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A refined method for the calculation of steel losses at alternating current

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Abstract: The ways of the improvement of the method for the determination of steel losses in the electrical devices of basic types are substantiated. The method is refined by taking into account the magnetic system properties at high saturation. The presence of the interrelation between the special features of the domain structure movement and the shape of the hysteresis loop is proved for laminated cores. It enabled the explanation of the causes for the abnormally high values of the losses in the steel and the atypical shapes of the hysteresis loops at its high saturation. The empiric dependence for the determination of steel losses is obtained. It provides for the high convergence of the calculated and experimental data at the actual degree of saturation and can be used in the direct-current operation of the analyzed devices.

Key words: domain structure, hysteresis loop, saturation degree, steel losses

1. Introduction

The saturation of the magnetic system of electrical devices (EDs) can exceed the calculated one due to the alterations introduced during the design process and also because of the variation of the properties of the basic structural materials such as the winding copper and the magnetic core steel. The possible causes for the magnetic system high saturation level may include the abnormal operation conditions or the long-term operation of the ED [1, 2]. In the former case, as e.g. in emergency supply induction generators (IG) [1], the high saturation of steel is the basis for the device operating principle. During long-term operation the additional saturation is explained by the specific features of the deterioration of the core laminated steel properties [3]. It is known from [4] that three-phase induction and synchronous electric machines (EMs) and voltage transformers (TRs) steel high saturation is characterized by the abnormal growth of steel losses. In particular, some research proved that steel losses in the magnetic cores, getting reverse magnetization in rotating magnetic fields, make up a significant share of the total power losses in EMs. So, for induction motors the steel losses in the high-voltage mode may reach 50% of the total losses [5–7], for transformers – more than 20% [8, 9], for capacitor-excitation induction generators – about 20–60% [10].

The physics of this phenomenon has not been studied, and the actual values of steel losses essentially differ from the ones conventionally obtained from their dependence on the squared frequency f and the active value of supply voltage U_1:

$$P_{Fe} = kfU_1^2 + mf^2U_1^2, \tag{1}$$

where: k, m are the coefficients typical of the analyzed device.

There are several points of view as to this case in the literature. So, e.g. the authors of papers [11, 12] relate the occurrence of hysteresis losses to the alternating rate of the shift of the domain boundaries, which gives rise to eddy currents.

At the same time, it is a well-known fact that the considerable growth of losses at the increase of the degree of saturation results from the domain structure (DS) dynamics behavior. Papers [13, 14] contain the detailed research of this phenomenon. This research proves that the irregularity of DS behavior determine the processes of the reverse magnetization of electric steel (ES) at the high degree of saturation. Such DS behavior makes it possible to explain the causes of the distortion of the hysteresis loop and the abnormal growth of steel losses occurring at high saturation.

The ambiguity of steel losses determination causes the necessity for the refinement of the determination methods.

2. The analysis of the previous research and the problem statement

To determine the steel losses in an ED both experimental and analytical calculation methods are used. They are mainly based on the representation of the total steel losses by the sum:

$$P_{Fe} = P_{Fe0} + P_{exc}, \tag{2}$$

where: P_{Fe0} is the fundamental steel losses; P_{exc} is the additional steel losses.

2.1. The calculation of the fundamental steel losses

There are a lot of theoretical and experimental methods [15–19] to determine the fundamental losses. Most often they come to separate expression of their basic components – hysteresis losses P_h and eddy currents P_{ec}:

$$P_{Fe0} = P_h + P_{ec}. \tag{3}$$

Concerning the solution to the posed problem, the general drawback of these methods consists in the absence of the possibility to take into account the alterations in ES at the high degree of saturation. It causes a sharp deterioration of their accuracy and adequacy of the obtained results.

For the high degree of saturation paper [20] proposes a modified expression for the calculation of steel specific losses p_{Fe}. Nowadays it is most often used in practice:

$$p_{Fe} = c f^{\alpha} B^{\beta}, \tag{4}$$

where: f is the frequency of steel reverse magnetization; B is the maximal value of induction; c, α and β are the respectively a design coefficients and constants characterizing the steel properties.

However, the calculation of steel losses using (4) also results in obtaining approximate values. It is related to the fact that coefficients α and β are constants independently of the degree of steel saturation.

A number of researchers [11, 12] additionally modify (4) to take into consideration the steel losses at the high degree of saturation. In this case, hysteresis losses P_h and eddy-current losses P_{ec} are represented in the form of dependences:

$$P_h = K_h(f, B) f B^2, \tag{5}$$

$$P_{ec} = K_e(f, B) f^2 B^2, \tag{6}$$

where: $K_h(f, B)$, $K_e(f, B)$ are the respectively the coefficients of hysteresis losses and eddy-current losses whose values vary depending on the frequency and magnetic flux induction.

These coefficients K_h, K_e are represented by polynomial dependences on induction B:

$$K_h(B) = K_{h3}B^3 + K_{h2}B^2 + K_{h1}B + K_{h0}, \tag{7}$$

$$K_e(B) = K_{e3}B^3 + K_{e2}B^2 + K_{e1}B + K_{e0}. \tag{8}$$

Paper [21] contains a hypothesis that the variation of steel losses is caused inter alia by the domain structure (DS) of the materials and directly by the behavior of the domains at the variation of magnetic induction. To consider this phenomenon it is proposed to introduce the frequency f_{eq} of magnetization reversal during the period T of magnetic induction change:

$$f_{eq} = \frac{2}{\pi^2 \Delta B^2} \int_0^T \left(\frac{\mathrm{d}B(t)}{\mathrm{d}t} \right)^2 \mathrm{d}t. \tag{9}$$

As a result, the expression for the determination of specific steel losses:

$$p_{Fe} = C_{SE} f_{eq}^{\alpha-1} B^{\beta} f_r^{\alpha}, \tag{10}$$

where f_{eq} is the equivalent frequency of magnetization reversal; f_r is the reference frequency of magnetization reversal; α and β are constants characterizing the steel properties; C_{SE} is the correction coefficient.

The analyzed approach makes it possible to additionally take into account the complex phenomena related to DS motion.

2.2. The determination of additional steel losses

The second summand of relation (2) – additional losses P_{exc}, as a rule, takes into account:

a) steel losses caused by the change of the structure of its sheets at mechanical treatment;
b) the losses in the structural parts and frames;
c) the losses in the points of sheet joints caused by the irregular distribution of magnetic induction and the increase of eddy-current losses.

As a rule, such losses cannot be directly calculated. Usually additional losses are assumed to be equal to 10–15% of the fundamental losses [16]:

$$P_{exc} = P_{Fe0}(0.1 - 0.15). \tag{11}$$

If it is necessary to have a more accurate account, one can use the below given proposals. So, according to [6], the power of the measured total magnetic losses is higher than the sum of the hysteresis losses and the eddy current losses. This difference in the losses for the modern electric steels makes more than 50% of total magnetic losses. To eliminate this contradiction the additional losses P_{exc} were introduced; they are called "abnormal losses".

In this case, the expression of magnetic losses, as the function of the frequency and the maximal value of the magnetic flux, can be represented by the dependence of the form:

$$P_{Fe} = P_h + P_{ec} + P_{exc} = C_{hyst} f B^2 + C_{ec} f^2 B^2 + C_{exc} f^{1.5} B^{1.5}, \tag{12}$$

where: C_{hyst}, C_{ec}, C_{exc} are the coefficients of the corresponding losses.

Coefficients C_{ec} and C_{exc} are determined as:

$$C_{ec} = \left(\pi^2 \sigma d^2\right)/6, \qquad C_{exc} = \sqrt{\sigma G V_0 S}, \tag{13}$$

where: d is the thickness of ES sheet (plate); G is the dimensionless constant; σ is the conductivity; S is the cross section of the sheet (plate); V_0 is the coefficient characterising the difference in the coercive force between two magnetic objects.

3. The purpose of the paper and the tasks of the research

The improvement of the method for the determination of the steel losses in alternating current electric generating plants (EGPs) by taking into account the properties of their magnetic system at the high degree of saturation.

To achieve the posed purpose it is necessary to additionally analyze the factors influencing the abnormal growth of steel losses in an EM and TR in the high-saturation mode.

4. The materials and results of the research

4.1. The special features of the determination of the steel losses in the zone of high saturation

If we take into account the special features of the posed task and the variation of the parameters and characteristics of the electric steel at the high degree of saturation, it is reasonable to calculate the steel losses and their components not by the integral but by the instantaneous values of currents, voltages and EMF. In this case, the expressions for the instantaneous power are to adequately describe real physical processes relating instantaneous magnetizing current $i_\mu(t)$ to inductance $L_\mu(t)$ and EMF $e(t)$ of the magnetizing circuit. The general dependences describing EMF $e(t)$ and instantaneous power $p(t)$ at the inductance are of the form [22]:

$$\begin{aligned} e(t) &= \mathrm{d}\left(L_\mu(t) i_\mu(t)\right)/\mathrm{d}t, \\ p(t) &= e(t) i_\mu(t). \end{aligned} \tag{14}$$

What is usually known is not the inductance dependence on time but flux linkage $\psi(i_\mu)$ and EMF $e(i_\mu)$ dependences on magnetizing current; they enable the determination of $L(i_\mu)$, then of $L_\mu(t)$ with the use of expression:

$$L_\mu(i_\mu) = \mathrm{d}\psi(i_\mu)/\mathrm{d}i_\mu, \tag{15}$$

at polynomial approximation [23]

$$\psi(i_\mu) = a_1 i_\mu + a_3 i_\mu^3 + a_5 i_\mu^5 + \ldots + a_{2n+1} i_\mu^{2n+1}.$$

The approximation of dependence $\psi(i_\mu)$ by this type of polynomial makes it possible to describe its variation at all typical sections with high accuracy.

After carrying out the transformations, dependence $L_\mu(i_\mu)$ will be of the form:

$$L_\mu(i_\mu) = a_1 + 3a_3 i_\mu^2 + 5a_5 i_\mu^4 + \ldots + (2n+1) a_{2n+1} i_\mu^{2n}. \tag{16}$$

The formation of the hysteresis loop results from the lag of the magnetizing process in relation to the magnetomotive force, which also causes the occurrence of losses at the dynamic reverse magnetizing. The presence of the lag results in the alteration of the form of the dependences $L_\mu(i_\mu)$ and $\psi(i_\mu)$. It can be taken into account by the introduction of the shift angle for each of the harmonics of the magnetizing current included into periodic dependence $i_\mu(t)$ [24, 25]:

$$i'_\mu(t) = \sum_{\nu=1}^{\infty} I_{\mu\nu} \cos\left(\nu\Omega t + \varphi_\nu - \gamma_\nu\right), \tag{17}$$

where: $I_{\mu\nu}$ is the active value of the magnetizing current of the ν^{th} harmonic; φ_ν is the phase shift of the ν^{th} harmonic; γ_ν is the angle of the shift of the flux linkage and the magnetizing current for the ν^{th} harmonic; Ω is the angular frequency.

The refined expression for the inductance in the function of time can be obtained by the substitution of the corrected dependence (17) into (16):

$$L'_\mu(t) = a_1 + 3a_3\left(i'_\mu(t)\right)^2 + 5a_5\left(i'_\mu(t)\right)^4 + \ldots + (2n+1) a_{2n+1}\left(i'_\mu(t)\right)^{2n}. \tag{18}$$

The EMF of the magnetizing circuit, taking into account the magnetic lag angle, can be written down as follows:

$$e(t) = \left(\frac{\mathrm{d}}{\mathrm{d}t}\left(L'_\mu(t) i_\mu(t)\right)\right) = \frac{\mathrm{d}L'_\mu(t)}{\mathrm{d}t} i_\mu(t) + \frac{\mathrm{d}i_\mu(t)}{\mathrm{d}t} L'_\mu(t), \tag{19}$$

The instantaneous power of steel losses is determined by dependence:

$$
\begin{aligned}
p_{Fe}(t) = e(t)i_\mu(t) &= \left(\frac{\mathrm{d}L'_\mu(t)}{\mathrm{d}t} i_\mu(t) + \frac{\mathrm{d}i_\mu(t)}{\mathrm{d}t} L'_\mu(t)\right) i_\mu(t) = \\
&= \frac{\mathrm{d}L'_\mu(t)}{\mathrm{d}t} i^2_\mu(t) + \frac{\mathrm{d}i_\mu(t)}{\mathrm{d}t} i_\mu(t) L'_\mu(t).
\end{aligned}
\tag{20}
$$

The losses at the inductance variation in (20) are equivalent to the hysteresis steel losses and the losses proportional to the rate of current variation are proportional to the losses in the elementary short-circuited contours. After the transformation and integration of (20), taking into consideration the fact that the integral of the harmonic function is equal to zero, we will obtain the steel losses expression including the hysteresis losses and eddy-current losses:

$$
P_{Fe} = \sum_{l=\nu=0}^{\infty} \frac{1}{2} I^2_{\mu\nu} a_l l \Omega \sin 2\gamma_l + \sum_{l=\nu=0}^{\infty} \frac{1}{4} I^2_{\mu\nu} a_l \nu \Omega \sin 2\gamma_l = \sum_{l=\nu=0}^{\infty} \frac{3}{4} I^2_{\mu\nu} a_l \nu \Omega \sin 2\gamma_l\,. \tag{21}
$$

It follows from the obtained dependences that all the values contained in them depend on the degree of steel saturation, i.e. on the distance to the right from the point of the magnetizing curve sharp bent where the operating points are situated at the periodic magnetization reversal.

The presented solution does not provide the final answer to the problem of hysteresis losses generation.

Paper [26] contains the substantiation of the dependence for the determination of the steel losses taking into account the nonlinear DS dynamics and the irregularity of their motion at the different cycles of reverse magnetization and providing a high convergence of the calculated and experimental data:

$$
P_{Fe}(I_\mu) = \frac{\xi}{\mathrm{d}E(I_\mu)/\mathrm{d}I_\mu} \left(E(I_\mu)\right)^2, \tag{22}
$$

where: I_μ is the active value of the magnetization current; ξ is the coefficient depending on ES characteristics; $E(I_\mu)$ is the EMF dependence on the magnetizing current.

Thus, at the non-saturated section of the ES magnetizing curve the rate of EMF growth $\mathrm{d}E(I_\mu)/\mathrm{d}I_\mu \to$ const and expression (22) takes the form analogous to expression (4). In the mode of ES high saturation the rate of EMF growth decreases $\mathrm{d}E(I_\mu)/\mathrm{d}I_\mu \to 0$ and expression (22) makes it possible to take into account the steel losses growth caused by the processes of the DS irregular behavior during ES magnetization reversal. This dependence is simpler and more accurate from the point of view of practical application as the measuring and calculation procedure of obtaining the EMF dependence $E(I_\mu)$ is much simpler than the procedure of obtaining the magnetic induction $B(t)$ dependence on time.

4.2. The researched ED and experimental equipment

During the research of the magnetic properties and losses in ES we used a ring-type magnetic core of the external diameter of 120 mm and the internal diameter of 100 mm. It consisted of 7 sheets of 0.5 mm 2212 isotropic ES used in the electric machine magnetic systems. Two windings were applied to it: a primary magnetizing winding and a secondary measuring one with the number of turns W_1 and W_2, respectively. The windings were applied regularly along the magnetic core with a constant pitch provided they are perpendicular to the ring tangent at each point. The measuring winding was applied above the magnetizing one.

The magnetic core parameters used in the calculations are given in Table 1.

Table 1. The parameters of the magnetic core made of 2212 grade ES

Parameter	**Symbol**	**Value**	**Unit**
Number of the turns of the magnetizing coil	W_1	455	
Number of the turns of the measuring coil	W_2	320	
Cross sectional area of the magnetic core	S	35×10^{-6}	m^2
Average length of the magnetic line of force	l	345.6×10^{-3}	m
Material density	ρ	7680	kg/m^3

The magnetizing winding was supplied from the alternating current network ($U = 200$ V, $f = 50$ Hz) via autotransformer T1 (Fig. 1). The primary measuring devices were represented by industrial certified modules of voltage sensors VS1, VS2 and a current sensor CS of the accuracy class 0.1 and the characteristics nonlinearity at the level of 0.08%.

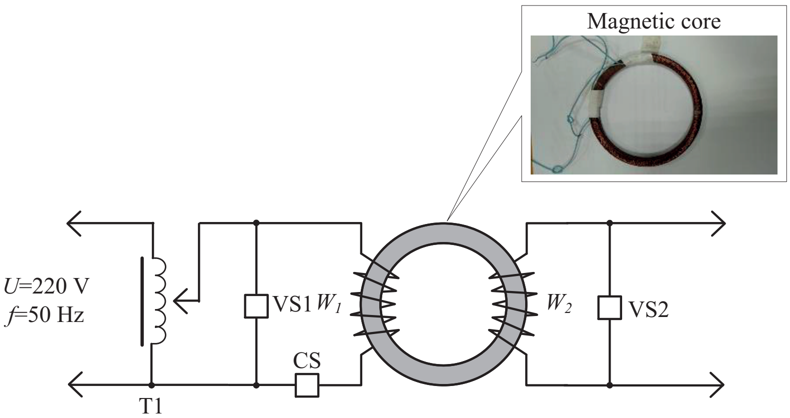

Fig. 1. functional diagram of the experimental measuring stand

The structure of the measuring complex (MC) corresponded to the scheme in Fig. 2 [27]. Here RS is the researched sample of the magnetic core. The parameters characterizing the test mode – current $i_1(t)$ and voltage $u_2(t)$ from RS come to the current sensor (CS) and the voltage sensor (VS2). Input signal $u_1(t)$ from the power supply comes to voltage sensor VS2.

The signals from the sensors came to an industrial computer via the input-output module. The computer gathered, stored and processes the information. In this MC we used as an IOM the certified measuring module E14-440D (L-Card) with applied software from the developer.

In the process of the problem solution, we substantiated the necessity for taking into account the special features of the reverse magnetization in alternating magnetic fields that differ in the

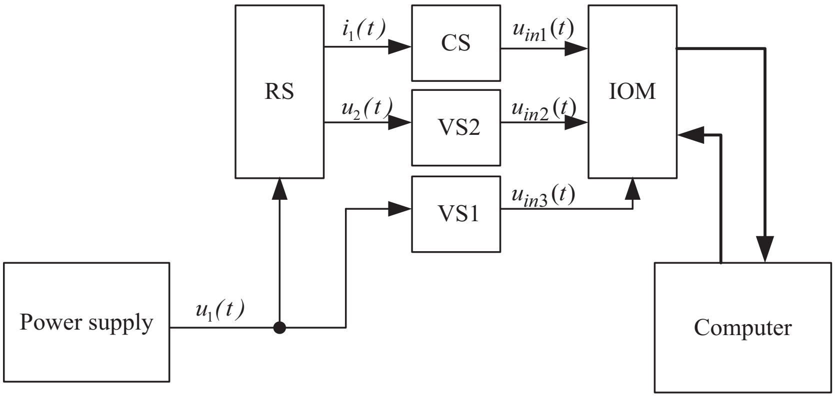

Fig. 2. The block diagram of the measuring complex for testing ES laminated cores

spectral composition of magnetic induction $B(t)$ and magnetic field strength $H(t)$ curves on the linear section of the magnetizing curve up to the point of saturation. We also formulated the conditions of their processing. The measuring complex is a metrologically attested means for the measurement of these parameters.

IM steel losses were determined by the results of the no-load test on the basis of the modified method taking into account the magnetic circuit saturation [3, 28].

4.3. The results of the research of the laminated magnetic core magnetic properties

The experimental research of the magnetic properties of the laminated magnetic core was performed by measuring the instantaneous values of voltage $u(t)$ and current $i(t)$ of the magnetizing winding during 3–5 periods of the frequency of the supply voltage.

Figs. 3 and 4 contain the results of the numerical calculation of flux linkage $\psi(t)$ dependence on magnetizing current $i_\mu(t)$ for the values of the magnetizing winding resistive impedance $R_0 = 5.1$ Ohm and leakage inductance $L_0 = 0.273$ H. In this case, the inductance dependence $L(i_\mu)$ on the magnetizing current was of the form:

$$L(i_\mu) = a_0 + a_1 i_\mu^2(t) + a_2 i_\mu^4(t) + a_3 i_\mu^6(t) + a_4 i_\mu^8(t) + a_5 i_\mu^{10}(t), \tag{23}$$

where the approximation coefficients:

$$a_0 = 0.273,$$
$$a_1 = -5.63 \cdot 10^{-4},$$
$$a_2 = 6.9 \cdot 10^{-5},$$
$$a_3 = -4.03 \cdot 10^{-7},$$
$$a_4 = -1.07 \cdot 10^{-9},$$
$$a_5 = -1.1 \cdot 10^{-12}.$$

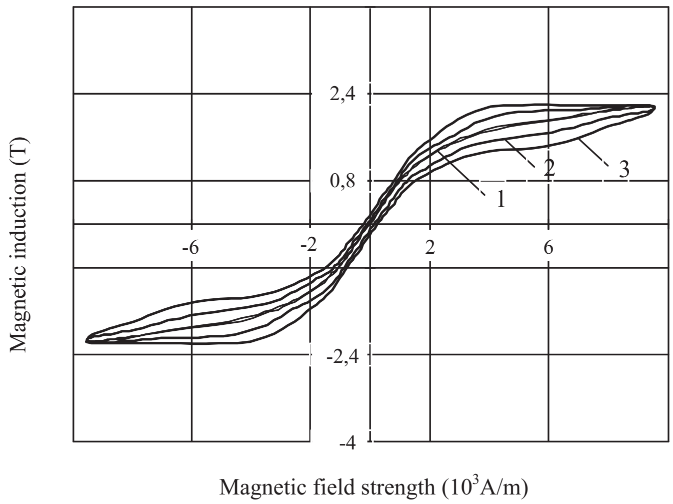

Fig. 3. The calculated hysteresis loops at the different values of the angle of the magnetic flux shift from the magnetizing current (for the first harmonic) and supply voltage U = const = 300 V: 1 – γ_m = 0.005 rad; 2 – γ_m = 0.05 rad; 3 – γ_m = 0.1 rad

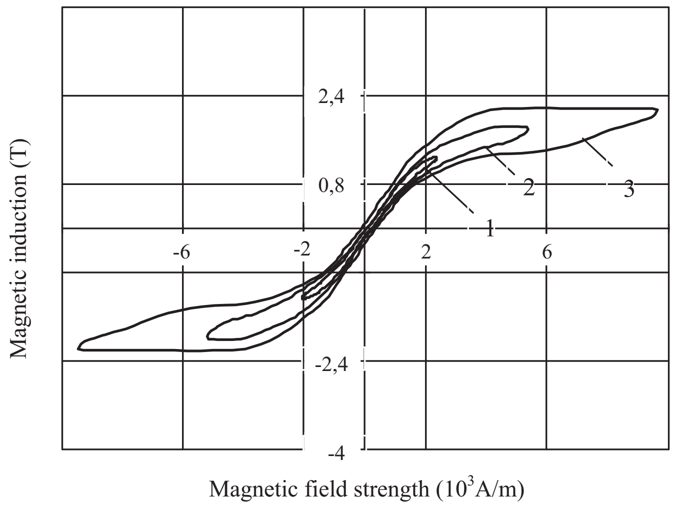

Fig. 4. The calculated hysteresis loops at the different values of the supply voltage and the angle of the magnetic flux shift from the magnetizing current (for the first harmonic) γ_m = const = 0.1 rad, 1 – U = 100 V, 2 – U = 200 V, 3 – U = 300 V

Such mathematical form of writing the magnetization inductance dependence on current allows its description by a continuous function and, consequently, the elimination of the discontinuous sections in such dependence, which takes place in the description by differential equations.

The numerical methods enabled us to determine that the lowest order of the power series equal to ten is sufficient for the admissible accuracy (the error – not exceeding 3%) of the approximation of the magnetizing curve in the range of the high values of magnetizing current. The magnetizing curve can also be described by polynomials of lower power. In this case the number of the approximation coefficients decreases but the accuracy of the description of dependence $L(i_\mu)$ also decreases. E.g. at the approximation of the magnetizing curve by the polynomial of the eighth order the maximal error grows up to 9%.

It is seen in Figs. 3, 4 that when the shift angle changes and magnetic inductance amplitude increases, the shape of the hysteresis loop changes – its widening can be observed.

Fig. 5 contains a family of hysteresis dynamic loops obtained by experiment at the magnetization reversal of the researched sample ES for the different values of the supply voltage. The form of these loops is atypical, which is explained by the growth of the rate of DS boundaries shift when the magnetic induction value increases along with its essential decrease when the field direction changes. Their width increases with the growth of the magnetic induction amplitude due to the inertia phenomena during DS motion. It confirms the existing relation between the DS motion and the shape of the hysteresis loops.

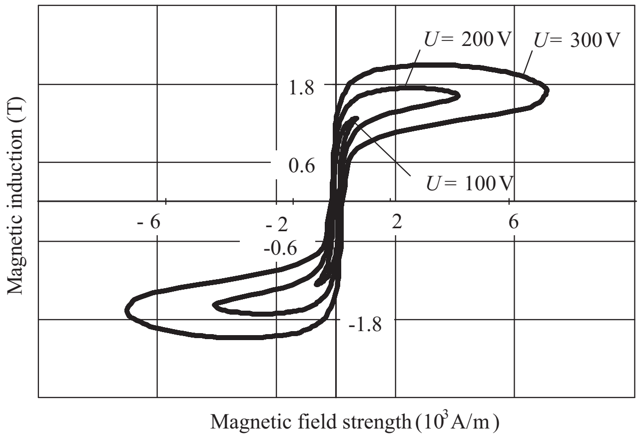

Fig. 5. Experimental hysteresis loops at the different values of the supply voltage

In this case the sharp growth of steel losses at the increase of the degree of saturation is caused by the processes of the generation and disappearance of the domains (the growth of the magnetization reversal first stages) as well as by the DS shift rates irregularity, increasing with the growth of magnetic induction, for the direct and reverse magnetic fields. It also certifies the difference of the boundaries energy at the magnetization reversal in the direction of the ascending and the descending branches of the hysteresis loop.

4.4. The experimental verification of the results

The results of the comparison of the steel losses dependence calculated according to (22) and the one obtained experimentally for the researched magnetic core sample made of 2212 ES are shown in Fig. 6. As the initial data for obtaining the steel losses curve, we used EMF dependence on magnetizing current $E\left(I_\mu\right)$ obtained experimentally according to [28] and used in expression (22).

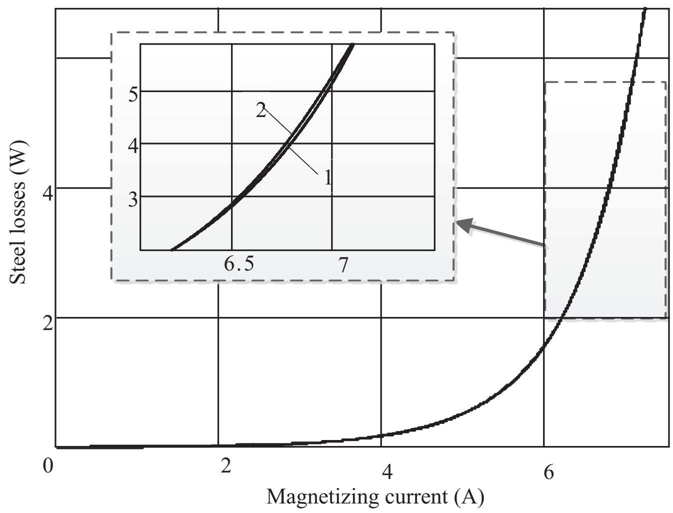

Fig. 6. The comparison of the experimental 1 and calculated 2 curves of steel losses P_{Fe} from the magnetizing current I_μ of the researched magnetic core sample

The numerical assessment of the adequacy was performed on the basis of such criteria as dispersion σ^2 and correlation coefficient R. In the process of the experiment it was determined that the obtained values of 2212 ES steel losses do not practically differ from the calculated ones (the adequacy dispersion $\sigma^2 = 0.028$, the correlation coefficient $R = 0.999$).

As ES is widely used in the manufacture of the magnetic circuits of EMs whose cores are subject to rotational reverse magnetization during the operation, the research was also performed for the magnetic cores of the stators of IMs of different powers (Fig. 7). Dependence $E(I_\mu t)$ for

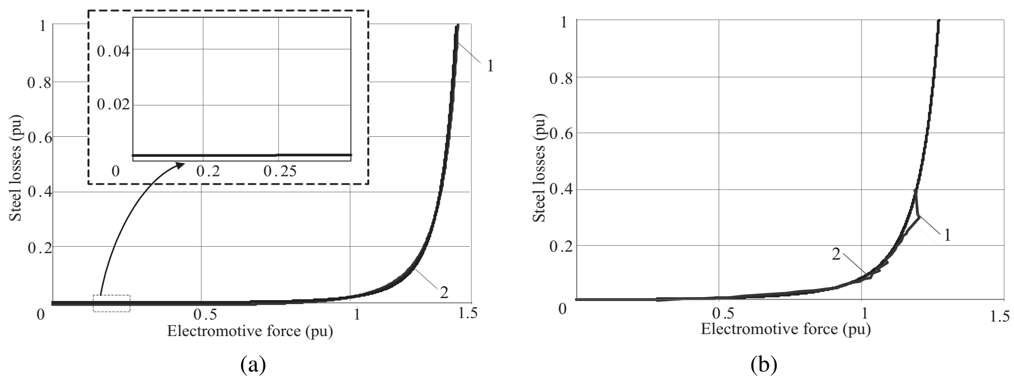

Fig. 7. The comparison of the experimental 1 and calculated 2 curves of steel losses P_{Fe} from EMF for IM: (a) P_n = 3 kW; (b) P_n = 1.4 kW

IM was obtained from the no-load test by the variation of the stator voltage within (0.6÷1.4) of the rated value [29]. It was proved that the developed method for the determination of the steel losses allows the description of their behaviour in IM highly saturated condition with high accuracy (σ^2 = 0.023, R = 0.996).

5. Conclusions

1. The relation between the steel losses and atypical alteration of the hysteresis loop shape in the mode of high saturation was determined in the course of the research.
2. It is demonstrated that the steel losses at magnetization reversal largely depend on the domain structure motion dynamics, which is especially manifested at high saturation. Considering this dynamics in calculation models makes it possible to research the particular causes for the abnormally high values of the steel losses and the special features of their variation in the alternating fields in the function of magnetic induction amplitude.
3. The method for the determination of steel losses in electrical devices has been developed and the empiric dependence describing their behavior both at the non-saturated section of the magnetizing curve and in the mode of electrical steel high saturation has been obtained.
4. The high convergence of the calculated and experimental data confirms that the developed method for the determination of steel losses makes it possible to describe their variation in the mode of high saturation with high accuracy and can be used for the calculation of the characteristics of the magnetic and electric circuits of the electrical devices of basic types.

References

[1] Zagirnyak M., Zachepa Yu., Chenchevoi V., *Estimation of Induction Generator Overload Capacity under Connected Direct Current Consumers*, Acta Technica, vol. 59, no. 2, pp. 149–169 (2014).

[2] Zobaa A., Bansal R., *Handbook of Renewable Energy Technology*, World Scientific Publishing Co Pte. Ltd., Sigapore (2011).

[3] Prus V., Zagirnyak M., Kolotylo I., Miljavec D., *Estimate and taking into account change of steel losses in induction motors in process of their aging*, Proceedings of International IEEE Conference EUROCON 2009, IEEE Catalog Number CFP09EUR-CDR, ISBN 978-1-4244-3861-7, Library of Congress Number 2009900519, Saint Petersburg, Russia, pp. 790–795 (2009).

[4] Sioshansi R., Short W., *Evaluating the Impacts of Real–Time Pricing on the Usage of Wind Generation*, IEEE Trans. Power Syst., vol. 24, no. 2, pp. 516–524 (2009).

[5] Cheng Y., Pillay P., *An improved formula for lamination core loss calculations in machines operating with high frequency and high flux density excitation*, Conf. Rec. IEEE-IAS Annu. Meeting, iss. 2, pp. 759–766 (2002).

[6] Krings A., Nategh S., Stening A., Grop H., Wallmark O., Soulard J., *Measurement and modeling of iron losses in electrical machines*, 5th International Conference Magnetism and Metallurgy (WMM), Gent, Belgium, pp. 101–119 (2012).

[7] Maged I., *Modeling of Core Losses in Electrical Machine Laminations Exposed to High Frequency and Non-sinusoidal Flux*, Master's thesis, Concordia University (2011).

[8] Alatawneh Natheer, *Design of a Test Fixture for Rotational Core Losses in Electrical Machine Laminations*, PhD thesis, Concordia University (2012).

[9] Chiesa N., *Power transformer modeling for inrush current calculation*, doctoral theses at Norwegian University of Science and Technology (2010).

[10] Lazarov V., Zarkov Z., Stoyanov L., *Experimental study of losses in doubly-fed induction generator*, Ecological Engineering and Environment Protection, no. 3, pp. 34–40 (2012).

[11] Dupre L., Bottauscio O., Chiampi M., Repetto M., Melkebeek J., *Modeling of electromagnetic phenomena in soft magnetic materials under unidirectional time periodic flux excitations*, IEEE Transactions on Magnetics, vol. 35, iss. 5, pp. 4171–4184 (1999).

[12] Herranz Gracia M., Langeand E., Hameyer K., *Numerical Calculation of Iron Losses in Electrical Machines with a modified Post-Processing Formula*, Proceedings of 16th COMPUMAG, Aachen (2007).

[13] Tiunov V., Filippov B., *Dynamic Realignment of Domain Structure and the Associated Magnetic Losses in Conducting*, Soft-magnetic, Single-crystal Plates in Rotating Magnetic Fields, Low temperature physics, iss. 36, pp. 756–760 (2010).

[14] Tiunov V., Korzunin G., *A Device for Measuring Magnetic Losses of Ferromagnets in Rotating Magnetic Fields*, Russian Journal of Nondestructive Testing, iss. 51, pp. 509–512 (2015).

[15] Bertotti G., *General properties of power losses in soft ferromagnetic materials*, IEEE Transactions on Magnetics, vol. 24, iss. 1, pp. 621–630 (1988).

[16] Kostenko M., Piotrovskii L., *Electric machines*, p. 1, 2nd edition, L.: Energiia (1964); p. 2, 2nd edition, L.: Energiia (1965).

[17] Steinmetz R., *Einige Bemerkungen uber Hysteresis*, ETZ (1891).

[18] Lifschitz M., *Electric machines*, v. II, Design and insulation: Trans. from Germ. M.: ONTI (1934).

[19] Lammeraner I., Shtafl M., *Eddy-currents*, Trans. from Czech. M.-L.: Energiia (1967).

[20] Steinmetz C., *On the Law of Hysteresis*, Proceedings of the IEEE, vol. 72, no. 2, pp. 197–221 (1984).

[21] Hilzinger R., Rodewald W., *Magnetic Materials: Fundamentals, Products, Properties, Applications*, Erlangen: Publicis, ISBN: 978-3-895-78352-4 (2013).

[22] Zagirnyak M., Prus V., Miljavec D., *Improved method for calculation of parameters of electromagnetic and power processes in electric circuits with steel in saturation mode*, Technical Electrodynamics, no. 4, pp. 12–18 (2015).

[23] Zagirnyak M., Prus V., Nikitina A., *Grounds for efficiency and prospect of the use of instantaneous power components in electric systems diagnostics*, Przegląd Elektrotechniczny, no. 12, pp. 123–125 (2006).

[24] Zagirnyak M., Rodkin D., Romashykhin Iu., Chenchevoi V., Rudenko M., *Identification of nonlinearities of induction motor equivalent circuits with the use of the instantaneous power method*, Proceedings of 2016 17th International Conference Computational Problems of Electrical Engineering (CPEE), Sandomierz, Poland, pp. 1–4 (2016).

[25] Zagirnyak M., Rod'kin D., Romashykhin Iu., Romashykhina Zh., Nikolenko A., Kuznetsov V., *Refined calculation of induction motor equivalent circuit nonlinear parameters by an energy method*, Eastern-European Journal of Enterprise Technologies, vol. 3, no. 5(87), pp. 4–10 (2017).

[26] Rodkin D., Ogar V., Chenchevoy V., *Nature Abnormal Growth of Losses in Electrical Steel in Deep Saturation mode*, Electromechanical and energy systems, modeling and optimization methods: conference proceedings of the 12th International conference of students and young researches Kremenchug, Ukraine, pp. 76–93 (2014).

[27] Zagirnyak M.V., Prus V.V., Lyashenko V.P., Miljavec D., *Structuring soft-magnetic composite materials*, Informacije MIDEM, Ljubljana, vol. 2, no. 41, pp. 86–91 (2011).

[28] Zagirnyak M., Romashykhina Zh., Kalinov A., *Diagnostic signs of induction motor broken rotor bars in electromotive force signal*, Proceedings of 2016 17th International Conference Computational Problems of Electrical Engineering, CPEE (2016).

[29] Zagirnyak M., Kalinov A., Ogar V., Lotous V., *Experimental Assessment of the Accuracy of the Method for Determination the Power on an Induction Motor Shaft*, published at 18th International Conference on Computational Problems of Electrical Engineering (CPEE), pp. 1–4 (2017).