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Modelling of directional power loss of electrical sheets at axial magnetisation

***Abstract**. Due to the Goss texture, electrical steel sheets (ES) exhibit strong anisotropy in magnetic properties. This phenomenon should be taken into account when designing magnetic circuits because it has undesirable effects, including: increased loss and vibrations. The paper presents an experimental model for calculating power loss in ES, taking into account the phenomenon of magnetic anisotropy. An analysis of the selection of experimental data for determining model coefficients was performed. The analysis was carried out for conventional M120-27N grain-oriented sheet steel used for the production of transformers.*

***Streszczenie.** Ze względu na teksturę Gossa blachy elektrotechniczne wykazują silną anizotropię właściwości magnetycznych. Zjawisko to należy uwzględnić w czasie projektowania obwodów magnetycznych, ponieważ ma ono niepożądany efekt m.in. wzrost strat i wibracje. W pracy przedstawiono eksperymentalny model obliczania strat mocy w blachach elektrotechnicznych uwzględnieniem zjawiska anizotropii magnetycznej. Przeprowadzono analizę doboru danych eksperymentalnych do określania współczynników modelu. Analizę przeprowadzono dla konwencjonalnej blachy o ziarnie zorientowanym gatunku M120-27N wykorzystywanych odpowiednio dla celów wytwarzania transformatorów. (**Modelowanie kierunkowej straty mocy blach elektrotechnicznych przy namagnesowaniu osiowy**m)*

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

Introduction

Electrical steel sheets (ES) are widely used in many different areas of electrical engineering, but they are still used to the greatest extent in the production of large rotating electrical machines and transformers. A commonly accepted criterion for the quality of the materials in question is the reduction of their unit power loss, which have been reduced several times over 50 years [1]. Currently, the best commercially available electrical sheets achieve values below 0.7 W/kg and this is determined at a magnetic flux density of 1.7 T [1, 2]. This improves the performance parameters of electrical devices manufactured from them, taking into account the investment and operating costs.

ES are also characterized by magnetic anisotropy [3-6]. Magnetic anisotropy, or the dependence of material properties on direction, is a characteristic feature of ES, which results from their crystalline structure. The phenomenon of anisotropy plays an important role in the design of magnetic cores and also occurs in non-oriented ES. A better understanding of the effect of anisotropy on total loss can provide additional information that can be used to improve the magnetic properties of ES. The best magnetic properties ES exhibits in the rolling direction, and are particularly poor in the direction of 55° and 90° to the rolling direction [7-9]. Electrical machines are designed in such a way that the magnetic flux causes the smallest loss. This requires the use of increasingly precise computational models that take into account the phenomenon of magnetic anisotropy during core magnetization.

Computational models of energy loss in ES taking into account the phenomenon of magnetic anisotropy can be divided into classical models resulting from the Poynting vector [6, 10], models based on finite element analysis (FEM) [11], hysteresis loop models [12], empirical models based on experimental data [13] or models based on the Orientation Distribution Function (ODF) [14].

The above example models were developed for one direction of magnetization, but they can be successfully used for different directions of magnetization. Taking into account anisotropy in these models is crucial for obtaining precise results and optimizing the design of devices.

The paper presents the calculation results of the proposed model of total loss P_S for grain-oriented ES. Example calculations were performed for the M120-27N sheet for magnetization with a frequency of 10 Hz.

Experimental models for calculating power loss in ES

Magnetic loss due to magnetization of ES causes heat release in the material and can be measured by the thermal method or, more conveniently, by the electrical method, which is correct by the Poynting theorem [15-18]. This model, considered classical, is also used today in the form of equation (1):

$$P_t = C_0 \cdot B_p^{\alpha} \cdot f + C_{ce} \cdot B_p^2 \cdot f^2 \qquad (1)$$

where: B_p – peak flux density, f – magnetization frequency, α – exponent of flux density, C_0 – hysteresis loss constant, C_{ce} – eddy current loss constant.

The C_{ce} coefficient is calculated based on the thickness d and resistivity ρ of the electrical sheet and is equal to $C_{ce} = \pi^2 \cdot d^2 \cdot (6 \cdot \rho)^{-1}$. The C_0 hysteresis loss constant is determined experimentally based on measurements as a function of frequency.

With the development of cold-rolled grain-oriented ES, the difference between measured and calculated loss increased. The resulting additional loss component is defined as excess loss P_{ex}. This component improves the accuracy of the loss calculation model [19, 20].

$$P_t = C_0 \cdot B_p^{\alpha} \cdot f + C_{ce} \cdot B_p^2 \cdot f^2 + C_2 \cdot B_p^{3/2} \cdot f^{3.2} \qquad (2)$$

where: the coefficients C_0 and C_2 are determined experimentally based on loss separation.

Equation (2) is a description of the magnetization phenomenon using statistics that take into account the randomness of domain wall movement and changes in loss depending on the material magnetization frequency [20, 21]. Using equation (2) to calculate power loss is relatively laborious.

The specific power loss of ES in different directions to the rolling direction was studied. The measurements were carried out in a non-standard single sheet tester (SST). The presented usefulness of the experimental model for calculating loss in ES presented in [22] was limited to 10 Hz due to the observed largest scatter of model parameters for this frequency.

Model description

The main assumption of the new model is the correlation of the hysteresis and the excess loss components, shown in works such as [5, 22-24]. Hence, the model of the directional total power loss $P_S(x)$ is proposed as follows [22, 23]:

(3)
$$P_S(x) = (P_h(x) + P_{ex}(x)) + P_{ce} = \\ = P_{h+ex}(x) + P_{ce} = F(x) + P_{ce}$$

where: x – magnetisation angle to rolling direction, P_{ce} – classical eddy current loss component.

The classical eddy current loss P_{ce} can be calculated based on the thickness and resistivity of the sample, as in formula (1). By performing the loss separation procedure, the hysteresis loss P_h and excess loss P_{ex} can be determined. The proposed model, applied to one frequency (in this work 10 Hz), does not require knowledge of the P_h and P_{ex} components and loss separation. Knowledge of the sum of P_h and P_{ex} loss is sufficient. For measurements performed for one magnetization direction, the difference between the total loss and the eddy current loss P_{ce} is calculated. The obtained sum of P_h and P_{ex} loss, constituting a function $F(x)$ (3), can be described by a function dependent on the magnetization angle x. Examples of such functions are the ODF function analyzed in [23] or the sigmoid function analyzed in [22]. An example of the results obtained for the sigmoid function is shown in Fig.4.

The dependencies of the hysteresis and excess components are strongly nonlinear, similarly to the dependence P_{h+ex} = f(Bp) and cannot be described by a simple power function in the whole range of flux density Bp. For this reason, the modified power function (4) proposed in [25] was used to describe the dependence P_{h+ex} = f(Bp). For one direction of magnetization x, it can be written as follows:

(4)
$$P_{h+ex} = aB_p^{(b0+b1B_p+b2B_p^2)}$$

where coefficients a and b are determined by fitting the above equation to the experimental data P_{h+ex} = f(Bp).

In the case of considering anisotropic properties, the coefficients a and b are functions of the magnetization angle and they are $a(x)$ and $b0(x)$, $b1(x)$ and $b2(x)$, respectively. The shape of the function is presented for example in [22, 26]. In previous works, for example [26, 27], the dependences of all model coefficients on the frequency and anisotropy of the loss factor ΔP_S^{90-0} for seven grades of tested ES were presented. The sheets differed in thickness in the range from 0.27 mm to 0.35 mm and in the loss factor anisotropy ΔP_S^{90-0} in the range from 49% to 59%. For the selected grades of grain-oriented ES, the coefficients of the second-order polynomial of the exponent of the flux density power B_p (5) $b0$, $b1$ and $b2$ depend very weakly on the frequency and anisotropy ΔP_S^{90-0} [27]. As mentioned, the measured loss for three magnetization directions are sufficient to determine them. The functions $b0(x)$, $b1(x)$ and $b2(x)$ are parabolas and three sets of coefficients are determined $b0_0$, $b0_1$ and $b0_2$ for the function $b0(x)$, $b1_0$, $b1_1$ and $b1_2$ for the function $b1(x)$ and $b2_0$, $b2_1$ and $b2_2$ for the function $b2(x)$. The Fig.1 shows the angular characteristics of the coefficients $bi(x)$, i.e. $b0(x)$, $b1(x)$ and $b2(x)$.

In Fig. 1, the continuous line shows the characteristics of the coefficients $b0(x)$, $b1(x)$ and $b2(x)$ for fitting data from equation (4) simultaneously for all angles, i.e. 0°, 30°, 45°, 60° and 90° and sheet M120-27N. The error bars show the scatter of the coefficients $bi(x)$ in relation to the fit to three experimental points $bi(0)$ and $bi(90)$ and the third point $bi(30)$ or $bi(45)$. A significant scatter was obtained for the coefficient $b1(x)$. In the case of the other two coefficients, the scatter can be considered acceptable. However, this indicates that three experimental points are not sufficient to precisely determine the course of the second-order polynomial function. Similarly, in the case of the characteristic described by the sigmoid curve $a(x)$ of equation (5), which is described below.

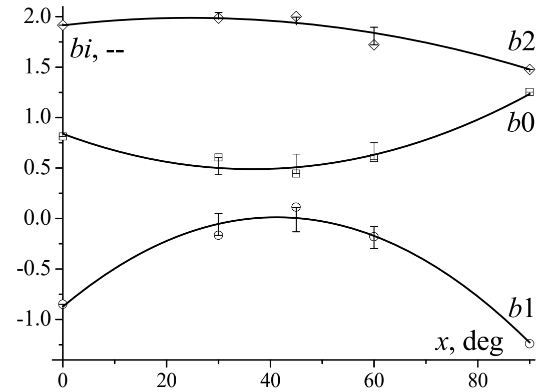

Fig.1. Angular dependencies of the bi coefficients of the exponent polynomial from formula (4)

The coefficients a describe the loss level for different directions of magnetization x in relation to the rolling direction RD, Fig. 4. The angular course of the coefficient $a(x)$ can be described by the Boltzmann function described as follows:

(5)
$$a(x) = a(90) + \frac{a(0) - a(90)}{1 + \exp(\frac{x - x_c}{m})}$$

where $a(0)$ and $a(90)$ are the values of coefficients a at an angles x = 0° and x = 90° respectively, x_c is an inflection point of curve a = f(x) and m is the slope of curve a = f(x).

In the fitting process, the coefficients $a(0)$ and $a(90)$ should remain unchanged for the selected grade of electrical sheet. The remaining two coefficients of equation (5) must be determined experimentally. With the increase of loss anisotropy ΔP_S^{90-0}, the coefficient $a(0)$ decreases linearly. On the other hand, the coefficient $a(90)$ does not change with the increase of ΔP_S^{90-0} for the tested electrical sheets [26, 27].

As mentioned in the description of equation (5), the coefficient x_c is an inflection point of curve a = f(x). The inflection point is the angle at which the curve a = f(x) reaches half the value ($a(90)$ + $a(0)$)/2. The value of this angle changes within narrow limits depending on the anisotropy ΔP_S^{90-0}. However, the dependence on frequency is already significant [26, 27]. For example, for the ES with the highest loss anisotropy in the range of frequency changes from 10 Hz to 100 Hz, the angle at which the curve a = f(x) inflection occurs changes within the range from 36° to 40.5°, as shown in Fig.2.

The second coefficient that must be found experimentally is the coefficient m describing the slope of the a = f(x) curve. The slope factor m of the a = f(x) curve changes inversely with the increase of the ES loss anisotropy, as shown in Fig. 2. Changing the magnetization frequency causes less significant changes in the coefficient m [26, 27].

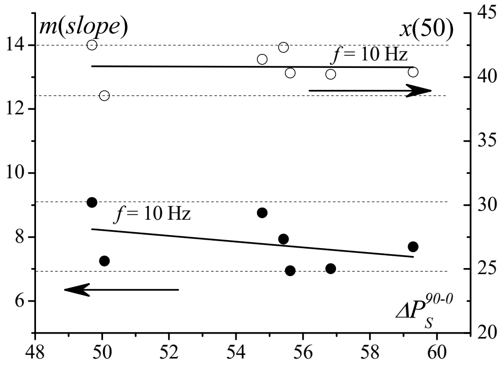

Fig.2. Dependencies of coefficients x_c and m of equation (5) for a group of seven ES sheets with different $\Delta P_S^{90\text{-}0}$ anisotropy and for a frequency of 10 Hz

The curve $a = f(x)$ curves obtained for different selected experimental points are shown in the figure below.

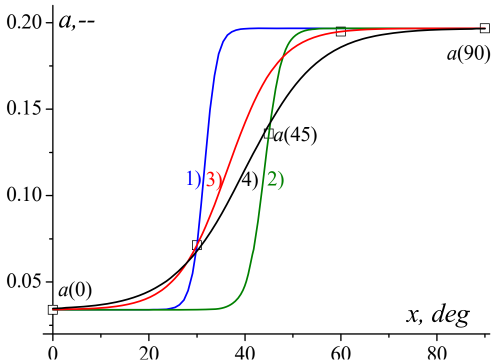

Fig.3. The curves of the dependence $a = f(x)$ determined for different values of the coefficients x_c and m

In Fig. 3, course 1) marked in blue was determined for points $a(0)$, $a(30)$ and $a(90)$, while course 2) (green line) was determined for points $a(0)$, $a(45)$ and $a(90)$. Curve 3) (red) was determined for four experimental points $a(0)$, $a(30)$, $a(60)$ and $a(90)$, while curve 4) marked in black was determined for all five experimental points. As can be seen in Fig. 3, it is not possible to determine exactly the course of the relationship $a = f(x)$ for three experimental points (curves 1) and 2)) using the least squares method. The relationship 3) marked in Fig. 3, determined for 4 experimental points, also does not correctly represent the course of the curve $a = f(x)$ obtained for all five experimental points. For curve 3), the angle of the point x_c = 36.4 and m = 5.3 was determined. These coefficients differ significantly from the range of the x_c and m coefficients for the entire group of materials, as shown in Fig. 2.

As shown in Fig. 2, the angle at which the curve $a = f(x)$ bends is approximately constant for the entire group of materials, i.e. seven types of ES. For this reason, Fig. 4 presents the courses of the dependence $a = f(x)$ by performing a fitting analogous to that presented in Fig. 3, but obtained for the average value of the angle of the point x_c equal to 40.4. The blue colour indicates the dependences determined for three experimental points $a(0)$, $a(30)$, $a(90)$ or green for points $a(0)$, $a(45)$, $a(90)$ using the least squares fitting method. The dependences marked in red and black were obtained for four (0, 30, 60 and 90) and for five (0, 30, 45, 60 and 90) experimental points, respectively.

As can be seen in Fig. 4, the determined curves for the three experimental points overlap similarly as for the four and five points. Dependencies 1) and 2) determined for the three points are characterized by the slope coefficient m = 8.5 and m = 8.6, respectively. On the other hand, dependencies 3) and 4) are characterized by m = 7.3 and m = 7.5, respectively. For such selected points, calculations of errors in calculating loss for different magnetization directions were performed. The calculation results are shown in Figs. 5 and 6.

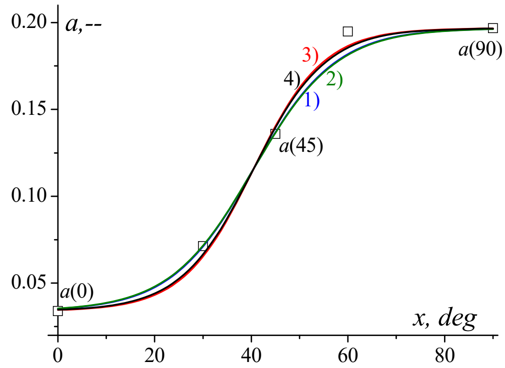

Fig.4. The curves of the dependence $a = f(x)$ determined for the angle x_c = 40.4 and different values of the coefficient m for M120-27N

Errors in loss determining

For the calculation of loss, the average values of the coefficients $bi(x)$, the value of the angle of the point x_c equal to 40.4° and the slope factor of the sigmoid curve m were assumed for the dependencies presented in Fig. 4. Whereas for the dependency determined for three experimental points 0°, 30° and 90° and 0°, 45° and 90° m = 8.55 was assumed. Fig. 5 presents the dependence of the errors in determining the loss for different directions of magnetization and the value of magnetic flux density B_p.

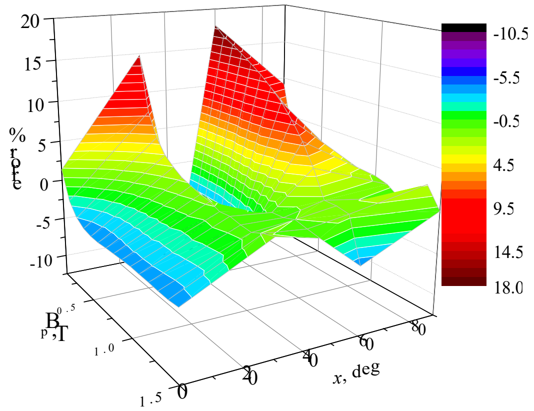

Fig.5. Percentage difference between power loss determined experimentally and calculated using the proposed model for three experimental points, coefficients x_c = 40.4° and m = 8.55 and for the M120-27N ES grade sample depending on the magnetization angle and magnetic induction B_p

As can be seen from Fig.5, the largest calculation errors occur in the range of low flux density values and reach up to 18%. However, for higher values of B_p, i.e. from about 0.9 T, the errors are within the range of +/- 5%. The calculation errors shown in Fig.5 should be considered relatively small. However, the error for low flux density values is mainly caused by imprecise approximation of the $P_S = f(B_p)$ relationship, which requires refinement.

For the dependencies determined for four and five points, m = 7.4 was assumed.

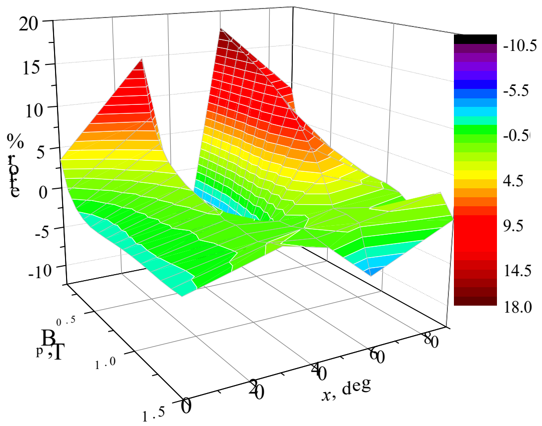

Fig.6. Percentage difference between power loss determined experimentally and calculated using the proposed model for four and five experimental points, coefficients x_c = 40.4° and m = 7.4 and for the M120-27N ES sample depending on the magnetization angle and magnetic induction B_p

The difference between power loss determined experimentally and calculated using the proposed model for four and five experimental points presented in Fig. 6 shows very similar values of calculation errors as in the case of three experimental points. This means that three experimental points are sufficient to determine the loss in any direction. However, it is required to know the inflection of the sigmoid curve for a given frequency defined for the ES group.

Summary

The correlation between the hysteresis loss component and the excess loss component of the three-component model allowed for the proposal of a new model taking into account the anisotropy of loss. The article demonstrates the usefulness of the proposed model for calculating the directional properties of loss for electrical sheets with oriented grain. Three experimental points and average data for a group of seven grades of ES were used for the calculations. It was shown that only three points are insufficient for the calculations, but it is relatively easy to supplement these data with the average angle of the inflection point of the sigmoid curve for the selected type of sheets. In the case of grain-oriented ES, this angle does not depend on the anisotropy of the sheet, but only on the magnetization frequency. The error in calculating loss for the M120-27N sheet is within +/- 5%, regardless of the presented method of their calculation. Only in the range of low values of magnetic flux density below approx. 0.9 T does the error increase to approx. 18%. This is mainly due to the inaccurate approximation of the loss curve P_S = f(B_p) in the range of low flux density values. The analysis of the new model indicates the need to extend the scope of research to non-oriented grain sheets.

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REFERENCES

[1] Moses A. J.: Core considerations. Magnetics Technology International 2011, 8-10
[2] https://www.thyssenkrupp-steel.com, May 2024
[3] Jiles D.C., Introduction to magnetism and magnetic materials. Chapman & Hall, 1991
[4] Landgraf F.J.G., Yonamine T., Emura M., Cunha M.A., Modelling the angular dependence of magnetic properties of a fully processed non-oriented electrical steel. *Journal of Magnetism and Magnetic Materials* 254-255 (2003), 328-330
[5] Pluta W.A., Anisotropy of specific total loss components in Goss textured electrical steel. *Journal of Magnetism and Magnetic Materials*, 499 (2020), 166270
[6] Yue S., Anderson P., Li Y. Yang Q., Moses A.J., A modified inverse vector hysteresis model for nonoriented electrical steels considering anisotropy for FEA. *IEEE Transactions on Energy Conversion* 36 2021, No 4 , pp. 3251-3260
[7] Tumanski S., Investigations of the anisotropic behaviour of SiFe steel, *Journal of Magnetism and Magnetic Materials*, 254-255 (2003), 50-53
[8] Cullity BD., Introduction to Magnetic Materials. *Addison-Wesley Publishing Company* (1972)
[9] Brailsford F., Physical principles of magnetism. D. Van Nostrand Company LTD, London 1966
[10] Chwastek K., AC loss density component in electrical steel sheets, *Philosophical Magazine Letters,* 90 (2010), No 11, 809–817
[11] M'zali N., Martin F., Sundaria R., Henneron T., Benabou A., Belahcen A., Finite Element Modeling of Magnetic Properties Degradation Due to Plastic Deformation, *IEEE Transactions on Magnetics*, 56 (2020), No 2, 1-1
[12] Chwastek, K., Szczyglowski J., Najgebauer M., A direct search algorithm for estimation of Jiles-Atherton hysteresis model parameters, *Materials Science and Engineering B*, 131 (2006), No 1-3, 22–26
[13] Najgebauer M., Scaling theory and its chosen applications in electromagnetism, *Przeglad Elektrotechniczny*, 84 (2008), No 12, 213–216
[14] Campos M.F.. Anisotropy of steel sheets and consequence for Epstein test: I theory. XVIII IMEKO WORLD CONGRESS Metrology for a Sustainable Development September, 17 – 22, 2006, Rio de Janeiro, Brazil.
[15] Griffits D.J., Podstawy Elektrodynamiki (Fundamental of electrodynamics), PWN (2005)
[16] Pfützner H., Zur Bestimmung der Ummagnetisierungs-verluste aus den Feldgrößen, Archiv für Elektrotechnik, 60 (1978), 177-179 (in German)
[17] Pluta W.A., Directional properties of loss components in electrical steel sheets, *International Journal of Applied Electromagnetics and Mechanics* 44 (2014), No 3-4, pp. 379–385
[18] Szczerbanowski R., Zakrzewski K., Obliczanie strat we współczesnych blachach transformatorowych. Przegląd Elektrotechniczny, 6 (2011), 193-197
[19] Bertotti G., General properties of power losses in soft ferromagnetic materials, IEEE Trans. on Magnetics, 24 (1988), No. 1, 621 – 630
[20] Berttoti G., Hysteresis in magnetism, *Academic Press* (1998)
[21] Fiorillo F., Measurement and Characterization of Magnetics Materials, New York: Elsevier Academic Press, 2004
[22] Pluta W.A., Moses A.J., Prediction of angular variation of specific total loss of Goss oriented electrical steel, *Physica B: Condensed Matter*, 544 (2018), 28-33,
[23] Pluta W.A., Calculating power loss in electrical steel taking into account magnetic anisotropy, *Przegląd Elektrotechniczny*, 94(2) (2018), 100-103
[24] Popescu M., Ionel D. M., A Best-Fit Model of Power Losses in Cold Rolled-Motor Lamination Steel Operating in a Wide Range of Frequency and Magnetization, IEEE Trans. on Magnetics, 43 (2007), no. 4, 1753-1756
[25] Chen Y., Pillay P., An Improved Formula for Lamination Core Loss Calculations in Machines Operating with High Frequency and High Flux Density Excitation, IEEE 37th IAS Annu. Meeting (2002), Vol. 2, pp. 759–766
[26] Pluta W.A., The Effect of Magnetic Anisotropy on the Computed Specific Total Loss in Electrical Steel, *Energies* 17 (2024), No 5, 1112
[27] Pluta W.A., Frequency behaviour of specific total loss model taking into account anisotropy of electrical steel, *Przegląd Elektrotechniczny*, 12 (2022), 129-132