Invited paper

Wojciech A. PLUTA

Czestochowa University of Technology

Core loss models in electrical steel sheets with different orientation

***Abstract**. Classical core loss models such as two components model or modified Steinmetz model are still popular and used by engineers to loss prediction in electrical machines. They may carry to increase discrepancy between calculated and measured values. This discrepancy increases with grain-orientation and with increasing discrepancy from sinusoidal magnetisation conditions. Statistical loss model shows better applicability for loss calculation however, it requires many measurements in frequency domain what is troublesome. The paper presents the frequency behaviour of classical and statistical loss models in grain and non-oriented electrical steel sheets.*

***Streszczenie.** Klasyczne modele strat są wciąż popularne i wykorzystywane przez inżynierów do przewidywania strat maszyn elektrycznych. Mogą one prowadzić do niezgodności pomiędzy obliczonymi i zmierzonymi wartościami strat. Niezgodność wzrasta ze zwiększeniem orientacji ziaren i odkształceniem od sinusoidalnego kształtu strumienia magnetycznego. Statystyczny model strat wykazuje lepszą stosowalność do obliczenia strat jednak wymaga czasochłonnych pomiarów w dziedzinie częstotliwości. Artykuł przedstawia właściwości częstotliwościowe klasycznych i statystycznych modeli strat w zorientowanych i niezorientowanych blachach elektrotechnicznych. (**Model strat w blachach elektrotechnicznych o różnym zorientowaniu**)*

Keywords: loss modelling, loss components, additional loss.
Słowa kluczowe: modelowanie strat, składowe strat, straty dodatkowe.

Introduction

Electrical steel sheets are used in several stages of electrical energy transformation from the generators to the ultimate user. In all of those stages not avoidable heating generation occurs which is also called generally 'magnetization loss'. The loss is tolerable in the economics of electrical power distribution and utilisation. However, electrical equipment should be designed in a way to keep the loss at a minimal level.

The physical nature of loss in electrical steel sheets (overall in ferromagnetic conducting media) is well known. The loss can be measured by thermal methods and it is described by Poyting's theorem [1, 2, 3]. However, serious difficulty arises in calculation of the loss in real materials [4, 5, 6]. This difficulty causes that many different model of magnetic loss were developed. One of the first model was developed by Steinmetz more than a hundred years ago by introducing experimental equation for hysteresis loss [7]. The dynamic loss component was derived from Maxwell equations [8] and it is called classical eddy current loss component.

The two component model was extended into three component model as a result of discrepancy between measured and calculated values. The three components model consist of hysteresis, eddy current and additional loss component. It is overall accepted that the additional loss component is associated with micro eddy currents generated by domain-wall creation and motion.

At present there are used for loss calculation different models consisting of one, two or three components. Those models posses many different limitations. The aim of the paper is an overview of some used iron loss models and their frequency behaviour in grain- and non-oriented material.

Loss modelling

Difficulty in loss calculation is caused mainly by not constant in time and space magnetic permeability as well as interdependence of hysteresis and eddy current phenomena that proceed during magnetisation cycle. The interdependence phenomena implicate that from physical point of view the loss separation into components is not justified. However, the justification comes from the fact that it helps in design and prediction of loss in electrical machines, actuators, power electronics and so on. Loss separation is also very useful for magnetic materials optimisation for example sheet thickness, grain diameter, controlling of domain structure etc.. An example of such use of loss separation is shown in Fig.1.

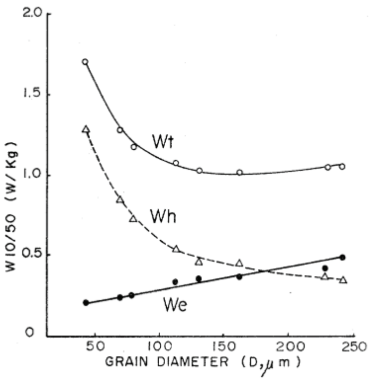

Fig. 1. Dependences of specific total loss components on grain diameter [9]

Many different factors have influence on grain size for example as presented in [9] the influence of sulphur. In Fig.1 is presented influence of grain diameter on loss components. As can be visible together with increase of grain diameter eddy current increase and the hysteresis loss component decrease determining optimum for total loss.

Analysis of electrical machines performance and iron loss prediction during design process is performed taking advantage of different iron loss modes. One of the earliest developed experimental loss model was proposed by Steimentz [10]. His model has empirical character and concerns hysteresis loss. It takes the well known form of equation (1):

$$P_h = C_0\, B_m^{\alpha}\, f \tag{1}$$

where: C_0 is the hysteresis loss coefficient (originally η) and α is the exponent of flux density.

The experimental work of Steinmetz [10] given by equation (1) posses some limitations concerning frequency f and flux density B_m. Additionally the model was developed for electrical steel sheets with maximum relative permeability μ_m lower than 5000. Meanwhile, the magnetic permeability of presently produced electrical steel sheets is higher in whole range of flux density except interval near saturation. The experimental work of Steinmetz pass well in limited range of flux density B_m from 0.2 T to 1.5 T. The magnetisation frequency should also be limited to the range between 30 Hz to 100 Hz (500 Hz).

In original formula (1) nearly for all electrical steel sheets the exponent α was equal to 1.6 [10]. In [7] is presented a wide spectrum of different magnetic materials that follows rule of exponent equal to 1.6. Later on it was possible to publish values of hysteretic constant C_0 as well as exponent of flux density α in tabular form [11, 12]. At that time, unknown parameter α of equation (1) could be easily found from such publications. At present, unknown parameters of equation (1) have to be found by fitting this equations to experimental points. Literature review [13, 14, 15] shows that for non-oriented model the exponent takes values from about 1.6 to 1.8 and for grain-oriented steel the exponent α takes values from range 1.9 to 2.5 and more.

The original Steinmetz equation was modified to form presented by equation (2). There was inserted exponent for frequency and the Steinmetz equation took a form of following equation:

$$P_t = C_m\, B_m^{\alpha}\, f^{\beta} \tag{2}$$

where: C_m is the material coefficient, α is the exponent of flux density and β is exponent of magnetising frequency f.

Although leakage of time, the equation (2) is still in use for loss prediction in electrical machines design process. In [7] it was possible to present for 3%Si electrical steel value of exponent α of flux density to be equal to 1.71 and for exponent β of frequency equal to 1.36 and the material constant C_m was equal to $7.3 \cdot 10^{-3}$ W/kg. At present, some authors propose values of exponents α and β to be range from 2 to 3 for α and from 1 to 3 for β [16]. Some authors even use this model (equation (2)), with some modifications [16], even in a case of PWM power supply what carry to large calculation errors.

Steinmetz the hysteresis loss component P_h described by eq. (1) added to eddy current loss component P_e described by the second part of equation (3), also presented in [10].

$$P_t = C_0\, B^{\alpha} f + C_e\, B^2 f^2 \tag{3}$$

where: C_e is the eddy current loss coefficient

The above equation can approximate frequency behaviour of magnetic loss of non-oriented electrical steel where dependence P_t/f = f(f) forms straight line, as it is shown in Fig. 2 for M530-50A electrical steel. This was also a case of electrical steel sheets produced years ago for which the formula was proposed that is hot rolled steel and without Si addition. It concerns equation (1) (2) and (3).

Due to the well developed domain structure the dependency of energy loss P_t/f = f(f) is very non-linear in grain-oriented electrical steel sheets. The non-linearity is particularly visible in low frequency as shown in Fig. 2 for M140-30S electrical steel. This shows that the use of eq. (2) and (3) is more justified for non-oriented than for grain-oriented electrical steel sheets.

The eddy current loss component was calculated from Maxwell equation [8]. At present this component is named classical eddy current loss and is described with some simplification by equation with general form:

$$P_e = \frac{\pi^2 d^2 B_m^2}{6\rho} f^2 \tag{4}$$

where: ρ is the resistivity and d is the sheet thickness.

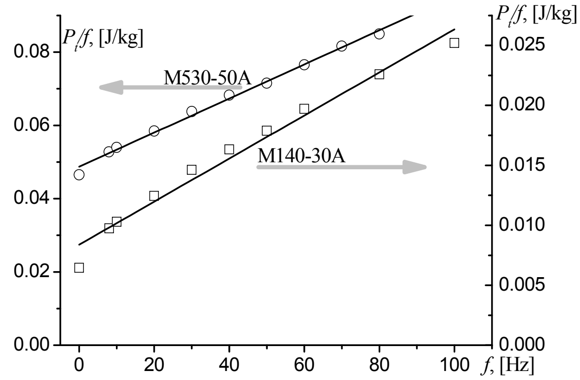

Fig. 2. Dependence of energy loss P_t/f = f(f) for non-oriented M530-50A and grain-oriented M140-30S electrical steel for maximum flux densities equal to 1.5 T

The eq. (4) was derived under important assumption such that the magnetic material is homogenous both under consideration of electrical and magnetic conditions. Usually the magnetic materials are magnetically not homogenous because of magnetic domains as well as they are electrically also not homogenous due to the resistivity [17]. The assumptions carry out to the following: constant in time and space magnetic permeability and uniform magnetisation with sinusoidal waveshape of magnetic flux. Additionally such phenomenon as screening effect of micro eddy currents occur [18] and average sinusoidal waveform of magnetic flux means that the magnetic flux is nonsinusoidal in elementary layer of electrical sheet [5]. Therefore equation (4) is valid for perfectly homogeneous conducting medium, that is, with no structural inhomogeneities and no magnetic domains [7]. These assumptions cause large discrepancy between calculated and measured loss values. The discrepancy was later included as a third component of total loss and it is associated with domain structure and locally generated eddy currents.

Equations (2) and (3) are used to extract coefficients from manufactures data. The data are published as a function of material, quality, and sheet thickness. Such procedure may carry to a different set of coefficients for given steel sheet grade. The frequency and flux density behaviour of loss models described by equations (2) and (3) can be seen after fitting of experimental data to those models. For investigation were chosen two grain-oriented (M130-27S and M140-30S) and two non-oriented (M300-35A and M530-50A) electrical steel sheets. The electrical steel sheet M300-35A consists of nearly 3% of silicon and poses 50% higher loss anisotropy than M530-50A [19]. This high anisotropy of M300-35A strongly influences magnetisation behaviour of this sheet which shows intermediate properties between non- and grain-oriented electrical steel sheets.

Measurements were performed by means of computerised system based on National Instruments DAQ card and on square sample with side length 100 mm. The non-standard single sheet tester consists of two wound C-cores 25 mm thick and magnetizing and B-sensing coils are wound over sample cross sectional area. Air flux compensating coil was also used there. The specific total loss was obtained under controlled sinusoidal magnetic flux waveform and the deviation from sine wave of magnetic flux was kept under 0.1% in whole frequency range.

For fitting was chosen non-linear Levenberg-Marquardt fitting method. This allow to fit all model coefficients at once. Than average value of model coefficients was chosen. Example of calculated exponents α and β of model (2) is presented in Fig. 3.

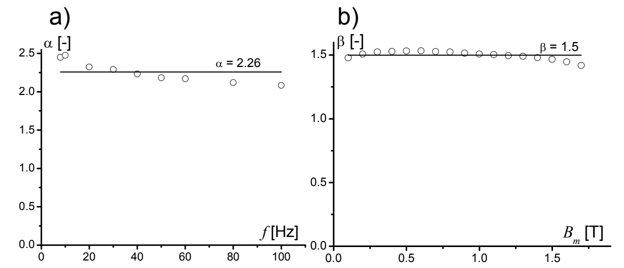

Fig. 3. Dependence of exponent: (a) α for different frequencies and (b) β for different flux densities after fitting to eq. (2) of power loss measured for grain-oriented steel sheet M140-30S

After setting up average value of exponents α and β values of material coefficients C_m for different pairs of B_m and f were calculated. Those are presented in Fig. 4.

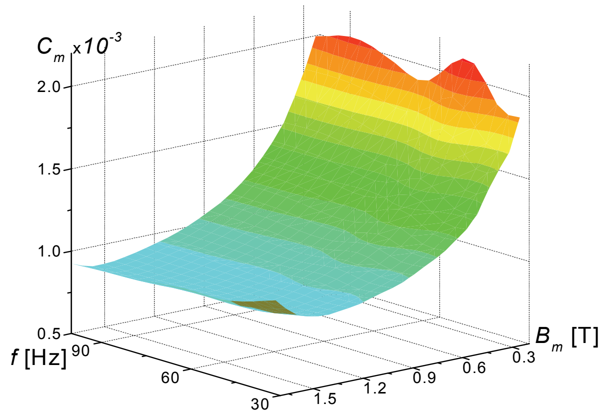

Fig. 4. Variation of material "constant" C_m with frequency f and flux density B_m for grain-oriented electrical steel grade M140-30S

As can be seen in Fig. 4 the parameter C_m of model (2) vary with B_m and f. The coefficient C_m is assumed to be constant with frequency and flux density but the variation with flux density is significantly large. The variation of C_m is much smaller if calculation is limited to Steinmetz experimental equation limitation as mentioned earlier. Data for different electrical steel sheets are presented in Table 1.

The behaviour of constants C_0, C_1 and α of loss model described by equation (3) for the same electrical steel sheets as above is presented in Fig.5.

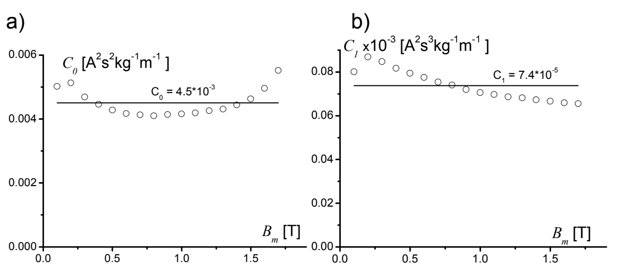

Fig. 5. Variation of "constants" C_0 for α = 2 (a) and C_1 (b) for grain-oriented electrical steel sheet grade M140-30S

From data presented in Fig. 5 average values of C_0 and C_1 were set up. They were used for calculation of total power loss. In Fig. 6 the difference ΔP_t between calculated P_{tc} and measured power loss P_{tm} is plotted versus flux density and frequency. The difference ΔP_t is calculated with equation (5):

$$\Delta P_t = \frac{P_{tc} - P_{tm}}{P_{tm}} 100\% \quad (5)$$

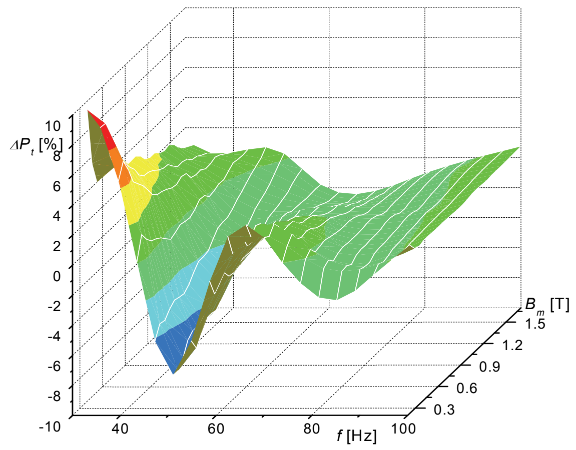

Fig. 6. Percentage difference in total power loss calculation ΔP_t in dependence on frequency f and flux density B_m for grain-oriented steel sheet M140-30S

Presented in Fig. 6 dependence of percentage difference in total power loss calculation ΔP_t shows that the calculated error can reach very high values. Additionally, it should be noted that data in Fig. 6 was calculated for the same magnetisation conditions. Similarly to previous model (eq. (2), Fig. 4) also the variation of percentage difference in total power loss calculated ΔP_t (Fig. 7) can be limited to ±10% if calculation limited to range of validation of Steinmetz equation. The error of loss calculation is smaller for non-oriented electrical steel sheets as can be seen from Table 1.

Table.1. Example of calculation of some loss models coefficients

	$P_t = C_m B_m^{\alpha} f^{\beta}$				$P_t = C_0 B^{\alpha} f + C_e B^2 f^2$				
	C_m×10^{-3}	ΔC_m [%]	α	β	C_0×10^{-3}	ΔC_0 [%]	α	C_0×10^{-3}	ΔC_0 [%]
M130-27S	1.2	72	2.2	1.5	4.4	24	2.0	0.074	27
M140-30S	1.2	106	2.3	1.5	3.9	6	2.0	0.061	17
M300-35A	8.2	106	2.2	1.3	15.2	7	1.9	0.084	18
M530-50A	13.5	24	1.8	1.3	25.3	1	1.7	0.195	7

After setting up constant exponents of flux density and frequency the change of material "constant" for one and two component model can be analysed. As can be seen from Table 1 the range of change of those material coefficients is significantly larger in grain-oriented electrical steel sheets than in non–oriented one. It is worth to note the loss mechanisms are different in grain-oriented and non-oriented electrical steel sheets [20, 21]. This shows that the loss models may be still used for loss calculation occurring in sinusoidal magnetizing conditions in electrical steel sheets with isotropic properties. As anisotropy of magnetic properties increases the analysed loss models. As stated in [16], these models can carry to very high calculation errors in the order of hundreds percent and therefore another models has been developed.

There were different attempts to improve calculation accuracy of loss models by omitting some assumptions under which the classical loss model eq. (4) where delivered. One of the assumption first omitted was the assumption of full penetration of magnetic flux over lamination cross section. This assumption certify the absence of permeability in eq. (4). However with change of magnetisation state and frequency the magnetic flux penetration depth change. The change of loss caused by classical eddy currents with taking into account permeability may be done by factor ξ described by eq. (6):

(6) $$\xi = \frac{3\sinh(kd) - \sin(kd)}{kd\cosh(kd) - \cos(kd)}$$

where: $k = \sqrt{\pi f \mu / \rho}$ and it is the wave dumping factor

The wave dumping factor k depends on frequency f and permeability μ and was delivered under assumption of linear permeability. This means that factor k takes the same value for pair of $\mu = 10^5$ and $f = 10^2$ Hz and for pair of $\mu = 10^4$ and $f = 10^3$ Hz.

Due to the hysteresis phenomenon the permeability is changing over magnetisation cycle and in very non-linear way respectively to the shape of the hysteresis loop. Real representation of hysteresis loop in analytical way is possible in a very limited cases when it takes elliptical shape. The cases are for example: Rayleigh magnetisation region or high frequency or for materials such as ferrites. Analytical approximation of hysteresis loop allows to take into account variable permeability over magnetisation cycle. This was taken into account in model developed by Zakrzewski [22] or more recent by Cardelli [23]. In both models the formula for loss calculation was derived from Maxwell equations where the authors introduced equivalent hysteresis loop angle. This assumes elliptical hysteresis loop and both the magnetic field and suitable flux density should be sinusoidal. In the case of electrical steel sheets the approximation of hysteresis loop by ellipse is adequate at high frequency and in low frequency range this carry to discrepancy between calculated and measured results. Carried out analysis has shown that the discrepancy is larger for grain-oriented sheet than for non-oriented electrical steel. This draw to obvious conclusion that it is necessary to take into account additional loss associated with domain-wall creation and motion.

Statistical loss model

The discrepancy between measured and calculated loss was main reason in development of three components loss model. The three component model consist of hysteresis loss component P_h, classical eddy current loss component P_e and additional loss component P_a. and is described by following equation:

(7) $$P_t = P_h + P_e + P_a$$

The hysteresis loss component P_h in above equation is described by equation (1). The classical eddy current loss component P_e is described by equation (4) and the additional loss component P_a is caused by micro eddy currents generated by moving domain walls. Hence, the additional loss component is mainly devoted to domain structure. Factor which shows the increase of the sum of both eddy current loss components P_e and P_a in comparison to loss calculated from equations based on classical electrodynamics is named relative additional loss factor η. This factor η is believed well describes the domain structure and can be calculated from following equation (6):

(8) $$\eta = \frac{P_t - P_h}{P_e}$$

The relative additional loss factor η calculated for grain-oriented electrical steel sheets can easily reach values of in the order of 5. The increase of loss over calculated values was explained by Pry and Bean model based on domain theory [4]. The Pry and Bean model still remains the basis for many calculations of influence of domain wall movement on additional loss. In this model, the additional eddy current loss per cycle P_e/f depends on the average domain walls spacing $2L$ divided by sheet thickness d. However, with this model it can not to explain very high values of the relative additional loss factor η which can reach values in the order of 10 and more [5, 24]. Because the difficulty in explanation so high values of factor η the loss are sometimes named "anomalous loss".

The three component model was developed for many years. It is difficult to overestimate the contribution of scientific community after 1956 [7, 25, 26, 27] in development of the three components loss model in ferromagnetic materials. One of the contribution carried out to formulate a statistical loss model proposed by G. Bertotti [28] and described by eq. (9).

(9) $$P_t = \underbrace{C_0 B_m^{\alpha} f}_{P_h} + \underbrace{C_1 B_m^2 f^2}_{P_e} + \underbrace{C_2 B_m^{3/2} f^{3/2}}_{P_a}$$

where: C_0 is the hysteresis loss coefficient, $C_1 = \pi^2 d^2 / 6\rho$ is the classical eddy current loss coefficient and C_2 is the additional loss coefficient

The additional loss component P_a originally in statistical loss model takes more complicated form and it is equal to $P_a = 2B_m f(8\sqrt{n_0^2 V_0^2 + 16\sigma G S V_o B_m f} - n_0 V_0)$. Because, in non-orientated electrical steel the value of n_o is in the order of few then n_o can be omitted and the equation for P_a simplifies. The additional loss coefficient C_2, eq. (7) is than equal to $8\sqrt{\sigma G S V_o}$. This simplification is most often used in both cases non-oriented and also grain-oriented materials. It is worth to note that the hysteresis loss component in eq. (7) the exponent of flux density is equal to 2.

The statistical loss model employs dependent on material coefficients and was extended into the time domain [29, 30]. However, it includes components P_h and P_e that were derived under some mentioned earlier assumptions e.g. sinusoidal magnetic flux and constant in time and space magnetic permeability. In consequence the model is applicable in assumed range of flux density and frequency. Although those limitations the statistical loss is very helpful for loss prediction and beyond that ranges the loss prediction accuracy decreases, as shown later. However, to perform accurate loss separation the model requires many measurements in frequency domain what is troublesome. Example of another three component model, that should be simpler in use, was presented in [31] or similar in [32] and called "Best fit" model. Coefficients of this model do not posses physical meaning as in a case of statistical loss model but in assumption, this model should present simplicity in use. The model is formulated by following equation [26]:

(10) $$P_t = k_h B_m^{\alpha} f + k_e B_m^2 f^2 + k_a B_m^{3/2} f^{3/2}$$

where: k_h, k_e and k_a are respectively hysteresis, classical eddy current and additional eddy current loss component coefficients.

Dependence of hysteresis loss component coefficient C_0 of statistical loss model eq. (9) and hysteresis loss coefficient of "Best fit" model k_h on flux density calculated for non-oriented M530-50A and grain-oriented M140-30S electrical steel sheets is presented in Fig. 7.

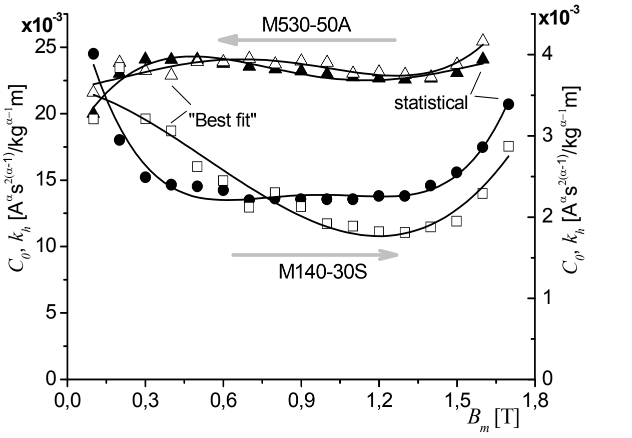

Fig. 7. Dependence of hysteresis loss component coefficient C_0 i k_h on flux density calculated for statistical and 'Best fit" models and for non-oriented M530-50A and grain-oriented M140-30S electrical steel sheets.

It should be mentioned that both hysteresis coefficients C_0 and k_h were calculated taking into account the same value of exponent of flux density α. In Fig. 7 it may be observed that dependency of both coefficients characterise relatively small deviation from average value for non-oriented steel. The deviation is significantly larger in a case of grain-oriented steel. In first case the deviation from average amount to ±17% and in the second the deviation amount to 80%. However, the deviation of Steinmetz hysteresis coefficient in assumed range of flux density is lower than 11%.

The classical eddy current loss component of statistical loss model consist of coefficient C_1 that does not depend on flux density as presented in Fig. 8.

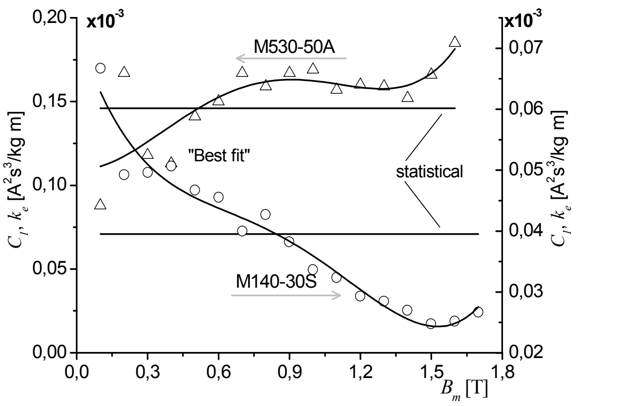

Fig. 8. Dependence of classical eddy current loss component coefficient C_1 i k_e on flux density calculated for statistical and 'Best fit" models and for non-oriented M530-50A and grain-oriented M140-30S electrical steel sheets

In Fig. 8 it can be seen that the variation of eddy current loss coefficient k_e is smaller for non-oriented than for grain-oriented electrical steel sheets. However, the change with flux density in both kind of electrical steel is opposite.

The dependence of additional eddy current loss coefficients C_2 or k_a on flux density characterises similarity in value and curve course between grain- and non-oriented electrical steel sheets. Hence, dependencies of eddy current loss coefficients versus flux density is very seldom presented in literature. Much more useful description of domain structure is included in relative additional loss factor η eq. (7). In following figure is presented dependence of relative additional loss factor η on flux density calculated from statistical loss model.

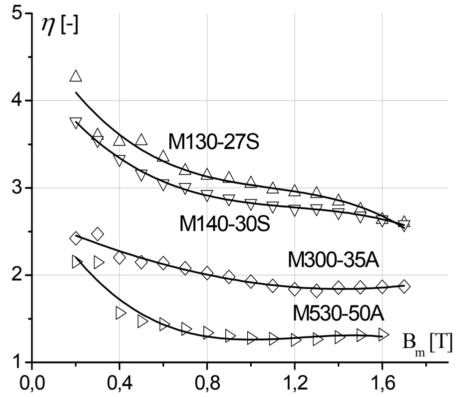

Fig. 9. The dependence of relative additional loss factor η on flux density calculated from statistical loss model

In Fig. 9 can be observed obvious dependence between additional loss factor η and grain-orientation. The factor η takes significantly lower values for non-oriented than for grain-oriented electrical steel sheets. Together with increase of grain-orientation factor η increases in both in value and in range of changes over flux density range. This also certify that the loss mechanisms are different in the case of grain- and non-oriented electrical steel. Additionally the mechanisms are changing with magnetisation state. This is also confirmed by the dependence of percentage contribution of P_a and P_h loss component to total loss in dependence on texture degree. The texture degree κ was determined by the anisometric method [17, 33] and is defined as a ratio of the volume of (110) [001] oriented crystals to the total volume of the sample.

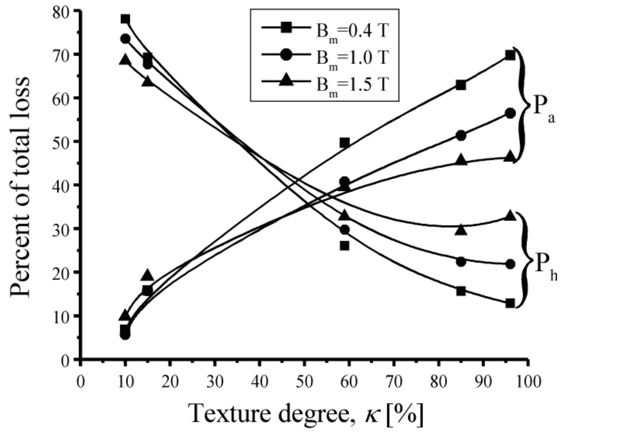

Fig. 10. Percentage contribution of P_a and P_h loss components to total loss in dependence on texture degree [21]

Fig. 10 shows the percentage of hysteresis and additional loss present in the total loss of sheets with different texture degrees. It can be seen that in non-oriented sheets (low texture) hysteresis loss is dominant but it significance decreases with increase of flux density. It is opposite to grain-oriented electrical steel where hysteresis loss component is less significant but its significance increases with increasing flux density. As may be seen in Fig. 10 the contribution of additional loss component to total loss do not change significantly with flux density in non-oriented electrical steel sheets. In grain-oriented sheets the additional loss play most significant role but its significance decreases as flux density increases. This may also be visible in Fig. 9 as the relative additional loss factor decreases with increase in flux density. The loss components contribute in different way to total loss in dependence on magnetisation state as well as in dependence on grain-orientation.

Summary

The paper presents the behaviour of classical and statistical loss models parameters. The models were investigated in flux density range 0.1 T - 1.7 T and frequencies between 5 Hz and 100 Hz. The frequency range was chosen because it allows to keep flux wave form factor distortion below 0.1% from ideal sinusoidal shape. The investigation was preformed for grain- and non-oriented electrical steel sheets with different thicknesses and different degree of texture.

Loss separation play an important role in magnetic material optimization and loss prediction of electrical machines. Together with development of magnetic materials and in power supply of electrical machines there is a need to develop also loss model. Together with development of electrical steel sheets the discrepancy between measured and calculated values increased. There was introduced third component called additional loss.

It is shown that classical loss models still may be used in loss prediction in case of non-oriented steel sheets presenting small texture and under sinusoidal work condition. As degree of grain-orientation increases or while in case of distorted power supply - the model becomes not applicable. There was also found that the statistical loss model can be used physical properties for analysing of electrical steel sheet, as it is kept in assumed ranges of flux density, and frequency

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***Authors**: dr inż. Wojciech A. Pluta, Czestochowa University of Technology, Department of Electrical Engineering, Al. Armii Krajowej 17, 42-200 Czestochowa, Poland, E-mail: plutaw@el.pcz.czest.pl.*