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Magnetization measurements in circle-shaped samples of typical dynamo steel sheets

***Abstract**. The paper describes a significant modification of the measurement method of the rotational magnetization in which circle-shaped samples of dynamo sheets are used. In the modified method, additional packages of sheet samples allow us to achieve a more uniform distribution of the magnetic field in the examined sheet sample with respect to conventional measurement methods using circle-shaped samples. Additionally, this paper includes the measurement verification of the equations of the magnetic field distribution which take into account a model of the rotational magnetization in typical dynamo sheets.*

***Streszczenie.** W artykule przedstawiono istotną modyfikację metody pomiarów przemagnesowania obrotowego, w której wykorzystywane są próbki blach prądnicowych w kształcie kołowym. W zmodyfikowanej metodzie dodatkowe pakiety próbek blach pozwalają uzyskać bardziej jednorodny rozkład pola magnetycznego w badanej próbce blachy w porównaniu z dotychczasowymi metodami, w których wykorzystywane są kołowe próbki blach. Dodatkowo, w artykule przedstawiono weryfikację pomiarową poprawności równań rozkładu pola magnetycznego, w których uwzględniono model przemagnesowania obrotowego typowych blach prądnicowych.(**Pomiary magnetyczne kołowych próbek typowych blach prądnicowych**).*

Keywords: dynamo steel sheets, equation of magnetic field distribution, magnetic measurement, rotational magnetization.
Słowa kluczowe: blachy prądnicowe, magnesowanie obrotowe, pomiary magnetyczne, równania rozkładu pola magnetycznego.

Introduction

Standards relating to the rotational magnetization in electrical steel sheets have not been developed yet in contrast to the standards concerning the axial magnetization. The main cause lies in difficulties in fast measurement methods of the magnetic field values during the rotational magnetization. Relatively simple devices like the Epstein frame and the Single Sheet Tester for measurements of the rotational magnetization processes have not been constructed yet. In these cases the magnetic measurements are carried out by means of the so-called Rotational Single Sheet Tester (RSST). Very often sheet samples have a square shape [1, 2, 3], sometimes these samples can have a hexagonal shape [4, 5]. Two mutually perpendicular coils allow us to record two voltages, which are next used for the calculations of magnetic flux densities in two perpendicular axes, usually in the rolling and transverse directions.

In some research centers, the circle-shaped samples of transformer or dynamo steel sheets are used [6, 7, 8]. The rotational magnetic field is excited by two coils which are placed in a stator of a typical three-phase induction motor. The magnetic measurements are performed for only one sheet sample which is placed inside the stator (Fig. 1). In this approach, measurement accuracy can raise substantial doubts, because the magnetic flux distribution inside the sheet sample is generally non-uniform, as it is presented in Figure 1.

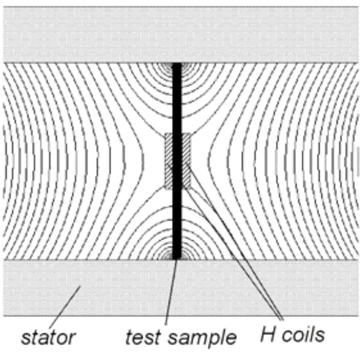

Fig.1. Pictorial drawing of the magnetic field distribution in the measurement system with one circle-shaped sample

The measurement system with additional sheet samples

The laboratory stand was constructed on the basis of the stator of a typical induction motor with the power in the range from 5 kW to 15 kW. The individual stator sheets were arranged every 60 degrees in order to avoid the possible effects of sheet anisotropy. Two windings were placed on the stator in two mutually perpendicular axes. These windings can be supplied separately from independent current character sources. It allows us to research the rotational magnetization processes in the conditions close to reality. The current frequency can be varied in the range from 5 Hz to 150 Hz. The circle-shaped test sample of the given dynamo sheet is placed in the middle of the stator. Two packages of additional sheet samples placed on both sides of the test sample are a novelty in the presented method. Each package consists of five sheet samples arranged in the same way as the test sample. It means that the rolling direction in all sheet samples is the same. The additional packages of the sheet samples provide a more uniform distribution of the magnetic field in the given sheet sample (Fig. 2). Similarly as in other mentioned methods, two coils for determination of the flux density and two coils for determination of the field strength were mounted on the test sheet sample. Voltage signals from the measuring coils are amplified and next recorded in the computer memory.

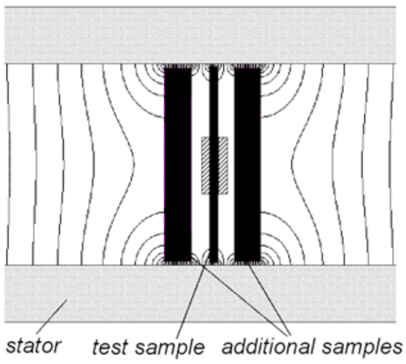

Fig.2. Pictorial drawing of the magnetic field distribution in the measurement system with additional sheet samples

The magnetic field distribution in the test sample and in the neighbouring samples is the same. It is understood that the accuracy of the field strength measurement depends on the thickness of the H coils. The differences of the field strength inside the test sample and in the space between test and neighbouring samples are about 10 per cent, which results from the numerical calculations carried out with the use of the MagNet software. It can cause a certain error in the determination of the field strength which occurs inside the test sample.

The correctness of the measurement system was verified by comparison of the hysteresis loops for the axial magnetization with the hysteresis loops measured by means of the Epstein frame[1]. The verification was performed for the typical dynamo sheets M530-50A produced in the Czech Republic. Figure 3 presents the hysteresis loops for the rolling direction (RD) and for the transverse direction (TD) respectively. It is worth underlining that the measurement accuracy depends first of all on the H coil thickness.

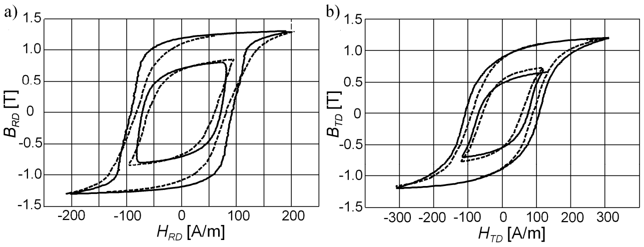

Fig.3. Hysteresis loops of the Czech dynamo sheet: a) for the rolling direction RD, b) for the transverse direction TD; continuous lines – loops determined with the use of the proposed measurement system, dashed lines – loops measured by means of the Epstein frame

Measurements of rotational magnetization

The proposed measurement system enables us to determine the magnetic flux density and field strength in the middle of the given sheet sample during circular, elliptical or axial magnetization for different frequencies. Measurements can be also carried out in the case where the stator windings are supplied separately from two one-phase voltage source inverters. It allows us to research magnetization processes in magnetic circuits of electrical machines whose currents have higher harmonics.

Magnetic properties of electrical steel sheets during the rotational magnetization are determined on the basis of the so-called pole figures and the waveforms of the flux density and field strength as time functions. The latter relations allow us to determine the lag angle between the flux density and the field strength in the analyzed part of the given sheet sample. For example, Figure 4 presents the pole figures of the M530-50A sheet for two maximum values of the magnetic field strength, whereas Figure 5 shows the waveforms of the flux density and field strength. This dynamo sheet has certain anisotropic properties, therefore both field quantities do not have a sinusoidal shape, and these quantities are not circles. Due to certain anisotropic properties of the examined dynamo sheet, the magnetic flux density along the rolling direction is slightly larger than the flux density value in the transverse direction. For the same reason, the field strength in the rolling direction is less than the value of the field strength in the transverse direction. It should be emphasized that the shape of the magnetic flux density is more important than the field strength because the flux density directly influences the magnetic flux changes.

[1] Hysteresis loops were measured in the Laboratory of Magnetic Measurements (Stalprodukt S.A.) in Bochnia (Poland).

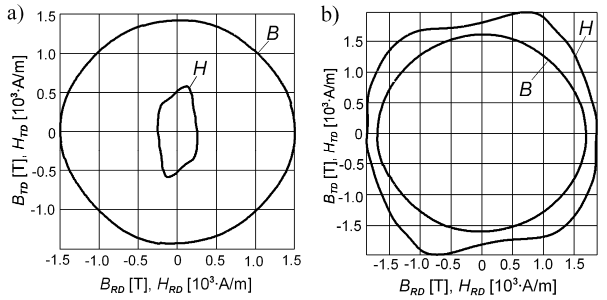

Fig.4. Pole figures of the flux density B and the field strength H for the sheet M530-50A: a) H_{max} = 550 A/m, b) H_{max} = 2000 A/m

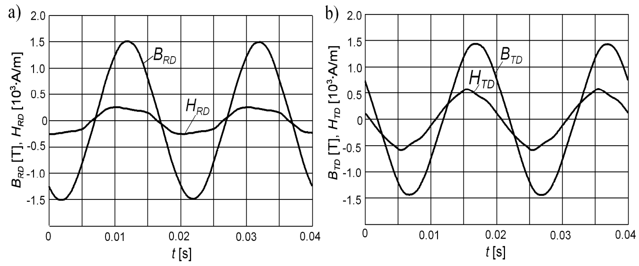

Fig.5. Waveforms of the magnetic flux density and the field strength during rotational magnetization along: a) rolling direction RD, b) transverse direction TD

Calculations of the magnetic field distribution during rotational magnetization

The proposed modified measurement system provides a wide range of possibilities in magnetic tests of electrical steel sheets for different conditions in magnetization processes. Additionally, by means of this system we can verify any model of magnetization processes, especially the model of the rotational magnetization. This process is caused by rotations of the field strength vector inside the sample of the given dynamo sheet [9]. Since magnetic properties are nonlinear, flux densities in individual parts of the steel sheet proceed differently, so the given dynamo sheet should be divided into elementary segments. Therefore, it is necessary to formulate the equations of the magnetic field distribution in which the field strength in individual segments is an unknown quantity. Naturally, these equations must take into account the rotational magnetization in individual elementary segments.

The applied model of the rotational magnetization was widely presented in [10, 11]. Here we present only main assumptions of this model. The surface of each elementary segment is divided into an assumed amount of specified directions (Fig. 6), similarly as in [12].

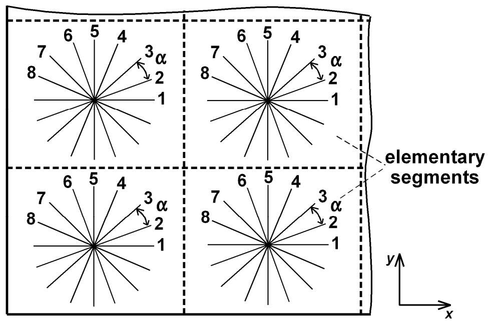

Fig.6. A part of a dynamo sheet with elementary segments

To each direction, a certain hysteresis loop, the so-called direction hysteresis, is assigned. The resultant flux density in the elementary segment is the vector sum of the flux densities in the specified directions. The parameters of these direction hystereses are calculated on the basis of such values like the saturation flux density, the remanence, and the coercive force of the given dynamo sheet. It is worth underlining that the direction hystereses differ from the hysteresis loop of the whole sheet sample and they cannot be determined directly by any measurement.

In order to include model of the rotational magnetization into equations of the magnetic field, the dependence between the flux density and the field strength should be written in the form of the direct mathematical relation. For this purpose, the appropriate components of field strengths and the appropriate components of flux densities are assigned to individual segments, as it is shown in Figure 7. It is preferable to determine the so-called tree as a system of branches connecting vertexes of all segments (nodes of this network) and not creating any closed path. The field strength components have the *m* subscript if they do not belong to the network tree, and the remaining components are depicted by the *p* subscript. The flux density components which are assigned to the left lower sub-segments have the *b* subscripts, and the *t* subscript depicts the components associated with the right upper subsegments.

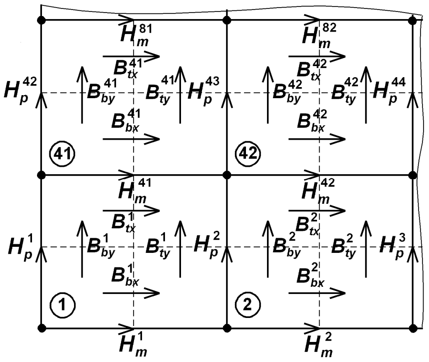

Fig.7. An example of the description of the field strength and flux density components; superscripts denote the consecutive numbers of the components

On the basis of the first Maxwell equation in the integral form we can formulate algebraic equations for independent meshes in the following form:

$$\sum_{k=1}^{4} a_k H_k = s_J J \qquad (1)$$

where H_k – a magnetic field strength component, a_k – the distance between the corresponding vertexes of the segment, J – density of an external current, and s_J – the area of the surface determined by a mesh.
All equations in the form (1) can be written as follows:

$$\mathbf{A_m H_m} + \mathbf{A_p H_p} = \mathbf{S_J J_{ex}} \qquad (2)$$

where $\mathbf{H_m}$, $\mathbf{H_p}$ – the column vectors of the components H_m, H_p respectively, $\mathbf{A_m}$, $\mathbf{A_p}$ – the matrixes of the distances a_k, which with the components H_m or H_p are associated ($\mathbf{A_m}$ is the square matrix), $\mathbf{S_J}$ – the matrix of areas s_J, $\mathbf{J_{ex}}$ – the column vector of the density values of external currents.

Using the Gauss law in its integral form for the magnetic field we can write algebraic equations for independent nodes of the network (Fig. 7) in the following form:

$$\sum_{k=1}^{ls} c_k B_k = 0 \text{ or } \Phi_{ex} \qquad (3)$$

where B_k – a flux density component, c_k – the area of the segment face which the magnetic flux with the flux density component B_k penetrates, l_s – the number of the magnetic flux density components associated with the given node, Φ_{ex} – a certain external magnetic flux which can flow into the given node.
All equations in the form (3) can be written as follows:

$$\mathbf{C_{bx} B_{bx}} + \mathbf{C_{by} B_{by}} + \mathbf{C_{tx} B_{tx}} + \mathbf{C_{ty} B_{ty}} = \mathbf{\Phi_{ex}} \qquad (4)$$

where $\mathbf{B_{bx}}$, $\mathbf{B_{by}}$, $\mathbf{B_{tx}}$, $\mathbf{B_{ty}}$ – column vectors of components B_{bx}, B_{by}, B_{tx}, and B_{ty} respectively, $\mathbf{C_{bx}}$, $\mathbf{C_{by}}$, $\mathbf{C_{tx}}$, $\mathbf{C_{ty}}$ – matrixes of segment face areas which are penetrated by magnetic fluxes with the corresponding components, $\mathbf{\Phi_{ex}}$ – the vector column of external fluxes.

The field strengths of the direction hystereses depend on the components H_m, H_p and on the angle between directions specified on the sheet surface and the *x* and *y* axes of the coordinate system. For example, the field strength for the direction numbered 4 (Fig. 6) in segment 42 (Fig. 7) equals:

$$H_{42d4} = \cos 3\alpha H_{m42} + \cos \alpha H_{p43} \qquad (5)$$

where α – the angle between two neighboring directions.

The flux density components B_{bx}, B_{by}, B_{tx}, and B_{ty} are equal to the sums of the projections on the *x*-axis and *y*-axis of flux densities in individual directions. For instance, the components B_{bx}, B_{by} in segment 42 can be written as follows:

$$B_{42bx} = B_{42d1} + \cos\alpha B_{42d2} + \ldots + \cos 7\alpha B_{42d8} \qquad (6)$$

$$B_{42by} = \cos 3\alpha B_{42d2} + \cos 2\alpha B_{42d3} + \ldots + \cos 3\alpha B_{42d8} \qquad (7)$$

where B_{ndk} are the flux densities of the direction hystereses.

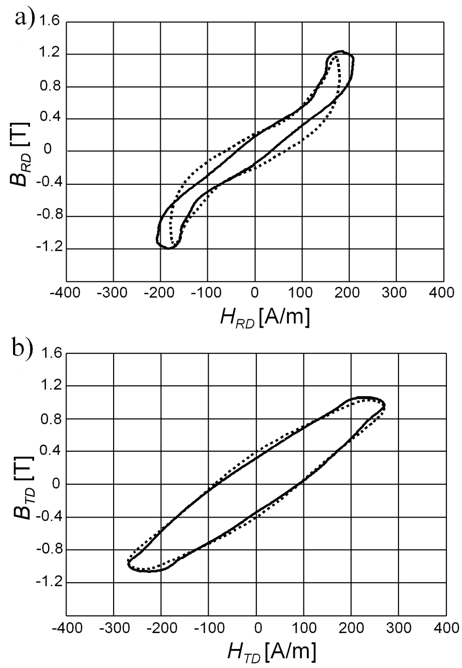

Fig.8. Hysteresis loops during the rotational magnetization of the Czech dynamo sheet along: a) the rolling direction RD, b) transverse direction TD: continuous lines – measured loop, dotted lines – calculated loop

The flux densities of direction hysteresis are nonlinear functions of the field strengths in individual directions, i.e. $B_{kd1}=f(H_{kd1})$, $B_{kd2}=f(H_{kd2})$, $B_{kd3}=f(H_{kd3})$, and so on. As a result, the components B_{bx}, B_{by}, B_{tx}, and B_{ty} are functions of the components H_m, H_p. All flux density components are arranged into appropriate column vectors. This allows us to transform (4) to the form in which the column vectors of the components H_m, H_p are unknown. It results from (2) that the column vector $\mathbf{H_m}$ is dependent on the vector $\mathbf{H_p}$. Then, only $\mathbf{H_p}$ is the unknown vector in the modified (4). The final equation of the magnetic field distribution is nonlinear and this equation is solved with the use of the Newton-Raphson method. It is worth underlining that due to the variable magnetic field, the calculations of the magnetic field distribution should be carried out with taking eddy currents into account. This is achieved by taking into consideration a separate network and additional equations for these currents.

Verification measurements were carried out by providing sinusoidal currents in the windings which generate a rotational field. Figure 8 shows hysteresis loops measured and calculated with respect to the rolling direction (RD), and transverse direction (TD). It is worth noting that the shape of these loops differs significantly from the well-known shape of the hysteresis loop during the axial magnetization. Due to the magnetic anisotropy, the maximum values of the flux density are higher than the corresponding values determined for the transverse direction.

Conclusions

Thanks to applying additional sheet packages, the magnetic field distribution in the examined sheet sample is more uniform with respect to the methods that use circular-shaped samples. It is important to ensure the uniformity of the magnetic field distribution in the tested sheet samples, especially in the vicinity of the measuring coils, since it affects the accuracy of both the flux density and field strength calculations. It is necessary to stress that measurement results significantly depend on the accuracy of the alignment of the sheet sample inside the two-phase stator. However, the precision of the measuring coils is also important. The presented system can be used in magnetic tests of electrical steel sheets, especially dynamo sheets.

The proposed method of the inclusion of the rotational magnetization model in the equations of the magnetic field distribution allows us to study different magnetization processes. Moreover, the magnetic field inside steel sheets can be induced by winding currents or by external magnetic fluxes. The exemplary comparison of the numerical calculation results with the measured results recorded during the rotational magnetization indicates the sufficient correctness of the proposed method. It allows us to take into account the rotational magnetization model. However, a comprehensive assessment of both the measuring system and the model of the rotating magnetization, measurements should be carried out for different magnetization conditions, including the deformed currents.

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