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ISSUES INVOLVED IN USING THE DIRECT METHOD FOR MAGNETIC FIELD STRENGTH MEASUREMENT OF ELECTRICAL STEEL SHEETS – REVIEW

ABSTRACT *The paper presents, based on a review of relevant literature, the existing problems of magnetic field strength measurements of electrical steel sheets by means of the indirect and direct methods. It also describes some attempts to solve these problems. The magnetic field strength sensors most widely used for testing electrical steel sheets are also discussed.*

keywords: *magnetic field strength measurements, magnetic field sensor, direct method of magnetic field measurement*
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1. INTRODUCTION

Electrical steel sheets are the basic magnetically soft material used for the production of magnetic cores for electromagnetic machines and devices.

The quality and magnetic properties of the magnetic core depend on the grade and quality of the electrical steel sheets used, and their manufacturing technology. The magnetic properties defined by standard methods such as the Epstein frame, the Single Sheet Tester (SST) or ring samples differ significantly from the properties of ready-made magnetic cores. They do not take into account the impact of the technological

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processes employed in machining the electrical steel sheets and the shape of the magnetic core, e.g. in a rotating machine. During the preparation of the final product, the starting material in the form of electrical steel sheets and semi-finished magnetic cores is subjected to a variety of technological processes such as cutting, gluing, stacking, riveting, etc. Their effect on the magnetic properties of the final product depends on the technological processes applied, the type of electrical sheet used, as well as the effective cross section of the magnetic core [37, 38, 8, 9, 20]. It is necessary, therefore, to monitor the magnetic properties of magnetic cores at key stages of their production. Any assessment of the impact of technological processes on the magnetic properties of magnetic cores and open-work punched parts of electrical steel sheets requires the local measurement of the magnetic properties of the semi-finished products. In general, each assessment of the magnetic properties of any object requires the measurement of its basic magnetic values, including magnetic induction B_m and magnetic field strength H_m and their proper assignment. It is necessary to ensure a uniform distribution of the tangential component of the magnetic field strength across the entire measurement area of the object. Meeting this requirement is very hard, even in the case of normalised test circuits with a closed magnetic circuit with a uniform and accessible cross-section.

In this paper, based on a review of the relevant literature, the problems of making measurements of the magnetic field strength of electrical steel sheets by means of the direct and indirect methods, and attempts to solve these problems, are presented.

2. POSSIBILITIES FOR MEASUREMENTS OF MAGNETIC FIELD STRENGTH

Technically, the measurement of the dynamic properties of electrical steel sheets is based on the possibilities of measuring the basic quantities which describe the electromagnetic condition of the examined object. According to electrodynamic models the momentary power p of an electromagnetic field in a free space limited by a closed surface equals the flux of the Poynting vector:

$$\boldsymbol{\Pi} = \boldsymbol{E} \times \boldsymbol{H} \tag{1}$$

flowing through this surface:

$$p = -\oint \boldsymbol{\Pi} \mathrm{d}\boldsymbol{s} = -\oint \Pi_n \, \mathrm{d}s \tag{2}$$

where: $\boldsymbol{E}$ – the vector of electric field strength, and $\boldsymbol{H}$ – the vector of magnetic field strength on the object’s surface.

Taking into account that the normal component of the Poynting vector:

$$\boldsymbol{\Pi}_n = \boldsymbol{E}_r \times \boldsymbol{H}_l \tag{3}$$

is determined by the mutually orthogonal components of magnetic field strength H_l and electric field strength E_r , tangential to the surface of the examined object, the equation (3) takes the form:

$$p = -\oint \Pi_n \mathrm{d}s = -\oiint E_r H_l \mathrm{d}l\mathrm{d}r \tag{4}$$

This shows that the magnetic properties of an electromagnetic object can be characterised only by means of the tangential component of magnetic field strength H_l and the tangential component of electric field E_r on the surface of this object. They constitute the object's reaction to the application of external electromagnetic fields and all the phenomena occurring inside the examined object.

However, the flux of the Poynting vector flowing through the surface of the entire examined object can be defined as:

$$p = -\oint \Pi_n \,\mathrm{d}s = -\oiint E_r H_l \mathrm{d}l\mathrm{d}r = -\oint E_r (\oint H_l \mathrm{d}l) dr \tag{5}$$

Assuming that the distribution of the magnetic field strength's tangential component H_l over the measured length l_p of the examined object is uniform and constant, the equation (5) takes the form:

$$p = -\oint \Pi_n \,\mathrm{d}s = -\oiint E_r H_l \mathrm{d}l\mathrm{d}r = H_l l_p \oint E_r \mathrm{d}r \tag{6}$$

Taking into consideration the law of electromagnetic induction:

$$e_0 = \oint E_r \,\mathrm{d}r - \frac{\mathrm{d}\phi}{\mathrm{d}t} = -S\frac{\mathrm{d}B}{\mathrm{d}t} \tag{7}$$

equation (6) can be written in the following form:

$$p = VH_i \frac{\mathrm{d}B}{\mathrm{d}t} \tag{8}$$

where: ϕ – the magnetic flux flowing through the cross section S of the examined object, B – the mean magnetic induction in the cross section of the examined object, V – the volume of the examined object on the surface of which there is the uniform distribution of the tangential component of the magnetic field strength.

The mean active power during the period of magnetic field changes produced in the whole volume of the object is determined by the equation (9):

$$P = \frac{1}{T}\int_0^T p\mathrm{d}t = \frac{V}{T}\oint H_l \,\mathrm{d}B \tag{9}$$

It indicates that in a uniformly magnetised object with volume V the active power is proportional to the area of the hysteresis loop of this object.

Thus, maintaining a uniform distribution of the tangential component of the magnetic field strength on the surface of the measurement area of the object is a necessary condition to properly determine the mean value of the power density in the object.

Determining the magnetic properties of a material thus requires proper measurement of the tangential component of the magnetic field strength and the voltage induced in the winding covering the cross section of the object with a uniform distribution of the tangential component of the magnetic field strength. In addition to this, in the case of power loss measurement, due to the non-linearity of the object, the regimented (usually sinusoidal) waveform of induction in the object should be provided.

The tangential component of the magnetic field strength is directly defined by the second Maxwell equation. When the integral path includes current flow, its integral form is as follows:

$$\oint_{C(S)} H\mathrm{d}l = \sum_{n=1}^{N} i_n = \Theta \tag{10}$$

Electromotive force Θ is determined by the current flowing along the integration path of the scalar product of the magnetic field's tangential component along closed curve C.

In general, the integration comprises the total current which consists of the conduction current i_p and displacement current i_d.

In the low frequency range, where the dynamic magnetic properties of electrical steel sheets are usually measured, the influence of the displacement current is minor. Thus, only the conduction current i_p appears, which, flowing in each of N magnetizing coils along the path of integration C, is defined by the following dependency:

$$\Theta = N i_\mathrm{p} \tag{11}$$

The constant, tangential component of the magnetic field strength vector H_l to the mean length of the path of integration $l_{śr}$, can be obtained by the direct method, from the following dependency:

$$H_l = \frac{N}{l_{śr}} i \tag{12}$$

on the basis of the measurement of the magnetising current i. In a case where the path of integration does not comprise the electric current flow, the equation (10) is as follows

$$\oint_{C(S)} \boldsymbol{H}\mathrm{d}\boldsymbol{l} = 0 \tag{13}$$

It indicates continuity of the tangential component of the magnetic field strength on the border surface of the ferromagnetic material and air. From the second Maxwell equation, it directly follows that there are two possibilities for determining the tangential component of the magnetic field strength. They are the indirect method, from the measurement of the current magnetising the sample (based on equation (12)), and the direct method, based on the continuity of the tangential component of the magnetic field strength on the border surface of the ferromagnetic material and air (equation (13)).

2.1. The indirect method

The indirect method is used above all in standard methods such as Epstein frame, the Single Sheet Tester or ring samples. The abovementioned circuits should provide a close relation between the magnetic field strength and the magnetising current. Moreover, the distribution of the magnetic field strength should be homogeneous along the entire length of the examined sample. However, in real-life conditions this does not happen. The material is magnetised non-uniformly due to its non-homogeneity, the presence of air gaps between the yokes and the examined object and the influence the sample's geometry.

These elements cause the effective magnetic flux path in the object to be dependent on the method and state of its magnetization, the object's magnetic properties, the frequency of the magnetizing field etc [13, 12, 4, 18]. For this reason, a mean length for the magnetic flux path for an Epstein frame [10] and an SST [11] has been arbitrarily chosen.

Moreover, the magnetic properties of ferromagnetic materials can vary in different areas (due to the non-homogeneity of the material) or can depend on the magnetic field's direction (magnetic anisotropy). The indirect method averages the magnetic field strength distribution and the non-homogeneity of the material over the entire length of the magnetic circuit.

This results in a certain level of error in the indirect method's determination of the magnetic field strength [16, 29, 30, 25]. In addition, this method is not appropriate for the measurement of the local magnetic properties of materials.

2.2. The direct method

The main drawbacks of the indirect measurement method of magnetic field strength are avoided by the direct measurement method. This method requires a strictly homogenous distribution of the magnetic field strength in the measurement area and parameters of the configuration of the magnetising circuit – the examined object. What is more, in contrast to the indirect method, it makes the characterisation of the non-homogeneity of the material possible. It is a very useful method for monitoring the effect of technological processes on the magnetic properties of semi-finished magnetic cores.

2.2.1. Sensors for magnetic field strength measurement in ferromagnetic materials by the direct method

Direct measurement of magnetic field strength is performed with the help of passive and active inductive sensors and various semiconductor and thin-film sensors, widely described in literature [3, 34-36]. For the measurement of magnetic field strength in electrical steel sheets the sensors most often applied are inductive sensors – the flat coil (H – coil), the Rogowski-Chattock Potentiometer (RCP) and the Hall sensor.

The H-coil sensor is made of a flat coil wound on a thin paramagnetic insulating core. The tangential component of the magnetic field strength is determined on the basis of electromagnetic force e induced in uniformly winded coil with N turns and cross-section S, according to formula (14)

$$H = -\frac{1}{\mu_0 \cdot N \cdot S} \int e \, \mathrm{d}t \tag{14}$$

It should be emphasised that the accuracy of the measurement signal conversion is determined mainly by the materials and construction parameters of the sensor, which can be assigned with high accuracy. Moreover, the flat coil is characterised by very good linearity and enjoys practically no limit with respect to the range of the magnetic field being measured. It is a passive and non-invasive sensor because it does not disturb the distribution of the measured magnetic field. Its drawback is the necessity of integrating of the output signal, which is proportional to the derivative of magnetic field strength, with respect to time. In addition to this, it is characterized by relatively low sensitivity in comparison to other sensors (about several dozen µV/(A/m)) [35]. The sensitivity can be improved by increasing the number of turns of the coil but this results in increasing the distance of the sensor from surface of the tested object. This leads to an increase in the level of measurement error for the magnetic field caused by the gradient of the tangential component of the magnetic field strength over the tested object. One reason for the non-linear gradient of the magnetizing field can be the pole sources of the non-uniform demagnetizing field resulting from the change in the normal component of magnetization at the boundary surfaces of the tested object.

The Rogowski potentiometer (RCP) is a special kind of inductive sensor with a coil uniformly wound on an elastic and non-magnetic core bent in such a way that its ends touch the surface of the tested object. Such a solution ensures the sensor is brought closer to the surface of the tested object at a distance equal to the radius of the wound wire's diameter. The output signal of such a sensor is proportional to the difference between the magnetic potentials at the ends of the sensor placed on the surface of the sample [27, 6].

If, over the distance l_p of the magnetic circuits between the ends of the sensor, there is a uniform distribution of magnetic field strength, the measured drop in magnetic potential $H \cdot l_\mathrm{p}$ will be proportional to the tangential component of the magnetic field strength. Thus, when the distance between the sensor ends is known, the magnetic field strength in this region can be determined without having to average it along the sample length, according to formula (15)

$$H = -\frac{1}{\mu_0 n l_p S} \int e \, \mathrm{d}t \tag{15}$$

where: S – the cross-section of the sensor [m^2], n – the number of coil turns per unit length [m^{-1}].

The main advantage of the Rogowski potentiometer is its linearity and the possibility it affords to measure the magnetic field strength directly on the sample surface. Its essential disadvantage is its low sensitivity (a range of nV/(A/m) [1]), the instability of its metrological parameters as a consequence of changes in the sensor's shape and the technical difficulties in its manufacturing [1]. That is why the RCP is applied mainly in hard magnetic material measurements.

The Hall sensor is an active sensor making use of the Hall effect. The Hall effect is the production of a potential difference (the Hall voltage u_H) across an electrical conductor, transverse to the electric current in the conductor and the magnetic field perpendicular to this current [26]. The magnetic field strength is determined from the following dependency:

$$H = u_H \, d / (C_H I_0) \tag{16}$$

where: C_H – Hall's constant dependent on the material used [$\Omega \cdot m^2/A$], I_0 – the current forced in the sensor [A], H – the external magnetic field strength [A/m], d – the thickness of the sensor's active material [m].

Hall sensors are made from semiconducting materials characterised by high mobility of the charge carrier (most often indium arsenide InAs, indium antimonide InSb, and mercury telluride HgTe), solid materials (germanium), and thin-film technology, for example vacuum deposition on a ceramic or mica substrate [28, 21, 22, 7]. Its small thickness (potentially just fractions of a millimetre) and high sensitivity (ranging from a few to a few dozen μV/A/m) are important advantages of Hall sensors.

However, the active nature of the Hall sensor is a disadvantage because it requires a current supply to provide the source of the magnetic field interference measurement.

In addition to this, in mass production it is very hard to obtain adequate repeatability of the sensors' characteristics. That is why Hall sensors with high quality parameters and low temperature error are still expensive.

2.2.2. Problems measuring the magnetic field strength by the direct method

Despite the availability of a wide range of sensors, measurement of magnetic field strength in electrical steel sheets by means of the direct method is still difficult and liable to a fairly high level of measurement error. The measurement of field strength must be performed directly on the surface of a tested object. Any distance between the sensor and the surface of the tested object results in an error in the direct method measurement. This error depends, among other things, on the sample's geometrical dimensions, magnetic permeability and the state and method of its magnetization. It is also influenced by the distance of the sensor from the object's surface and the width of the air-gaps between the magnetizing yoke and the tested object. These factors influence the distribution of the demagnetizing field, and in consequence, the gradient of the tangential component of the magnetizing field over the surface of the object [5].

Due to the magnetic field strength gradient the sensor should be placed as close as possible to the object's surface. Usually, due to design restrictions, the distance of the sensors for the direct measurement of magnetic field strength can be up to a few millimetres from the object's surface.

For this reason, measurement of the magnetic field is often carried out at several heights over a sample's surface. The value of the field on the surface of the object is then determined by linear extrapolation of these results. Such a solution was proposed by Nakata et al. [17, 19]. They used two H-coils placed in an SST at a distance of 1.5 and 4.5 mm above the sample's surface. In this case, by applying linear extrapolation of the results, the level of measurement error for the magnetic field strength of a grain-oriented steel sheet was reduced from 10% to 0.5%. The method has proved very popular and is employed for the measurement of the constant component of the magnetic field strength using both a flat coil [2, 33, 14, 15] and Hall sensors [24, 32].

However, this raises a number of concerns which include the averaging measurement of the magnetic field strength by means of sensors which are rather thick with respect to the magnetic field gradient, and the uncertainty in determining the very small distances between the sensor (or sensors) and the surface. It is also necessary to validate (by numerical calculations or experimentally) the distance from the sample's surface where the magnetic field gradient is still linear. The region of monotonic changes in the magnetic field above the surface depends on various factors, but particularly on the method of the sample's magnetisation. In the case of symmetrical magnetisation (with a double C-yoke), the magnetic field strength gradient is linear even at a large distance above the sample surface. Moreover, the magnetic field strength increases in value much more slowly in comparison to asymmetrical single yoke magnetisation [33]. When single yoke, asymmetrical magnetisation is applied a large magnetic field gradient appears above the sample's surface, especially in the case of small C-yokes with the presence of air-gaps between the sample and the yoke legs, which in real measurement conditions are impossible to avoid.

It should be noted that even small changes in the dimensions of the yoke have a significant impact on the value of the field gradient. For example, in [24], as calculated by the finite element method, it is shown that in the case of a C-yoke with a height h = 33 mm, cross-section S 10 mm x 25 mm and length between yoke legs L = 20 mm, an increase of 0 to 0.1 mm in the air gap between the sample and the yoke legs can result in a rise in the field gradient of up to 170%. However, for a larger yoke, with dimensions h = 70 mm, S = 20 x 20 mm and L = 40 mm, such a change in the air gap's dimension caused an increase in the field gradient of only about 15 – 25%. In addition, the value of the field gradient and its profile over the sample's surface depend on the arrangement of the driving coils on the magnetizing yoke. In the case of single driving coil placed on the horizontal part of the yoke, a field above the surface decreases linearly at a distance of a few millimetres. In the case of two driving coils arranged symmetrically on the yoke legs, close to the yoke-sample contacts, the magnetic field changes above the surface are not linear. Moreover in the presence of air-gaps between the sample and the yoke legs the magnetic field changes are actually non-monotonic. In this case, the magnetic field strength on the sample's surface, as determined by linear extrapolation, is liable to a high degree of error.

This error can be significantly reduced by shielding the magnetic field strength sensor or sensors from the yoke and the driving coils' stray fields. Placing magnetic shields (made of grain-oriented electrical steel sheet) on both sides of the magnetic field sensor between the legs of the yokes, reduces the gradient field over the surface of the object by five to ten times, and its profile is linear over a large distance (10 mm) from the sample surface, even in the presence of an air gap of 0.2 mm between the sample and the yoke leg. Shields can suppress most of the flux leakage from the yoke legs and the driving coils guiding the flux from air to the sample. This greatly diminishes the level of error in the magnetic field strength measurement both when the single sensor and extrapolation methods are used. The shielding effectiveness depends on the magnetic permeability of the shielding plates, their cross-section and the quality of the contact between the magnetic shield and the sample [23, 31].

3. SUMMARY

Measurement of magnetic field strength by means of the direct method makes it possible to measure the magnetic properties of electrical steel sheets in the form of non-standardized and open samples. It also provides an opportunity to determine the local magnetic properties of the material and to assess the influence of technological processes on the magnetic properties of magnetic cores. However, despite many years of research, the direct method still creates a lot of substantial metrology problems associated with the presence of stray fields and, consequently, with the measurement error generated by the gradient of the tangential component of the magnetizing field strength over the sample, which in turn generates the method error.

Therefore, applying the direct method for the measurement of magnetic field strength requires many factors that determine the accuracy of the measurement to be taken into account. They primarily include: the method of the sample's magnetization, the type of sensor used, and the presence of air gaps between the magnetizing yoke and the sample. These issues are also analysed at the Wroclaw Electrotechnical Institute.

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PROBLEMY POMIARU NATĘŻENIA POLA MAGNETYCZNEGO BLACH ELEKTROTECHNICZNYCH METODĄ BEZPOŚREDNIĄ – PRZEGLĄD

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STRESZCZENIE *W artykule, na podstawie dokonanego przeglądu literatury, przedstawiono istniejące problemy pomiaru natężenia pola magnetycznego metodą pośrednią i bezpośrednią w blachach elektrotechnicznych oraz próby ich rozwiązania. Opisano czujniki składowej natężenia pola magnetycznego stosowane najczęściej do pomiaru natężenia pola magnetycznego w blachach elektrotechnicznych.*

Słowa kluczowe: *pomiar natężenia pola magnetycznego, czujniki pola magnetycznego, pomiar natężenia pola magnetycznego metodą bezpośrednią*