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doi:10.15199/48.2022.12.32

Frequency behavior of specific total loss model taking into account anisotropy of electrical steel

***Abstract**. Due to Goss texture electrical steel displays strong anisotropy of magnetic properties. This phenomenon shoud be taken into account by designers of magnetic circuits as it has undesirable effect e.g. vibrations and noise. Several approaches for anisotropy of magnetic properties can be found in the literature. In this paper are presented frequency behavior of parameters of anisotropy P_S loss model based on three components specific total loss model.*

***Streszczenie.** Ze względu na fakturę Gossa stal elektryczna wykazuje silną anizotropię właściwości magnetycznych. Zjawisko to powinno być brane pod uwagę przez projektantów obwodów magnetycznych, ponieważ ma ono niepożądany efekt m.in. wibracje i hałas. W literaturze można znaleźć kilka podejść do anizotropii właściwości magnetycznych. W artykule przedstawiono charakterystykę częstotliwościową parametrów anizotropii modelu strat P_S w oparciu o trzyskładnikowy model strat całkowitych. (**Zachowanie częstotliwościowe określonego modelu strat całkowitych z uwzględnieniem anizotropii stali elektrotechnicznej**)*

Keywords: electrical steel, specific total loss, magnetic anisotropy
Słowa kluczowe: blachy elektrotechniczne, jednostkowe straty mocy.

Introduction

Grain oriented GO electrical steel ES is important material for industrial applications e.g. magnetic cores of transformers. As a results of introduction of Goss patent with addition of silicon at production of ES it exhibits a strong magnetocrystalline anisotropy with a (110)[001] orientation. GO ES has a high magnetic flux saturation and magnetic permeability and low specific power loss at an easy magnetization direction. In the Goss texture, the easy magnetization direction is <001> is parallel to the rolling direction RD. The worst magnetic properties are determined at an angle of 55° (<111>) with RD. Intermediate magnetic properties occur at an angle 90° to RD that is transverse direction TD. Production of large transformers requires magnetocrystalline anisotropy to be taken at design process in order to minimize the core losses and the magnetizing currents. Cores of large transformers are made of tape cut along RD but at T-joints and corners the magnetic flux deviates from the easy magnetization axis [1-7]. At these places anisotropy of magnetic properties of ES adversely affects some technical parameters of the final product. The energy loss has particular significance for large transformers which convert all produced electrical energy. Hence, taking into consideration the anisotropic properties of ES at the design stage can lead to considerable energy and material savings.

The modeling of anisotropic properties of specific power loss in electrical steel ES is a topic of intensive research. Much research has been devoted to modeling the effect of anisotropy on the magnetic properties of GO ES. We can distinguish, for example, models based on the Néel phase theory [8], on the reluctivity tensor [9] or based on the co-energy concept [10]. The experimental models describe the angular properties of power loss based on various functions. One of them is based on a third-order polynomial [11], and the other on the orientation distribution (ODF) function used in crystallographic studies [12] or model presented in [13]. Most often these models cannot be applied to high magnetic induction values, such as where grain oriented electrical sheets often work in transformer cores.

In this paper is presented analysis of frequency and flux density behaviour of specific total loss parameters of model taking into account directional properties of GO ES. The analysis is performed using novel model of directional properties of specific total loss based on loss separation approach [13, 14]. The investigation was preformed for GO ES. There was found that the model presented in [13] can be used for analyzing of directional properties of ES as it is kept, in assumed ranges of flux density, permeability and frequency [2].

Measurements and specific total loss separation

A. Experimental setup

The experiment was carried out on conventional GO ES sheets with Goss texture. Thickness of chosen for tests ES grades varied in the range form 0.27 mm to 0.35 mm and specific total loss anisotropy calculated from Eq. (1) varied from about 50% to 60%.

$$\Delta P_S^{y-0} = \frac{P_S^y - P_S^0}{P_S^y + P_S^0} \quad (1)$$

where: y - angle x in respect to rolling direction,

The anisotropy of specific total loss is calculated for the magnetization angles y = 90° and x = 0° at the flux density 1.5 T. Samples of ES grades were cut at six to seven different angles to RD in dependence on ES grade.

Determination of the specific total loss P_S has been carried out with a computerized system based on a 16 bit DAQ card. The P_S loss was measured for sinusoidal waveform and under controlled value of form factor (FF) [15] and total harmonic distortion (THD) of magnetic flux. Measurements were taken under axial magnetisation in a non-standard Single Sheet Tester (SST) on square samples of 100 mm width [2]. The magnetization frequency was from the range 2 Hz to 100 Hz and measurements were performed at 10 frequencies.

The flux density range was varied in dependence on the grade of ES and on the magnetization direction. In the direction around 60° to RD the peak flux density B_p range was from 0.1 T to 1.3 T and in rolling direction the flux density B_p range was from 0.1 T to 1.9 T.

B. Loss separation

It is overall accepted that the specific total loss P_S consists of three components: hysteresis, classical and excess eddy current. The frequency dependence of the three components can be described by three component model. The P_S loss components were separated in the commonly used way as [17]:

(2) $$P_S / f = P_h / f + P_{ce} / f + P_{ex} / f = \\ = C_h B_p^{\alpha} + C_{ce} B_p^2 f + C_{ex} B_p^{3.2} f^{1/2}$$

where: C_h is the hysteresis loss coefficient, α is the exponent of flux density, $C_{ce} = \pi^2 d^2 (6\rho)^{-1}$ is the classical eddy current loss coefficient under sinusoidal magnetization, C_{ex} is the excess loss coefficient, ρ is the resistivity and d is the sheet thickness.

Classical eddy current of the P_S loss component Eq. (2) shows isotropic character. The hysteresis and excess eddy current loss components display anisotropic character. Both components show similarity due to their common origin [16, 17, 18]. To obtain two unknown coefficients of Eq. (2) C_h and C_{ex} for given magnetization angle x and peak flux density B_p, both sides of Eq. (2) are divided by frequency f. As a result P_S loss can be obtained. From fitting of Eq. (2) to experimental values the coefficient $C_h(B_p, x)$ was obtained by extrapolation of results to 0 Hz frequency and the coefficient $C_{ex}(B_p, x)$ could be calculated. Later, the hysteresis P_h and excess P_{ex} loss components were calculated. It is worth to noting all three P_S loss components follow exponential law for all considered magnetization angles in all ES under consideration.

In Fig.1 are plotted experimental data and fitted using Eq. (2) energy loss versus frequency for three magnetizing directions obtained for ES steel M150-35S grade at B_p = 1.2 T.

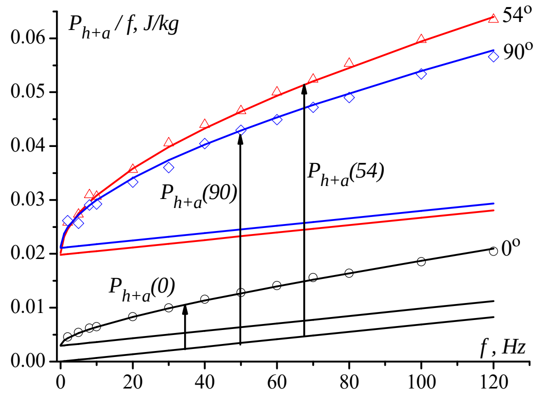

Fig. 1. Energy loss per unit mass versus frequency for different magnetizing directions obtained for steel grade M150-35S at B_p = 1.2 T

The P_S loss separation procedure described below was performed according to the three component model Eq.(2) for each magnetization angle. The results showed high nonlinearity of magnetic anisotropy of ES on frequency. In a case of ES the Eq. (2) is valid for any magnetization angle x [19].

From Fig. 1 it can be seen non-linear and significant increase of the sum of hysteresis and excess eddy current specific total energy loss components for "hard" magnetization angles x = 54° and x = 90° over that for magnetization along RD (at angle x = 0°). Additionally, specific total loss increases much faster with frequency for “hard” magnetization angles 45° ≤ x ≤ 90° what can be attributed to “the growing number of involved Bloch walls” [19].

Results and discussion

The main circumstance for the new model presented in [13] was the interdependence of the hysteresis and eddy current excess loss components, showed in the works [20]. This allowed proposing a model of the properties of the directional power loss $P_S(x)$ presented in [13]. This model can be used for description of anisotropic properties of the sum P_h+P_{ex}, Fig. 2. As P_{ce} is isotropic for given ES grade the model allows description of anisotropic properties of GO ES.

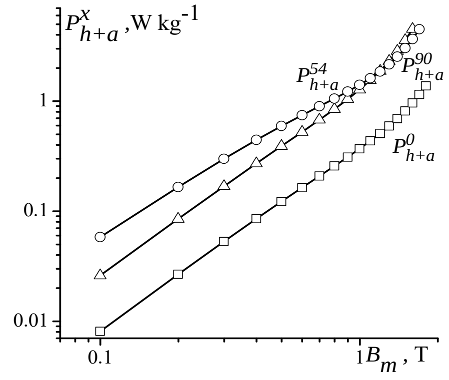

Fig. 2. Directional curves of a sum of P_h and P_{ex} components of ES grade M150-35S [13]

Presented in Fig. 2 directional dependences of the sum of P_h+P_{ex} follow exponential function as in Eq. (2). However, it is accurate only in limited range of flux density approximately up to 1.5 T. Above the range curves presented in Fig. 2 deviate from the curve marked by a simple exponential function. Therefore they were used modified exponential function with expanded exponent as Eq. (3).

(3) $$P^x_{h+ex} = a B_p^{b(B_p)}$$

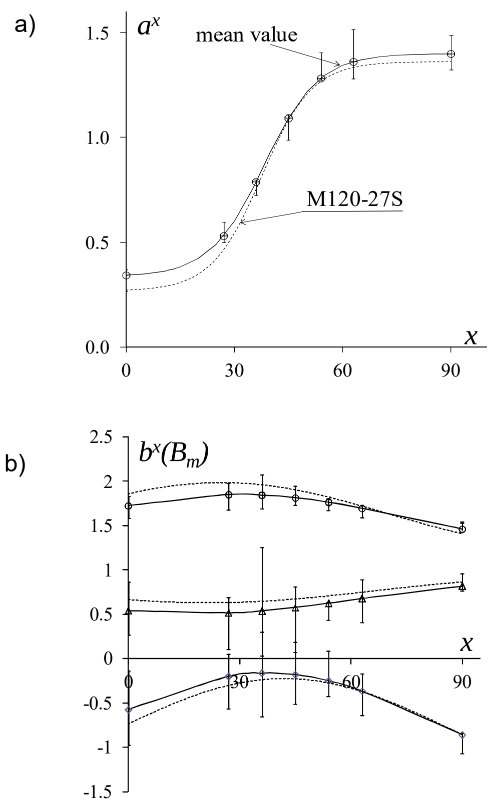

Fig. 3. Parameters of exponential function used for extrapolating directional curves in Fig. 2 [13]

In Fig. 3 a) and b) are presented the angular dependence of parameter $a(x)$ and polynomial coefficients

$b(x)$. Presented in Fig. 3 a) the angular dependence of parameter $a(x)$ of exponential function Eq. (3) can be described by the following equation:

$$a(x) = a(0) + [a(90) - a(0)] \cdot \left[1 + \exp\left(\frac{x50 - x}{m}\right)\right]^{-1} \tag{4}$$

The parameters $a(0)$ and $a(90)$ determine minimum and maximum of curve $a = f(x)$ presented in Fig. 3 a). In Fig. 4 are presented behavior of parameters $a(0)$ and $a(90)$ of Eq. (4).

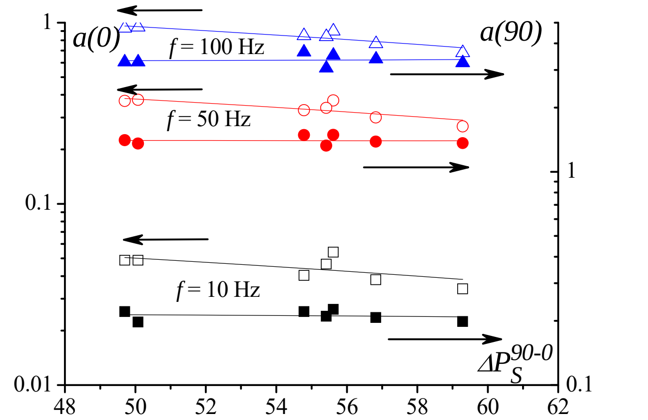

Fig. 4. Parameters a(0) and a(90) of Eq. (4) as a function of anisotropy $\Delta P_S^{90\text{-}0}$ and frequency

As can be seen in Fig. 4 the parameter $a(90)$ concerning transverse direction weakly depends on anisotropy $\Delta P_S^{90\text{-}0}$ in opposite to the parameter $a(0)$. The parameter $a(90)$ depends on frequency but for given frequency it is independent on P_S loss anisotropy. The difference between $a(0)$ and $a(90)$ can be due to different magnetization process at RD and TD.

Parameters m and $x(50)$ of Eq. (4) as a function of loss anisotropy $\Delta P_S^{90\text{-}0}$ and frequency are presented in Fig. 5.

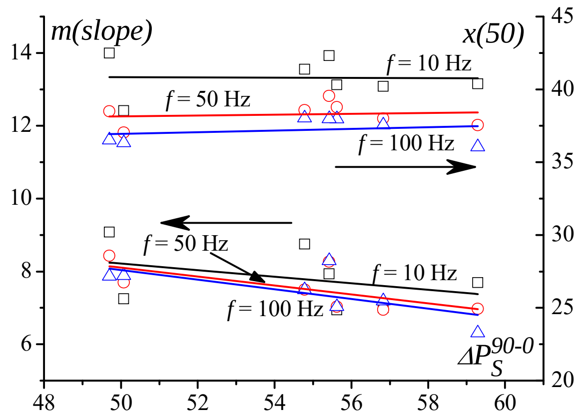

Fig. 5. Parameters m and $x(50)$ of Eq. (4) as a function of specific total loss anisotropy $\Delta P_S^{90\text{-}0}$ and frequency f

The parameter $x(50)$, Fig. 5, depends on frequency and nearly does not depend on anisotropy $\Delta P_S^{90\text{-}0}$. The parameter $x(50)$ can be easily calculated as angle at an average between x = 0° and 90°. The parameter m, Fig. 5 describing the slope of curve $a(x)$ weakly depends on frequency. Its dependence on anisotropy $\Delta P_S^{90\text{-}0}$ *is* shows stronger dependence.

Coefficients of exponent $b(B_p)$ of peak flux density (Eq. (3)) can be described by Eq. (5). The dependence of the three coefficients of Eq. (5) on anisotropy $\Delta P_S^{90\text{-}0}$ for frequencies 10 Hz, 50 Hz and 100 Hz are presented in Fig. 6.

$$b_i = z_0 + z_1 \sin\left[2\left(x\frac{\pi}{180} - z_2\frac{\pi}{180}\right)\right] \tag{5}$$

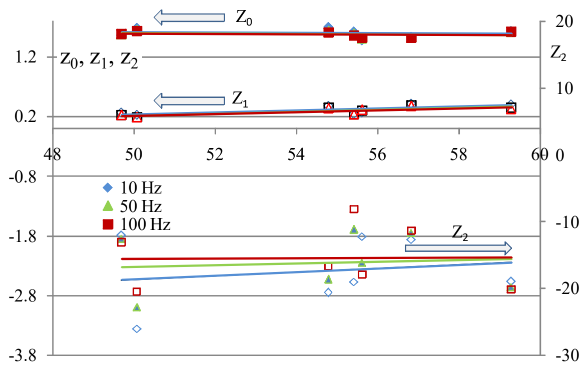

Fig. 6. Parameters z_0, z_1 *and* z_2 of (5) as a function of anisotropy $\Delta P_S^{90\text{-}0}$ and frequency

Parameters z_0, z_1, z_2, differently depend on frequency and anisotropy $\Delta P_S^{90\text{-}0}$. The parameter z_0 does not depend on anisotropy and frequency. The parameter z_1 does not depend on frequency but weakly depends on anisotropy of P_S loss. The parameter z_2 is characterized by larger dispersion associated with anisotropy and frequency. The dispersion with frequency decreases with anisotropy $\Delta P_S^{90\text{-}0}$ showing lower changes in grades with larger orientation. This can be associated with the effect of micro and classical eddy currents increasing significantly with frequency and peak flux density.

Summary

The anisotropy of specific total loss components is a very non-linear phenomenon. As it was mentioned the modeling of GO ES anisotropic properties of P_S loss can be realized in different ways. In the paper were evaluated parameters of model of directional properties of specific total loss in Goss textured electrical steel. The advantage of this model is the possibility to modeling anisotropy of P_S loss even at high flux density. It was observed larger influence of frequency on anisotropy of specific total loss in electrical steel grades with smaller grain orientation. The influence of frequency and associated with it eddy currents is observed for parameter related to sum P_h and P_a components at rolling direction. Weak influence of frequency on anisotropy shows constant parameter of exponent of flux density of the sum P_h and P_a components. The main influence of frequency was observed in rest parameters responsible for curvature of directional P_{h+a} curves.

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