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Calculating power loss in electrical steel taking into account magnetic anisotropy

Streszczenie. *Badanie właściwości anizotropowych jednostkowych strat mocy przy przemagnesowaniu osiowym i różnej częstotliwości przeprowadzono przy użyciu niestandardowego aparatu SST. Analiza zależności pomiędzy składowymi histerezową, dodatkową wiroprądową oraz anizotropią magnetyczną uzasadnia rozpatrywanie tych składowych razem. Celem niniejszego artykułu jest zaproponowanie metody obliczenia strat mocy z uwzględnieniem zjawiska anizotropii magnetycznej i częstotliwości przemagnesowania.*

Abstract. *Study of anisotropic properties of specific total power loss under axial magnetization and at different frequencies was carried out using a non-standard SST apparatus. Analysis of the relationship between hysteresis components, additional eddy current and magnetic anisotropy justifies considering these components together. The purpose of this article is to propose a method for calculating power losses taking into account the phenomenon of magnetic anisotropy and the magnetizing frequency. (**Obliczanie strat mocy w blachach elektrotechnicznych z uwzględnieniem anizotropii magnetycznej**).*

Słowa kluczowe: składowe stratności, anizotropia magnetyczna, blacha elektrotechniczna.
Keywords: specific total loss components, magnetic anisotropy, electrical steel.

Introduction

Electrical steel (ES) is the most widely used soft magnetic material in the electrical industry. Better understanding of the magnetization processes associated with magnetizing frequency and influence of magnetic anisotropy can help in improvement of modeling of magnetic properties of ES. Better modeling of ES means correct hysteresis modeling which is mandatory for an accurate design of circuits including magnetic cores. These models are implemented in electronic circuit simulators and should include frequency and anisotropic behavior of magnetic parameters. Particularly, the influence of magnetizing frequency increases its significance as increases working frequency of electrical devices and thereby their magnetic cores. Together with increasing frequency new, thinner ES with Goss texture are produced. This shows that the importance of the magnetic anisotropy increases as it changes with frequency.

An investigation of the specific total loss (P_S) separation in ES at different angles x to rolling direction (RD) was performed. The separation of the specific total loss into components was performed using three components model. The dependence of the hysteresis and additional eddy current P_S loss components on magnetic anisotropy is shown as well as their interdependence. It was found that both hysteresis and additional eddy current loss components are strongly dependent on the magnetization angle x and their flux density behavior is very similar to each other. Better understanding of anisotropy influence on P_S loss also may offer additional information for improvement of magnetic properties of ES. The aim of this paper is to present calculation method taking into account not only frequency but also magnetic anisotropy. It also provides a contribution to the better understanding of P_S loss in ES.

Measurements setup

The measurements were carried out in a non-standard Single Sheet Tester (SST) with square sample shape of 100 mm width. The magnetizing and B-sensing coils were wound over sample cross sectional area. The magnetic flux from sample closes through two C-cores 25 mm thick. Air flux compensating coil was also used. Determination of P_S loss has been carried out in computerized system based on LabVIEW™ programming platform presented e.g. in [1].

The measurements were carried out under controlled sinusoidal magnetic flux waveform and in the range of magnetic flux density B_m varied from 0.1 T to 1.8 T in dependence on magnetization angle x. The ranges were chosen in such a way that it was possible to keep the deviation from sine wave of magnetic flux under 0.5% in whole range of magnetizing frequency, which is considerably under 1% required for example by standard [2]. In the case of specific total loss P_S measurement, the standard deviation was equal to or less than 1.5% from average. The experiment was carried out on five grain-oriented (GO) ES M120-27S, M150-27S, M140-30S, M150-35S and M165-35A grades with Goss texture.

Experimental results

One of the first specific total loss model consisted of two hysteresis and eddy current components loss [3, 4]. The model well fitted experimental data obtained for ES produced at that time. The dependence $P_S/f = \mathrm{f}(f)$ of these ES was nearly linear. This is due to weakly developed and fine domain structure of these ES, mainly hot-rolled steel. Although this, the two component model fits well experimental data of currently manufactured non-oriented ES [3, 4]. In a case of modern GO ES well developed domain structure cause significant non-linearity of a dependence of specific total energy loss versus frequency $P_S/f = \mathrm{f}(f)$, Fig. 1. This non-linearity is well described by three component P_S loss model. This P_S loss model was developed for many years by many scientists [5, 6] and finally proposed by G. Bertotti [7, 8]. The three components P_S loss model for different magnetization angles x describes the following equation [1]:

$$P_S(x) = \underbrace{C_0(B_m, x) B_m^{\alpha} f}_{P_h(x)} + \underbrace{C_1 B_m^2 f^2}_{P_{ce}} + \underbrace{C_2(B_m, x) B_m^{3/2} f^{3/2}}_{P_a(x)} \quad (1)$$

where: $C_0(x)$ is the hysteresis loss coefficient, $C_1 = \pi^2 d^2 /(6\rho\ \gamma)$ is the classical eddy current loss coefficient, $C_2(x)$ is the additional eddy current loss coefficient, ρ is the resistivity, d is the sheet thickness, γ - mass density.

The classical eddy current P_{ce} component is calculated from Maxwell equations among others under assumptions that ferromagnetic material is homogenous and isotropic. The lack of fine and weakly developed domain structure in hot-rolled ES was the main reason for quite accurate eddy current loss prediction in early years. Together with introduction of Goss texture larger discrepancy between measured and calculated loss values using hysteresis P_h and classical eddy current P_{ce} appeared. This caused introduction of third component of P_S loss called additional eddy current loss P_a, eq. (1). Description of the additional eddy current loss component is given by the statistical loss model [7, 8]. However, this description cannot be used for magnetization angle x different than rolling direction as in a case of GO ES as so called simultaneously moving magnetic object reaches negative values [9]. The simplified form (1) of the statistical loss model the three components model can be used for specific total loss $P_S(x)$ analysis for different magnetization angles x [1].

As mentioned above, in (1) only classical eddy current component P_{ce} can be calculated. Two residual components have to be determined on experimental way, usually by fitting $P_S(x)/f$ = f(f) to experimental points. Performing measurements $P_S(x)$ at many different frequencies f is obviously time consuming. But proper determination of coefficients value $C_0(x)$ and $C_2(x)$ requires obviously more than two numbers of experimental data. This is especially important in low frequency range at which hysteresis loss component is determined (see Fig. 1) otherwise the hysteresis loss component is determined in quasi static condition. In this work it was assumed that fitting by the use 10 or more measurement points can be seen as the proper one.

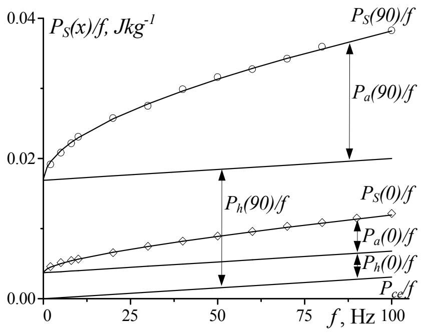

Fig. 1. Energy loss per unit mass versus frequency obtained for GO ES grade M165-35S at flux denisty B_m = 1.0 T

As it is visible in Fig. 1, the dependence of $P_S(x)/f$ = f(f) for ES grade M165-35S experience larger non-linearity at low frequency range and for angle x = 90°. The magnetization frequency was varied in the range from 2 Hz, 5 Hz to 100 Hz. Both, frequency and flux density values were set with precision better than 0.05%. This limits the error of loss separation caused by not precise setting of both quantities which can carry to large discrepancy of experimental points. As an effect errors in loss separation can occur. Another source of error in loss separation can cause shape of magnetic flux estimated by the form factor (FF). The FF causes difference in value of measured P_S loss value by influence of FF on classical and additional eddy current loss components and hence, it influences the accuracy of loss separation. The significance of FF defined as the ratio between RMS and average value of magnetic flux increases as increases importance of both classical and additional eddy current loss components. This is because the FF has no influence on hysteresis loss [8]. It is worth to mention that standardized magnetic measurements require the value of FF should differ from ideal value (1.11072) not more than 1% [2]. The presented in [10] measurements results show that even if FF changes from its ideal value of 1.11072 ± 1% the specific total loss can differ as much as 14% from average value. There is no clear dependence between change of P_S and FF factor. The conclusion drawn in [10] is that if the FF differs less than 0.5% from its ideal value than the P_S loss spread does not exceed 1% and the deviation from sine wave of factor FF of magnetic flux derivative was kept well under 0.5 %.

Results of P_S loss separation for different angle x using the three loss model in form (1) are presented in Fig.2.

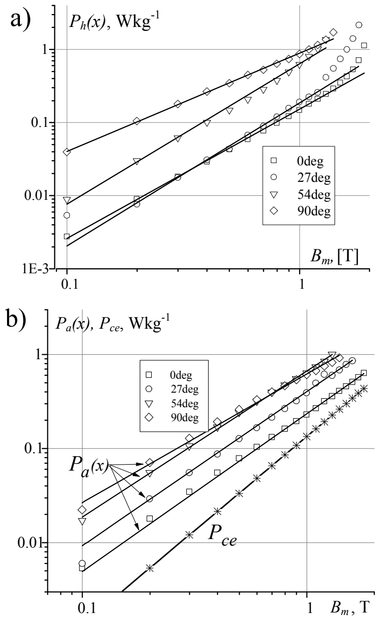

Fig. 2. Hysteresis a), additional and classical eddy current b) specific total loss components versus flux density for different magnetizing angle x of M165-35S ES magnetized at 50 Hz

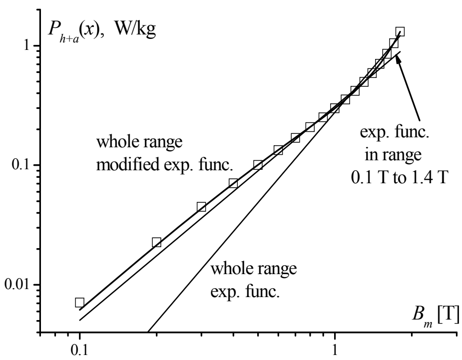

Fig.3. Fitting sum of hysteresis and additional eddy current specific total loss components $P_{h+a}(x)$ with modified exponential function (4), exponential function $a(x)B_m(b(x))$ in whole range of flux density and in limited range up to 1.4 T

Difference occurs in frequency behavior of both hysteresis P_h and additional eddy current P_a loss components. As can be seen in Fig.2, both dependencies of $P_h(x)$ = f(B_m) and $P_a(x)$ = f(B_m) depart from a straight line at "upper" flux density region. The straight lines in Fig. 2 correspond to the exponential function $aB_m{}^b$ with constant exponent b as originally written in three component loss model [Bertotti 1998]. This shows that the form of equation (1) is correct only in limited range of flux density. Therefore, selection of the flux density range in which exponential function parameters are calculated is particularly important for accurate P_S loss description. On the other side the working flux density of GO ES continuously increases and at present is reaches value from 1.6 to 1.75 T. To overcome this problem instead of constant value of the exponent $b(x)$ can be used a parabolic function as below [11]:

(2) $$P_{h+a}(x)/f = a(x)B_m^{\,b(B_m,x)}$$

where: exponent $b(B_m,x) = b_2(x)B_m^2 + b_1(x)B_m + b_0(x)$.

In Fig.3 are presented different methods of fitting of dependence of sum of hysteresis and additional eddy current loss components at RD. It is visible that fitting with single value exponent of exponential function can be source of significant error. It is also visible importance of choosing fitting flux density region. Choosing whole range of flux density can carry to error in the order of 60% at low flux density region. Fitting experimental data, in limited range of flux density carry to smaller error but still in the order of dozens of percents.

Both hysteresis P_h and additional eddy current P_a specific total loss components possesses similar origin which is domain walls movement hence, their angular dependencies are very similar and complex. The hysteresis loss component P_h is more significant for magnetically hard magnetization directions, as in Fig. 4.

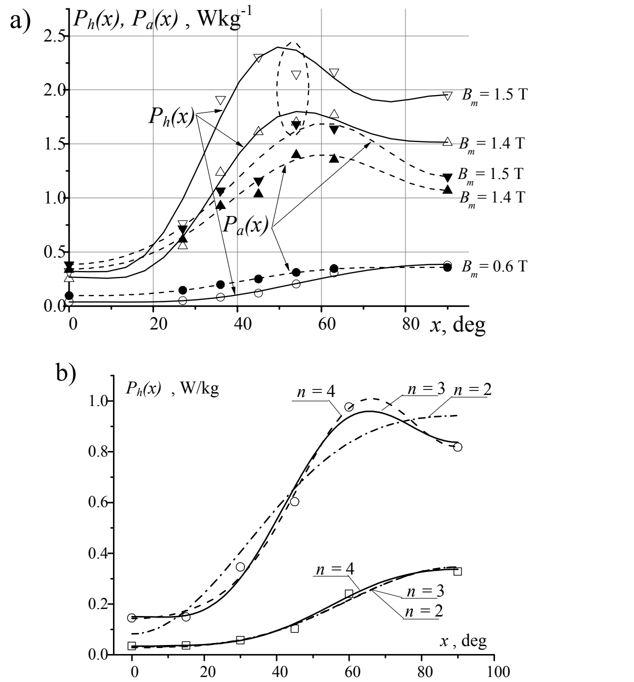

Fig. 4. Angular dependencies of specific total loss components at 50 Hz and at different flux densities B_m for ES grade M140-30S: a) hysteresis $P_{h,y}(x)$ and additional eddy current $P_{a,y}(x)$ components and b) example of fitting angular dependences of $P_h(x)$ component for "lower" and "upper" fitted with (2) with $n + 1$ components (lines) (circle made by a dotted line mark the extrapolated points)

As can be seen in Fig. 4 the influence of magnetic anisotropy can be separated into two regions of flux density which differ by loss mechanisms that occur in both regions. At "lower" flux density region, up to about 1.1 T, both hysteresis P_h (Fig. 4a) and additional eddy current P_a specific total loss components continuously increase with increasing angle x. At "upper" flux density region, above about 1.1 T, both components increase with increasing angle x up to 45° and then decrease up to angle x = 90°. The decrease is faster as flux density increases. This shows that also loss models should be able to reflect this phenomenon in these two "lower" and "upper" flux density regions.

Presented in Fig. 4 a) angular dependences of hysteresis $P_h(x)$=f(x) and additional eddy current $P_a(x)$=f(x) specific total loss components can be represent by series of trigonometric functions as in [12, 13, 14]. Experimental points presented in Fig. 4 a) can be fitted with trigonometric function as below, [1]:

(3) $$F(x) = \sum_{i=0}^{n=4} A_i \cos(2x\,i)$$

where: A_i are coefficients that vary with flux density.

Number of components of (3) depends on flux density range and magnetic anisotropy. In [13] were used five components n = 4 even in a case of NO ES but three components (n = 2) as in [14] was sufficient. In a case of GO ES due to Goss texture angular dependences of $P_h(x)$ and $P_a(x)$ are much more complex and the number of components of (3) n must be increased. As can be seen in Fig. 4 b) three components of (3) (n = 2) fits well to experimental data in GO ES only up to about B_m < 1.0 T, that is in "lower" flux density region, Fig. 4 b). For GO ES and "upper" flux density region (B_m > 1.0 T) Goss texture manifest itself and n should be equal to 3 or 4 in dependence on magnetic anisotropy of ES. Variation of first three coefficients A_i of (3) with flux density for sample M140-30S are presented in Fig. 5.

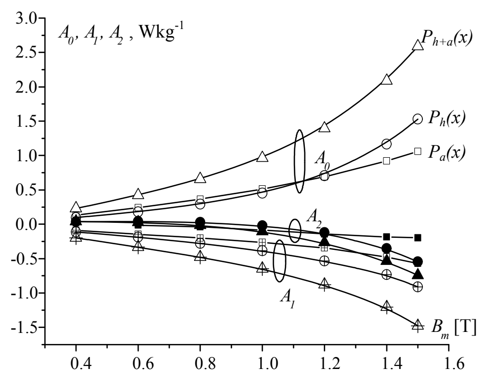

Fig. 5. Variation of first three coefficients A_i of (3) versus flux density B_m at 50 Hz for sample M140-30N fitting hysteresis $P_h(x)$ (circle), additional eddy current $P_a(x)$ (square) specific total loss components, and sum of hysteresis and additional eddy current $P_{h+a}(x)$ components (crossed), empty symbols A_0, crossed A_1 and filled symbols A_2

In Fig. 5 it is visible that dependences of coefficients A_i obtained from fitting angular dependences of hysteresis $P_h(x)$ loss component and additional eddy current $P_a(x)$ loss component are similar. These similarities can be seen also in Fig. 2 and 4 a). This is caused by the fact that both loss components have the same source that is domain walls movement and the micro eddy currents are generated even at quasi static magnetization conditions as well as at higher magnetization frequency. So, the different frequency behavior of both P_S loss components is the main reason to separate them from each other.

As mentioned the classical eddy current loss component has isotropic character in contrast to the first and the third component (1) whose show a strong angular dependence [1]. The influence of magnetic anisotropy on both hysteresis and additional eddy current loss components as presented in Fig. 2, 4 a) and 5 as well as in presented in another way in [9] allows to propose specific total loss $P_S(x)$ model as follows:

(4) $$P_S(x) = (P_h(x) + P_a(x)) + P_{ce} = F(x) + P_{ce}$$

The function $F(x)$ can be any function describing angular dependence of hysteresis and additional eddy current specific total loss components. Closure of hysteresis and additional eddy current loss components in one bracket is caused by similarity in $F(x)$ function describing angular behavior of these two P_S loss components. Additionally, it limits the number of coefficients needed for calculation of angular properties of $P_S(x)$ loss. In Fig.6 are presented dependences of five coefficients A_i of (2) calculated from fitting to angular behavior of sum $P_{h+a}(x)$ for five grades of GO ES under consideration.

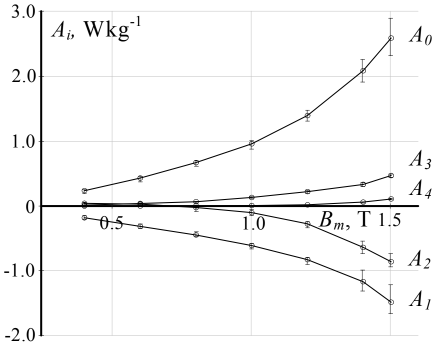

Fig. 6. Dependences of five coefficients of (2) calculated for sum of $P_{h+a}(x)$ for five grades of GO ES under consideration.

As can be seen in Fig.6 dependences of each of five coefficients calculated for GO ES under consideration lays very close to each other. It is worth to underling that the GO ES grades differs significantly by anisotropy of specific total loss $\Delta P_S^{90\text{-}0}$ (50% to 59%) [1] as well as by thickness and resistivity. The dispersion of each coefficient for all grades reaches 25% at "lower" flux density range but at "upper" flux density range the dispersion decreases to about 15%. This justifies summing of hysteresis and additional specific total loss components.

Modified exponential function (3) allow significant improvement in calculation of specific total loss as presented in Fig. 7.

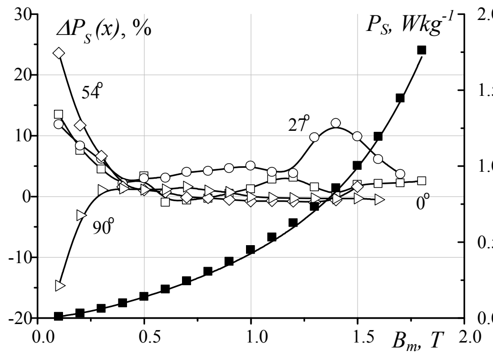

Fig. 7. Specific total loss of GO ES grade M140-30S measured (points) and calculated (lines) from (3), (4) and (2). Calculation errors and experimental data points for x = 0° (RD) and calculated from average data (line) from Fig. 6.

In Fig. 7 presented example of calculation error for GO ES M140-30S. The calculation were carried out on a base of (2) with n = 4 and (3). The calculation error in flux density range from 0.5 T to 1.8 T does not exceed 15%. If to calculations are taken average coefficients values of approximating angular dependences of the sum $P_{h+a}(x)$ (as in Fig.6). The error will obviously drop down if for calculation is taken coefficients for selected grade of ES.

Summary

The specific total loss separation was performed by means of SST measurement at minimum 10 different frequencies. On the base of the measurements specific total loss separation using statistical loss model were performed. Both hysteresis and additional eddy current loss components strongly depend on magnetic anisotropy. It was shown that in the case of GO ES for modeling of angular dependence can be approximated using four or five components of trigonometric functions.

Similarity between hysteresis and additional eddy current loss components was also observed and confirmed. This similarity was taken into account in loss modeling taking into account anisotropy phenomenon. Presented model provides accurate modeling of angular properties of electrical steel. Additionally, the advantage of proposed model (4) is that that it can be used with three component specific total loss model to characterize anisotropy of the loss at different frequency.

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