B* or the winding of the inductive sensor for measuring magnetizing current. The area of this loop $A_{H,B}$ can be calculated using the estimator

$$A_{H,B} = \sum_{k=1}^{n-1}(B_{k+1} - B_k)\frac{H_k + H_{k+1}}{2} + (B_1 - B_n)\frac{H_1 + H_n}{2}. \tag{4}$$

If the loop area is given, then the loss P_1 is calculated from formula (5).

$$P_1 = \frac{P}{m} = \frac{f}{\gamma}A_{H,B} \tag{5}$$

where γ – the density of the specimen's material, $f = 1/T$, m – specimens mass, P – active power,

Estimator (4) does not require that the intervals between the successive instantaneous values (samples) to be exactly equal. The samples do not need to precisely fill the period. It is enough that they fill the period of energetic process with an accuracy of one sample since the loop is closed by the last term of estimator (4) An important property of loop area is that it is independent of the constant components which may arise as a result of signal processing. But because of its relatively long time of measuring a single pair of instantaneous values, the integral method of measuring the instantaneous values of the fluxes in coils *H* and *B* is not used in practice.

Measurement results

A specimen of M350-50A electrical steel sheet (16 strips with dimensions 300.2 mm x 30.1 mm) was tested in the Epstein tester immersed in oil and supplied from the mains. The results presented below were determined from synchronously measured (by an inductive sensor) sequences of instantaneous values of the magnetizing current and instantaneous values of the flux associated with the secondary winding of the Epstein frame.

The middle part of hysteresis loop of the tested specimen of electrical sheet is shown in figure 4. Monotonic arrangement of measured points even in the case of mains supply and very deep saturation shows correct reproducing of the hysteresis loop.

An occurring additional (false) signal phase shifts in the measuring circuits of processed values (caused by different reasons) results in additional kink appearance in the peak part of the hysteresis loop. Then repeatedly polarized

surfaces appears which, because of their different signs underrate the value of the resultant hysteresis loop area.
The applied measuring system did not cause any additional kink of hysteresis loop up to the peak polarization value of 1.94 T (fig. 5). However a kink occurred at polarization values above 1.94 T. It results in incorrect determination of loss values what can be cause of bending of the loss characteristic. It should be noted that in spite of kink of hysteresis loop the loss characteristic of the tested sample bent at a polarization of about 1.7 T (fig. 6).

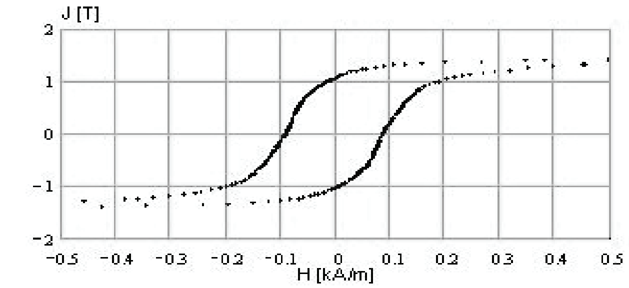

Fig.4. Middle part of hysteresis loop

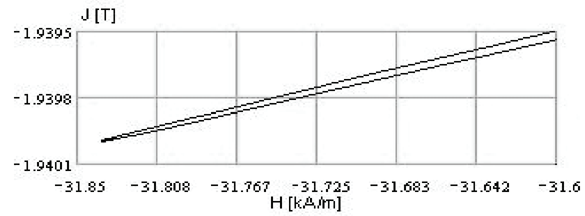

Fig.5. Peak part of hysteresis loop

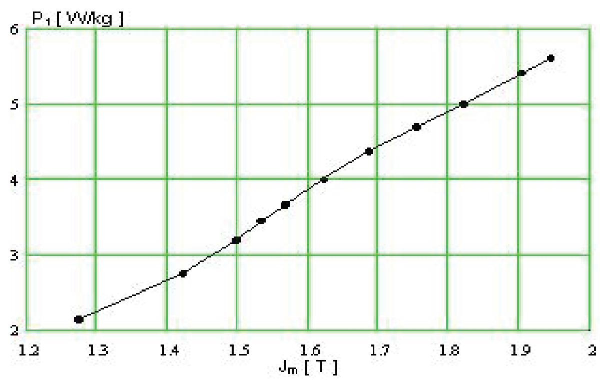

Fig.6. Dependence between loss and peak polarization value

Conclusions

The presented results of measurement of electrical steel sheets indicate that the integral sampling method is suitable for measuring loss in the magnetic saturation and very deep saturation areas of ferromagnetic. It results from:

– high accuracy of the instantaneous polarization and tangent magnetic field strength component values determination,
– elimination of essential impact the accuracy of the run of magnetizing field period designation on the uncertainty of the loss calculation. This is especially important in the case of large share of reactive power occurring in a state of deep magnetic saturation of electrical steel sheet sample,
– direct determination of the instantaneous values of magnetic quantities on the basis of derivative of the magnetic waveforms,
– determination of loss by planimetring the hysteresis loop by means of the estimator which does not require that instantaneous polarization and tangent component of magnetic field strength values be uniformly distributed along the axes,
– no requirement to accurately determine the number of samples precisely filling the period of measured runs,
– an easy determination of reactive power on the base of generalized reactive power theory.

Furthermore, it should be noted that the presented measuring meter circuit is simple and easy to implement for computerized systems designed for measurements of dynamic magnetic properties of soft magnetic materials.

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Autorzy:
dr inż. Jerzy Bajorek, Politechnika Wrocławska, Instytut Maszyn, Napędów i Pomiarów Elektrycznych, ul. Smoluchowskiego 3a, 50-372 Wrocław, e-mail: jerzy.bajorek@pwr.wroc.pl; dr inż., mgr inż. Dominika Gaworska-Koniarek, Instytut Elektrotechniki Oddział we Wrocławiu, Pracownia Materiałów Magnetycznych i Stykowych, ul M.Skłodowskiej-Curie 55/61, 50-369 Wrocław, e-mail: gaworska@iel.wroc.pl