INFLUENCE OF MAGNETIC ANISOTROPY ON THE ROTATIONAL MAGNETIZATION IN TYPICAL DYNAMO STEEL SHEETS

Abstract: Most of typical dynamo steel sheets have anisotropic properties. These properties were determined on the basis of magnetic measurements carried out by means of the Epstein frame for several specified directions of selected dynamo sheets. For engineering purposes, it is desirable to assess the influence of these properties on the magnetization process in dynamo steel sheets, especially during the rotational magnetization. This assessment can be performed with the use of the appropriate model of the rotational magnetization, which was briefly presented in the paper. Anisotropic properties were taken into account with the use of the special function of the grain distribution in the given dynamo sheet. Analysis was performed for the axial and rotational magnetization for a few selected dynamo sheets. The influence of the magnetic anisotropy on the magnetization process was briefly discussed for both types of the magnetization processes. Measurements of the rotational magnetization were compared with numerical calculation results.

Keywords: anisotropic properties, dynamo steel sheet, magnetization process, rotational magnetization

1. Introduction

Electrical steel sheets, which are produced as Fe-Si alloys, can be divided into two basic groups. The first one refers to dynamo steel sheets, and the second group concerns transformer sheets. Dynamo sheets are used first of all in constructions of stators and rotors of induction and synchronous motors. Magnetization processes in these parts of magnetic circuits can have a different character. In the stator cores the magnetization process has rotational character, mainly elliptical character. On the other hand, in stator teeth this process has very often axial character. Due to their applications, dynamo steel sheets can be magnetized in different directions. Therefore, these sheets should have isotropic properties, and they are produced as non-oriented steel sheets. Such properties of dynamo sheets are quite frequently assumed in some studies [1]. However, different magnetic measurements carried out by means of both the RSST\(^1\) devices and the Epstein frame have shown that dynamo sheets have certain anisotropic properties both in terms of the magnetization curves and power losses [2, 12]. Therefore, an appropriate model of the magnetization process should be used in calculations of the magnetic field distribution and power losses during the rotational magnetization. It is understood that this model should allow engineers to take into account the magnetic anisotropic properties of these dynamo sheets, and it also could be applied for different conditions of the magnetization processes. It is necessary to stress that dynamo sheets are quite often used in the construction of cores of small power transformers. From these sheets different shapes for transformer cores are cut out. Worse magnetic properties in the transverse direction with respect to the rolling direction of the given dynamo sheets cause the value of the total magnetic flux in a transformer core to decrease.

2. Model of magnetization process

Models of the rotational magnetization, which are currently used, base frequently on a division of the sample plane of the given dynamo sheet into an assumed amount of specified directions. Flux densities in individual directions proceed differently, so the resultant flux density is the vector sum of the flux densities in individual directions. These models are based on the so-called vectorization of a scalar model of the hysteresis phenomenon, and the Preisach model is used most often [3, 4].

Certain difficulties in the creation of the magnetization process models refer to the problem of how to take into account the magnetic anisotropy. It should be noted that methods allowing engineers to take this phenomenon into consideration have been

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\(^1\) RSST – rotational single sheet tester; it allows to research any type of magnetization process in rectangular-shape samples (less frequently hexagonal-shape) of the given electrical steel sheet.
already presented in several papers [5, 10], however, these proposals concern non-hysteresis materials. Sometimes this problem is solved by an appropriate modification of a chosen vector hysteresis model [6].

For engineer’s purposes, it was assumed that all iron grains in a certain dynamo sheet have the same size and they have one easy magnetization axis, as it is suggested in [11]. Due to the magnetic anisotropy, to each individual direction a different number of grains (whose easy magnetization axis is parallel to the given direction) is assigned (Fig. 1). Assuming that the sample of the given dynamo sheet is divided into 12 directions, the arrangement of grains can be described by means of the so-called the grain distribution function $d(k)$ [7, 9]

$$d(k) = d_1, d_2, ..., d_k, ..., d_{11}, d_{12}$$  \hspace{1cm} (1)

where: $d_k$ – relative amount of grains which are assigned to the $k$-th direction; the sum of all function values must be equal to 1.

![Fig. 1. Simplified drawing of the grain distribution in a certain anisotropic sheet: RD, TD – rolling and transverse direction respectively](image)

To each direction a certain hysteresis loop, further called the direction hysteresis, is assigned. These direction hystereses are described by such parameters as: the saturation flux density $b_{sk}$, the residual flux density $b_{rk}$, and the coercive force $h_c$. It should be stressed that these parameters and direction hystereses cannot be measured and they differ from the hysteresis of the whole dynamo sheet sample. The parameters of the direction hystereses are calculated on the basis of the measurements of the limiting loop and some partial hysteresis loops. Determination of these parameters was widely discussed in [7, 9]; in this paper we present only the basic formulas. The saturation flux density $b_{sk}$ for the given $k$-th direction is defined as

$$b_{sk} = d_k B_s$$  \hspace{1cm} (2)

where: $B_s$ – saturation flux density (determined by measurements) of the given dynamo sheet. The remanence $b_{rk}$ of the individual direction hysteresis is equal to the $b_{rc} d_k$ product, where $b_{rc}$ equals

$$b_{rc} = \frac{B_r}{d_1 \cos 5\alpha + d_2 \cos 4\alpha + ... + d_{12} \cos 5\alpha}$$  \hspace{1cm} (3)

The parameter $B_r$ denotes the remanence measured with respect to the rolling direction in the given sheet, and $\alpha$ denotes an angle between two neighboring directions (Fig. 1).

The coercive force $h_c$ of the direction hystereses equals

$$h_c = H_c \frac{N_{cr}}{D_{cr}}$$  \hspace{1cm} (4)

where: $H_c$ – the coercive force of the given dynamo sheet with respect to the rolling direction RD,

$$N_{cr} = b_{r1} \cos^2 5\alpha + b_{r2} \cos^2 4\alpha + ... + b_{r12} \cos^2 5\alpha$$

$$D_{cr} = b_{r1} \cos 5\alpha + b_{r2} \cos 4\alpha + ... + b_{r12} \cos 5\alpha$$

The parameters of the individual direction hystereses are dependent on the grain distribution function. It is understood that in order to obtain correct results of numerical calculations, this model of the rotational magnetization must be included in the equations of the magnetic field and eddy current field distribution, which was widely described in [8].

It is worth underlining that this model can also be applied for the modeling of the axial magnetization process.

### 3. Anisotropic properties during axial magnetization

Anisotropic properties of some dynamo sheets are expressed by differences of the measured and calculated magnetization characteristics for different directions on the sample plane of the given dynamo sheet. Figures 2 and 3 present hysteresis loops of two selected, typical
dynamo sheets marked as M530-50A. One of them is produced in the Czech Republic and the other one is manufactured in South Korea.

Fig. 2. Hysteresis loops of the Czech dynamo sheet; $B_{\text{max}} = 1.5$ T

Fig. 3. Hysteresis loops of the Korean dynamo sheet; $B_{\text{max}} = 1.5$ T

Differences between remanence values are about 18 per cent in the case of the Czech dynamo sheet; for the Korean sheet these differences are significantly bigger. Magnetic measurements and corresponding numerical calculations have shown that relevant differences between the flux density values determined for the rolling direction and the transverse direction occur when the field strengths are less than 200 - 300 A/m. If the field strength values are bigger than this range, the flux densities in typical dynamo sheets increase more slowly, and the differences of the magnetization characteristics are getting smaller.

Magnetic measurements were carried out in Laboratory of Magnetic Measurements in Stalprodukt SA, Bochnia (Poland).

4. Influence of anisotropy properties on the rotational magnetization

As it was previously mentioned, dynamo steel sheets are produced as non-oriented sheets, and therefore they should have isotropic properties. It means that hodographs of the flux density or field strength during the rotational magnetization should have a circular shape. However, due to anisotropy which occurs in the majority of typical dynamo sheets, hysteresis loops measured and calculated along different directions on the sheet plane differ from each other. Hodographs of the flux density or field strength do not have a circular shape even when one of these field quantities has the constant amplitude during the rotational magnetization.

Magnetic measurements were carried out with the use the laboratory stand, which was constructed on the basis of the stator of a typical induction motor of 5 kW. Two sinusoidally distributed windings were placed on the stator in two mutually perpendicular axes. Two coils for indirect determination of the flux density and two coils for determination of the field strength were mounted on the test dynamo sheet, as it is applied in existing methods of magnetic measurements during the rotational magnetization [3, 5, 12]. The circle-shaped sample of the given dynamo sheet was placed in the middle of the stator. Additionally, two sheet packets, each of which consists of five sheets, were placed on both sides of the test sheet sample (Fig. 4). These additional sheet packages provide a more uniform distribution of the magnetic field in the given sheet sample.

Fig. 4. Pictorial drawing of the measurement system; lines present the magnetic field distribution in cross-section of the measurement system
Measurements were carried out by providing sinusoidal currents in the windings which generate a rotational field. Figure 5 shows hysteresis loops measured and calculated with respect to the rolling direction (RD), and hysteresis loops presented in next figure (Fig. 6) concern the transverse direction (TD).

Fig. 5. Hysteresis loops along the rolling direction RD during the rotational magnetization of the Czech dynamo sheet: continuous line – measured loop, dotted line – calculated loop

Fig. 6. Hysteresis loops along the transverse direction TD during the rotational magnetization of the Czech dynamo sheet: continuous line – measured loop, dotted line – calculated loop

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. The influence of the anisotropy on the rotational magnetization can be clearly seen in the example of the changes of the flux density components. Also useful for this analysis are the so-called pole figures showing the hodographs of the flux density or field strength vector during the magnetization process. Figure 7 presents, for example, changes of the flux density vector obtained numerically with an assumption that the magnitude of the field strength is constant during the rotational magnetization and it is equal to 250 A/m. Changes of the flux density components for a hypothetical isotropic material are shown, for comparison, as a dashed line in this figure; it is known that this line has a circular shape. In turn, Fig. 8 presents the pole figure of the field strength vector during the rotational magnetization wherein the amplitude of the flux density vector does not change its value, and the amplitude of this rotating vector was equal to 1.3 T.

Fig. 7. Changes of the flux density components during the rotational magnetization: continuous line – for anisotropic material, dotted line – for hypothetical isotropic material

Fig. 8. Pole figure of the field strength vector during the rotational magnetization
It should be emphasized that pole figures and relations between flux density components or field strength components can be obtained using the RSST devices or by carrying measurements in the measurement system described in this paper. However, measurement results, obtained in this way present usually average values of the flux density in chosen part of the given test dynamo sheet. Determination of the field distribution in the middle layer of this sheet, which is desirable for higher frequencies, it is possible only by numerical calculations.

5. Conclusions

This paper briefly presents the influence of the magnetic anisotropy on the magnetization processes in dynamo sheets. This anisotropy can cause quite significant differences between magnetization processes occurring in the different directions on the dynamo sheet plane. It is understood that these differences depend on the anisotropy degree. Therefore, further studies on a given problem should focus on the assessment of errors which arise due to the neglecting of the magnetic anisotropy.

Research concerning the anisotropic properties of dynamo sheets was performed for two types of dynamo sheets. However, in order to obtain meaningful results and to formulate general conclusions, appropriate studies should be carried out for a greater number of typical dynamo sheets produced by different manufacturers.

The magnetic anisotropy was taken into account with the use of the grain distribution function. For simplification of the magnetization model it was assumed that all iron grains in dynamo sheets have only one easy magnetization axis. However, in reality the cube-shaped iron grains have three easy magnetization axes. Therefore, further studies should also focus on the errors related to this assumption.

6. References


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