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Estimation of power losses in dynamo steel sheets during axial magnetization

***Abstract**. Estimation of power losses in dynamo steel sheets during the axial magnetization is still a significant problem. The paper deals with calculations of hysteresis losses and their dependence on the direction of the axial magnetization. Attention was also paid to the power losses caused by "classical" eddy currents, and excess losses which are a result of eddy currents occurring around moving domain walls. Measured power losses of five typical dynamo sheets were compared with results obtained on the basis of analytical formulas.*

Streszczenie.** Określanie strat mocy w blachach prądnicowych jest nadal znaczącym problemem. W artykule omówiono wyznaczanie strat histerezowych i ich zależność od kierunku przemagnesowania osiowego. Zwrócono również uwagę na straty powodowane przez „klasyczne" prądy wirowe oraz straty nadmiarowe, które są skutkiem występowania prądów wirowych wokół przesuwających się ścian domenowych. Zmierzone straty dla pięciu typowych blach prądnicowych porównano z wynikami otrzymanymi na podstawie wzorów analitycznych. (**Wyznaczanie strat mocy w blachach prądnicowych podczas przemagnesowania osiowego)

Keywords: dynamo steel sheets, hysteresis losses, eddy current losses, excess losses
Słowa kluczowe: blachy prądnicowe, straty histerezowe, straty wiroprądowe, straty nadmiarowe.

Introduction

Magnetization processes in typical dynamo steel sheets can have twofold character. In some parts of stator cores of induction and synchronous machines the rotational magnetization occurs usually; this process has mainly elliptical character. On the other hand, in stator teeth the axial magnetization occurs very often.

In spite of many studies, estimation of power losses during the axial magnetization in dynamo sheets is not completely solved. Firstly, calculated hysteresis losses can significantly differ with respect to the measured hysteresis losses, even more than twenty percent. Secondly, even greater differences can occur in relation to eddy current losses due to the occurrence of the so-called domain eddy currents [1, 2]. Differences between measured losses and estimated losses can also occur when a winding current is distorted with respect to the sinusoidal shape; this problem is considered among others in [3, 4]. It is worth underlining that most of typical dynamo sheets have a certain anisotropy in terms of both the magnetic properties and power losses. It means that the amount of the power losses depends on the direction of the magnetic field changes on the sheet plane with respect to the rolling direction. It should be noted that dynamo steel sheets are quite often used in constructions of cores of small power transformer, so worse magnetic properties in directions other than the rolling direction cause to decrease the value of the resultant magnetic flux in a transformer core.

Estimation of rotational power losses is qualitatively difficult problem, and they are usually calculated with the use of the basic formula [5, 6, 7]:

$$P_r = \frac{1}{T}\int_0^T (H_x \frac{dB_x}{dt} + H_y \frac{dB_y}{dt})\, dt \tag{1}$$

where: B_x, B_y – components of the flux density in a certain elementary segment of the given steel sheet, H_x, H_y – components of the magnetic strength.

This formula can be used for any conditions of the magnetization process. However, application of this relation requires to calculate earlier the magnetic field distribution in the examined dynamo sheet for assumed conditions of the magnetization process. It is worth underlining that in recent years some researchers have attempted to formulate analytical relationships for estimation of the rotational power losses [8, 9].

Analysis of power losses during the axial magnetization was carried out for following five different dynamo steel sheets: M530-50A (produced in the Czech Republic), M530-50A (South Korea), M400-50A, M800-50A (both produced in Sweden), and M600-50A (Romania); the thickness of all sheets is equal to 0,5 mm. It is worth stressing that dynamo steel sheets of the same type but produced by different manufacturers may have different real values of the specific power loss. Some manufacturers have intentionally declared higher values of the specific power loss in order to avoid any possible complaints.

Hysteresis power losses

Total power losses are treated as a sum of hysteresis losses, eddy current losses, and excess losses which are caused by the domain eddy currents in electrical steel sheets [7, 10]:

$$P_{tot} = P_h + P_{ed} + P_{exc} \tag{2}$$

where: P_h – hysteresis losses, P_{ed} – eddy current losses, P_{exc} – excess losses.

Reasons of power losses during the axial and rotational magnetization processes are similar, but their estimation varies considerably due to a different mechanism of each of these processes. In practice, losses occurring in steel sheets are determined per mass unit and they are called as the specific power loss. Unlike losses in the rotational magnetization, power losses occurring during the axial magnetization can be estimated with the use of some analytical formulas. The Steinmetz formula, determining the hysteresis losses, is well-known [11, 12, 13]:

$$P_h = \eta\, f\, B_m^p \tag{3}$$

η – coefficient depending on the given material, f – frequency of magnetic field changes, B_m – maximum value of the flux density during the magnetization process, p – exponent, which most often is equal to 1.6 (Steimetz's formula) or 2.0 (Richter's formula).

The value of the coefficient η depends on the type of the given electrical steel sheet, so it is not recommended to use the same coefficient for any dynamo steel sheet. On the other hand, magnetic measurements should be carried out in order to determine the value of this coefficient for the given dynamo sheet. Determination of the value of the exponent *p* in the formula (3) is a separate problem. The value of this exponent is taken between 1.6 and to 2.0.

Analytical formulas can help to estimate the hysteresis power losses. However, in order to reduce the differences between the measured values and estimated losses the value of the coefficient η and the exponent *p* in relation (3) should be determined simultaneously. For this purpose the hysteresis power losses were determined by means of the Epstein's frame and as the area of the static hysteresis loop of the given dynamo sheet. The hysteresis losses are usually determined for two typical value of the flux density 1.0 T and 1.5 T. The measured hysteresis loops of the two examined dynamo sheets (M530-50A produced in South Korea, M600-50A) are shown in Figure 1 and Figure 2. The hysteresis loops of the sheet M800-50A are similar to the loops presented in Figure 1. In turn, hysteresis loops of the dynamo sheet M400-50A were presented in [14], and loops of the dynamo sheet M530-50A produced in the Czech Republic were included in [15]. The coercive forces, remanences, and characteristic values of the field strengths of all considered dynamo sheets are given in Table 1.

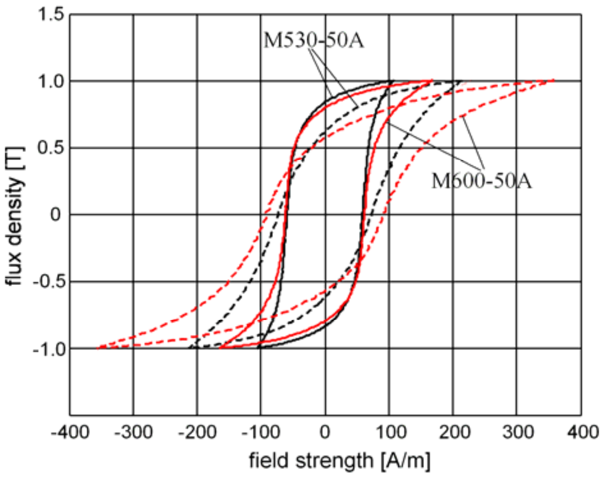

Fig. 1. Hysteresis loops for the flux density 1.0 T of the dynamo sheets M530-50A (South Korea) – black lines and M600-50A – red lines; continuous lines – for the rolling direction (0°), dashed lines – for the transverse direction (90°)

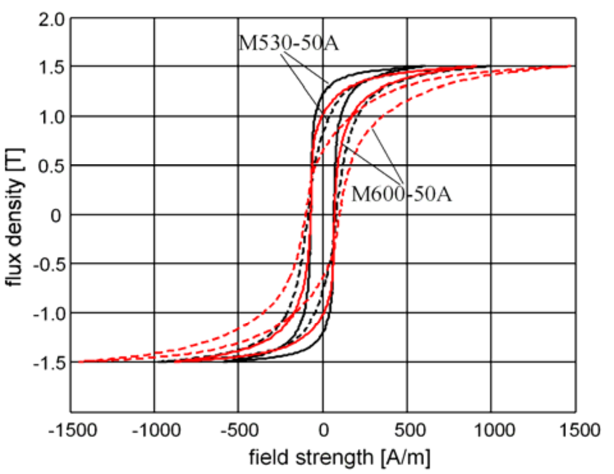

Fig. 2. Hysteresis loops for the flux density 1.5 T of the dynamo sheets M530-50A and M600-50A; line markings as in Figure 1

The hysteresis loops of the both dynamo sheets measured for the flux densities 1.0 T and 1.5 T and for direction 45° (with respect to the rolling direction) are close to the loops for the rolling direction (0°). The presented hysteresis loops have shown that these dynamo sheets have certain anisotropic properties which are caused by occurrence of some textures in dynamo sheets [16, 17]. Due to this fact, the hysteresis power losses depend also on the magnetization direction; this also makes it difficult to estimate the hysteresis losses. For all examined dynamo sheets the coefficient η was determined for the flux density 1.0 T (Table 1). These coefficients have similar values for sheets, whose the specific power loss is relatively low (e.g. M400-50A, M530-50A); the same conclusion concerns sheets which have higher values of the specific power loss (e.g. M600-50A, M800-50A). When we assume that the coefficient η has values as in Table 1, then it turns out that the exponent *p* in the formula (3) can have the constant value 1.6 when the flux density is lesser than 1.1 T. For higher values of the flux density the exponent *p* in the formula (3) has to be increased. In order to simplify the estimation of the hysteresis losses we propose to determine the exponent *p* according to the following relationship:

(4) $$p(B_m) = 0.05B_m^2 + 0.5B_m + 1$$

This formula is similar to the proposal which has been presented by Chen and Pillay in [18], but in that case they have inserted this form only for one chosen steel sheet to take into account the dynamical hysteresis loop instead the static loop. In our approach the relationship (4) allows us to estimate the hysteresis losses for five above mentioned dynamo sheets, however this proposal should be checked for a larger number of typical dynamo steel sheets.

Characteristics of the measured hysteresis losses along the rolling direction in comparison with the characteristic of the estimated power losses with the use of the proposed approximation are shown in Figure 3 and Figure 4 for two chosen dynamo sheets.

Dependence of the hysteresis losses on the magnetization direction

The hysteresis losses depend not only on the flux density value, but the direction of the axial magnetization influences the amount of these losses; this issue was discussed among others in [19, 20, 21]. As it was earlier mentioned, this is caused by occurrence of certain textures in dynamo sheets. The hysteresis losses measured for angles greater than 15° with respect to the rolling direction can be higher even twenty per cent in comparison to the hysteresis losses which occur during the magnetization along the rolling direction. Measurements of the hysteresis losses for some directions of the axial magnetization are quite troublesome because it is necessary to cut strips of the examined dynamo sheet along different directions.

On the basis of the measured hysteresis losses we can formulate a relationship which allows us to estimate the hysteresis losses for any direction of the axial magnetization:

(5) $$P_h(\alpha) = P_h(0°)\left[1 + \left(\frac{P_h(90°)}{P_h(0°)} - 1\right)\left(1 - e^{-\frac{\alpha}{\tau}}\right)\right]$$

where: $P_h(90°)$, $P_h(0°)$ – hysteresis losses for the transverse direction (90°) and for the rolling direction (0°) respectively when the flux density is equal to 1.0 T, α – angle between the magnetization direction and the rolling direction, and τ – an "attenuation" coefficient.

In order to use the formula (5) we have to know the hysteresis losses for both the rolling and transverse directions. However, comparing the hysteresis losses along the transverse direction (90°) we can take their average value for this direction. Then the coefficient τ in the formula (5) is equal to $\pi/3$. The comparison of the measured hysteresis losses and the estimated losses with the use of the proposed formula is presented in Table 1 for two magnetization directions 45° and 90°. The estimated specific hysteresis losses for the rolling direction (0°) are the same as the measured values. Figure 3 and Figure 4 show, for example, the characteristics of the estimated and measured specific hysteresis losses as the dependence on the flux density for two chosen dynamo sheets. The maximum error of the estimated losses with respect to the measured hysteresis losses is lesser than 8 per cent. So, in order to calculate the hysteresis specific power loss for any value of the flux density and for any direction during axial magnetization we should know the value of the η coefficient and the angle between the magnetization direction and the rolling direction. Quite significant differences occur for flux densities higher than 1.6 T but then the magnetization characteristics are significantly nonlinear and the given dynamo sheet is quite close to the saturation state.

Power losses caused by eddy currents

Measured power losses caused by the eddy currents were determined as differences between the total losses and the hysteresis losses for the assumed frequency 50 Hz

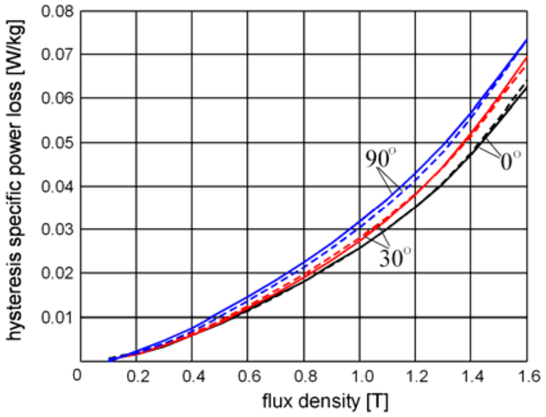

Fig. 3. Hysteresis specific power loss of the dynamo sheet M530-50A for three directions on the sheet plane; continuous line – measured values, dashed line – approximated values

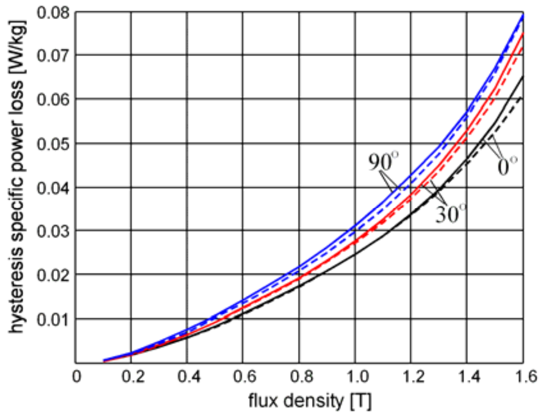

Fig. 4. Hysteresis specific power loss of the dynamo sheet M800-50A for three directions on the sheet plane; continuous line – measured values, dashed line – approximated values

and 100 Hz and for the rolling and transverse direction; values of these losses are presented in Table 2. Measurements carried out for all examined dynamo sheets have shown that the eddy current losses do not depend on the direction of the axial magnetization when the frequency is lesser than about 50 Hz. For higher frequencies these losses increase with the angle between the direction of the magnetization process and the rolling direction when the maximum value of the flux density is lesser than 1.0 T. For higher flux densities the dependence of the eddy current losses on the magnetization direction has inverse character. Values of the eddy current losses for the flux density 1.0 T and 1.5 T and for three direction of the axial magnetization are presented in Table 2. Differences between losses measured in the rolling direction (0°) and losses measured in the transverse direction (90°) are not higher than about 15 per cent for 1.0 T and about 11 per cent for 1.5 T.

Eddy current losses are usually estimated by means of the formula [11, 12, 13]:

(6) $$P_{ed} = \frac{\sigma \pi^2 d^2 f^2 B_m^2}{6}$$

where: σ, d – conductivity and thickness of the given dynamo sheet, respectively.

This formula was created with the assumption that the magnetic permeability has a constant value. However, magnetization characteristics of dynamo sheets have a curvature when values of the flux densities are about 1.0 T. So the magnetic permeability does not have a constant value in the whole range of the flux density changes. It is worth underlining that the magnetic field is not homogeneous inside dynamo sheets with the thickness of 0.5 mm or more when the frequency is equal to 50 Hz or higher. The amount of the calculated losses with the use of the formula (6) depends also on the determination accuracy of the parameters occurring in this formula; this remark especially concerns the value of the conductivity of the given dynamo sheet. Information in scientific papers about these conductivities is quite scant. Even when the conductivity is given in a paper, then it only refers to the one chosen electrical sheet. Comparison between the losses calculated on the basis of the formula (6) and the eddy current losses which were measured for three magnetization directions are, for example, shown in Figure 5 and Figure 6.

The conductivity of all examined dynamo sheets was determined with the use of the Thomson bridge and by means of the technical methods . Results of measurements, performed at 25 Centigrade, are included in Table 2. Differences between conductivities are lesser than 3 per cent with respect to the conductivities determined with the use of the Thomson bridge. Estimation of the eddy current losses with the use of the formula (6) do not take into account the direction of the axial magnetization with respect to the rolling direction.

It is well known that measured losses caused by the eddy currents are greater than the eddy current losses calculated using the formula (6). In dynamo steel sheets the excess losses caused by domain eddy currents are lesser than analogous losses in transformer sheets, however, they cannot be neglected with respect to the “classical” eddy current losses. The excess losses are determined as differences between the total eddy current losses and losses calculated by means of the formula (6).

Table 1. Magnetic parameters and specific hysteresis loss P_h in W/kg per one cycle

Type of dynamo sheet		**M400-50A** Sweden		**M530-50A** Czech Republic		**M530-50A** South Korea		**M600-50A** Romania		**M800-50A** Sweden	
Flux density [T]		1.0	1.5	1.0	1.5	1.0	1.5	1.0	1.5	1.0	1.5
Coercive force [A/m]	0°	31	36	53	63	59	68	62	70	61	74
	45°	35	40	65	74	66	76	74	85	73	86
	90°	37	41	66	75	73	84	91	102	77	88
Remanence [T]	0°	0.77	0.99	0.88	1.29	0.84	1.21	0.80	1.02	0.87	1.31
	45°	0.70	0.88	0.77	1.01	0.76	1.05	0.67	0.82	0.75	1.09
	90°	0.64	0.78	0.71	0.90	0.62	0.79	0.57	0.64	0.64	0.90
Field strength [A/m]	0°	95	1092	95	715	107	603	167	896	108	635
	45°	117	1588	173	1364	155	1194	229	1158	166	1039
	90°	138	1687	203	1301	214	989	358	1464	207	1051
η	---	0.0148		0.0247		0.0260		0.0286		0.0280	
P_h, 0°	measured	0.015	0.030	0.025	0.055	0.026	0.055	0.029	0.061	0.028	0.061
P_h, 45°	measured	0.017	0.040	0.030	0.067	0.029	0.063	0.033	0.067	0.038	0.069
	estimated	0.016	0.040	0.028	0.062	0.029	0.061	0.034	0.073	0.037	0.068
P_h, 90°	measured	0.018	0.041	0.031	0.067	0.032	0.065	0.039	0.074	0.034	0.070
	estimated	0.017	0.042	0.030	0.066	0.031	0.064	0.037	0.079	0.032	0.071

Values of the excess losses are included in Table 2. A cause of these losses is occurrence of the so-called domain eddy currents which appear around moving domain walls. The model of iron grains with taking into account domain wall proposed by Pry and Bean allows us to estimate power losses only in transformer sheets [2], but the vast majority of grains in typical dynamo sheets is arranged randomly [14]. G. Bertotti have been proposed a certain statistical approach to estimate the eddy current losses [1, 10]. He assumed that the movement of domain walls during the magnetization process consists of random jumps in iron crystals of dynamo sheet. He treated fragments of these walls as certain magnetic objects. Bertotti has proposed to estimate the excess losses in non-oriented steel sheets using the formula which can be written in the following form:

$$P_{exc} = 8\sqrt{\sigma\, G\, S\, V_0}\left(B_m f\right)^{\frac{3}{2}} \tag{7}$$

where: G – constant value equaled to 0.1356, S – area of the sheet cross-section, V_0 – material parameter which depends on the flux density value [1, 22, 23].
determine the grain size of the examined dynamo sheet.

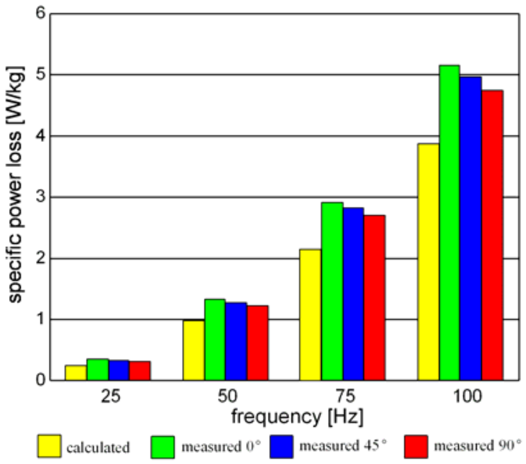

Fig. 5. Specific power losses of the dynamo sheet M530-50A for four frequencies of the magnetization

The parameter V_0 depends strongly on the average grain size of typical dynamo sheets. Values of this parameter were determined on the basis of the Bertotti's approach for two values of the flux density 1.0 T and 1.5 T (Table 2). It was assumed that average grain size was equal to 100 μm [1]. Values of the excess losses determined with the use of the Bertotti's approach are included in Table 2. The estimated excess losses are generally higher than the excess losses determined as the differences between the total eddy current losses and the losses calculated using the formula (6). In most cases, differences between the excess losses amount even several tens of percent. This may be due to the fact that the grain size of the dynamo sheets are in the range of 30 to 300μm [1], and the vast majority of the grains in these sheets is distributed randomly contrary to the transformer sheets with the Goss texture. It seems that in order to estimate the excess losses on the basis of the Bertotti's approach, crystallographic studies should be earlier carried out to

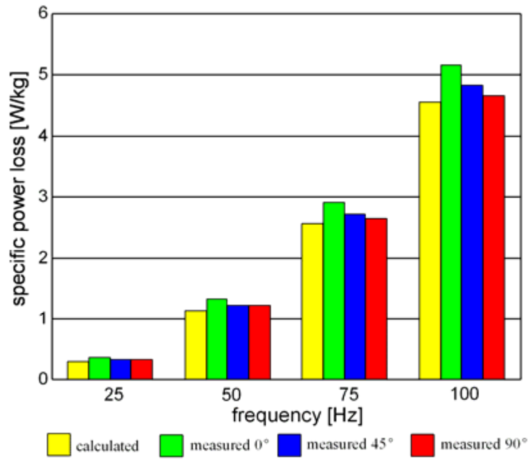

Fig. 6. Specific power losses of the dynamo sheet M800-50A for four frequencies of the magnetization

Conclusions

In the paper the modification of the Steinmetz's formula is proposed. The essence of this modification is the dependence of the exponent value on the flux density along the rolling direction in the given dynamo sheet. However, in order to obtain correct results of the hysteresis loss estimation the value of the coefficient η in the formula (3) have to be determined on the basis of the hysteresis losses for the flux density 1.0 T.

Estimation of the hysteresis losses for other direction than the rolling direction can be carried out using the proposed approximating function. For this purpose it should be known the angle between the given and rolling direction and the value of the hysteresis losses for the rolling direction; the second ones can be estimated using the formula (3).

Table 2. Conductivities and eddy current losses in W/kg

Type of dynamo sheet		M400-50A Sweden		M530-50A Czech Republic		M530-50A South Korea		M600-50A Romania		M800-50A Sweden	
Conductivity [1/Ω*m]*10^6	Thomson bridge	2.36		2.90		3.16		3.57		3.75	
	T. method DC	2.33		2.85		3.18		3.58		3.75	
	T. method AC	2.30		2.84		3.12		3.53		3.66	
Flux density [T]		1.0	1.5	1.0	1.5	1.0	1.5	1.0	1.5	1.0	1.5
P_{tot}, 50 Hz, 0°	measured	1.264	3.022	1.815	4.041	1.885	4.049	2.182	4.614	2.014	4.379
P_{tot}, 50 Hz, 90°	measured	1.479	3.415	2.157	4.632	2.129	4.465	2.671	5.237	2.213	4.703
P_{ed}, 50 Hz	estimated (6)	0.315	0.708	0.386	0.869	0.425	0.958	0.481	1.082	0.502	1.131
P_{exc}, 50 Hz	estimated (7)	0.274	0.503	0.307	0.562	0.324	0.594	0.352	0.645	0.348	0.638
V_0 [A/m]	calculated	0.035	0.041	0.060	0.071	0.067	0.077	0.070	0.079	0.069	0.084
P_{ed}, 50 Hz, 0°	measured	0.514	1.522	0.565	1.291	0.585	1.299	0.732	1.564	0.614	1.329
	excees	0.199	0.814	0.179	0.422	0.160	0.341	0.251	0.482	0.112	0.198
P_{ed}, 50 Hz, 90°	measured	0.579	1.365	0.607	1.282	0.529	1.215	0.721	1.537	0.513	1.203
	excees	0.264	0.657	0.221	0.413	0.104	0.257	0.240	0.455	0.011	0.072
P_{tot}, 100 Hz, 0°	measured	3.427	8.099	4.630	10.579	4.769	10.602	5.748	12.136	5.003	11.270
P_{tot},100 Hz,90°	measured	3.918	8.878	5.450	11.635	5.269	11.221	6.684	13.385	5.425	11.650
P_{ed}, 100 Hz	estimated (6)	1.261	2.838	1.547	3.483	1.704	3.837	1.926	4.336	2.013	4.531
P_{exc}, 100 Hz	estimated (7)	0.773	1.421	0.864	1.589	0.913	1.679	0.992	1.824	0.981	1.804
P_{ed}, 100 Hz, 0°	measured	1.927	5.099	2.130	5.079	2.169	5.102	2.848	6.036	2.203	5.170
	excees	0.666	2.261	0.583	1.596	0.465	1.265	0.922	1.700	0.190	0.639
P_{ed},100 Hz,90°	measured	2.118	4.778	2.350	4.935	2.069	4.721	2.784	5.985	2.025	4.650
	excees	0.857	1.940	0.803	1.452	0.365	0.884	0.858	1.649	0.012	0.119

P_{tot} – total power losses

The maximum error between measured and estimated hysteresis losses are lesser than eight per cent.

Formulation of a method which would allow us to estimate the excess losses requires further research. It seems that in this case the emphasis should be placed on the determination of the correction coefficients which would be dependent on the dynamo sheet type. However, the formulation of more general conclusions requires studies of a larger number of typical dynamo steel sheets, especially with respect to the estimation of the excess losses.

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