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RESEARCH OF HIGH-FREQUENCY REMAGNETIZATION MODEL IN LAMINATED MAGNETIC CORES OF ELECTROMECHANICAL AND ELECTROMAGNETIC ENERGY CONVERTERS

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The object of research in the work is charged magnetic conductors of electric machines and transformers.

Laminated magnetic wire together with windings are important active parts of electric machines that participate in electromechanical energy conversion.

The reliability of the entire machine is mainly determined by the actual condition of the inter-sheet insulation. Violation of the insulation causes parasitic eddy current circuits, which increases the specific losses, and also significantly affects the additional heating of the magnet wire and winding.

The normative method for determining the quality of the charged core is the assessment of specific losses at a frequency of 50 Hz and an induction of 1 T, which should not exceed 2.5–4 W/kg. To determine local damage to the core, methods of local heating and fixation of overheating sites are used, which should not exceed 45 °C compared to the main part of the magnetic core.

In the work, a two-dimensional field mathematical model of a charged magnetic circuit is developed. This makes it possible to carry out electromagnetic calculations in a near-real magnetic conductor, taking into account the variability of magnetic permeability, hysteresis, and the interaction of currents in adjacent plates of the magnetic conductor with each other, the so-called "proximity effect".

On the basis of the developed models, graphs of current distribution and distribution of magnetic induction in one, two and three sheets were obtained. The resulting graphs show how the effect of current displacement increases with increasing frequency, where at a frequency of 100 kHz the magnetic induction density in the middle of the sheet goes to zero. The results of the research confirm the correctness of the model development in comparison with the classical calculation models also given, which allows them to be used for further research of high-frequency processes in charged magnetic circuits of electric machines

Keywords: charged magnetic wire, high-frequency remagnetization processes, eddy currents, surface effect

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1. Introduction

The laminated magnet wire of electric machines (EM) is one of the most important active parts of any type of electromechanical energy converter. On the one hand, the specific energy indicators depend on the quality and efficiency of its work, and on the other hand, the reliability of the operation of electric machines.

The processes in the layered magnetic circuit at the industrial frequency of electric machines and devices have been studied almost in full. There are many studies aimed at calculating hysteresis losses and eddy currents. Accounting for the influence of higher harmonics on heart losses and work has not been fully studied [1, 2]. Classic works on this topic are presented in [1, 2]. Many works are aimed at researching charged magnetic conductors and evaluating their quality. As a rule, these are varieties of the method of determining the quality of the charged magnetic core by measuring the specific losses on remagnetization.

High-frequency and impulse processes in a layered core are physically significantly different from remagnetization processes at an industrial frequency. The analysis of these phenomena in the classical setting by solving integral equations was carried out using analytical methods [1]. Significant assumptions and simplifications were introduced to obtain an adequate analytical mathematical model. The appearance of modern system packages of field calculation programs based on numerical methods makes it possible to refine the mathematical model and bring it closer to real physical processes. The basis for creating appropriate models is the finite element method for solving Maxwell's equations.

The development of a field model for calculating high-frequency processes in charged cores that takes into account changes in magnetic permeability, magnetic delay and the influence of currents in adjacent plates on each other is an urgent task. The study of high-frequency processes in a layered magnetic core over a significant range of frequencies can be used for practical purposes in order to assess the condition of the magnetic conductor, first of all, the quality of the inter-sheet insulation.

2. Literature review and problem statement

Losses in the magnetic core make up a significant part of the total losses in electric machines. This must be taken into account when designing electric machines in accordance with real research projects. In [3], the characteristic operating points of the magnetization curve under different operating conditions at different power supply frequencies are distinguished. A harmonic analysis of the flux density in the air gap, phase current, losses in the core was carried out and a detailed comparative analysis was performed. A new method of comprehensive analysis of losses in the magnetic core of the stator for vehicles is proposed, which reveals the law of losses at maximum torque and pulse width modulation of the spatial vector. The method was tested using a prototype experiment in which actual losses in the core were measured. The proposed method shows a good result at operating frequencies of 15–400 Hz, but it loses its adequacy when the operating frequency is increased.

In work [4], an experimental study of losses in the magnetic core was carried out under real operating conditions of a synchronous machine with permanent magnets. The machine is high-frequency (>1 kHz) due to which it has high specific power indicators (4 kW/kg) and is used for aerospace systems. Measurements were made on different charged stator cores using steel grades NO20 and M270-35A for the silicon-iron alloy and Vacodur49 (0.2 mm) for the cobalt-iron alloy. Losses in the core were measured without load and in a wide range of frequencies up to 1400 Hz. The results of the measurements are compared with those obtained using the finite element model in ANSYS Maxwell. This made it possible to determine the iron loss addition coefficient (K_{add}), which takes into account additional magnetic losses in the ferromagnetic material. There is no analysis of physical processes occurring in the ferromagnetic core at high frequencies in the work.

The dependence of ferromagnetic hysteresis on frequency and associated losses in the core is studied in [5]. Below a set frequency, known as the quasi-static threshold, the hysteresis loop remains unchanged. An accurate estimate of this threshold is fundamental to modeling and accurately estimating the magnetization behavior at higher frequencies. But this assessment is challenging, especially due to the unique observation of hysteresis loops and due to instrument limitations. By using an alternative magnetic loop known as a magnetic incremental permeability hysteresis loop, improvements in the observation of magnetization behavior and the estimation of the quasi-static threshold are proposed. This work is a step forward in understanding the low-frequency magnetic behavior of laminated sheets. To evaluate the behavior of the hysteresis loop under the action of high-frequency currents, it is necessary to conduct additional studies.

In [6], the size of interlayer contacts formed by burrs is estimated using a new method of thermographic measurement and an analytical method. The initial temperature rise of the contacts is used in the analytical model to estimate the contact size. Formulations of electromagnetic and thermal finite elements confirm the results obtained using the analytical method. In addition, the results obtained as a result of the measurement, the analytical method, and the finite element method are compared. The study shows that the initial temperature rise method can be used to estimate the interlayer contact size and electromagnetic losses if the temperature is measured immediately after voltage is applied to the sheets. The research was conducted at an industrial frequency of 50 Hz, although high-frequency methods can be considered a more effective method.

A detailed design of a new rotary testing device for a single magnetic core sheet is proposed, which allows for complex multiaxial magnetomechanical analysis of ferromagnetic sheets [7]. The problems that arose at the stages of mechanical and magnetic design are considered. The practicality of the device was verified by conducting magneto-mechanical measurements on a sheet of M400-50A electrical steel. It is shown that the effect of multiaxial stress on losses in steel can be much more significant than that of uniaxial stress. There is no assessment of measurement error and signal comparison of defective and non-defective inter-sheet insulation in the work.

Tests of ferromagnetic alloys in the frequency range from 1 Hz to 5 kHz and flux density in the range from 0.1 T to 2 T are considered in [8]. Materials considered include the commonly used materials M36 and 65C600. In applications where rotor speed and temperature are high, solid core rotors are more reliable than charged rotors. Therefore, EN353 and EN8 are promising considered rotor materials. This paper reports on a large-scale experimental study of the magnetic characteristics of these materials in a wide range of frequencies. The results include B-H curves, static magnetization curves, and power loss curves. Loss curves are used to estimate losses in magnetic material at different frequencies and for different values of peak flux densities. These experimental data are important for the analysis, design and performance evaluation of high-speed electric machines. The work lacks an analysis of the processes in this core when defects appear in the core and their impact on the characteristics of the machine.

An alternative solution for measuring local magnetic hysteresis cycles through a multilayer magnetic core is described in [9]. Due to the reduced spatial gap separating the two charged plates, it is impossible to insert conventional magnetic sensors (wound coil, Hall sensor). In this study, the problem is solved by printing a needle probe method to monitor the magnetic state and using a micrometric large magnetic resistance. Magnetic stacking, including for monitoring, is designed and sequentially moved to each stacking position of the entire laminated ferromagnetic core. Accurate hysteresis loss mapping is reconstructed from all local measurements and averaged values compared to classical measurement methods obtained with a wound coil. However, there is no comparison of experimental data with calculated data in the work, which would allow to confirm the adequacy of the obtained results.

In [10], an improved model for calculating losses in the core based on the finite element method is proposed. It includes: a hysteresis loss model based on piecewise variable parameters, an eddy current loss model taking into account different cross-sections of the magnetic circuit and power waveform, as well as improved excess loss coefficients. Experimental verification on various materials, nanocrystalline alloy in 11 kVA intermediate frequency transformer, ultrathin silicon sheets in 10 kW high-speed permanent magnet motor and nanocrystalline alloy in 3 kW wireless power transmission system. The lack of analysis of the mutual influence of eddy currents in individual sheets of the charged magnetic core can be considered a drawback of the work.

A new methodology and experimental setup for measuring losses in a charged magnetic core during power supply with pulse width modulation is described in [11]. A unique feature of the proposed technique is the measurement of losses in iron when the DC magnetization is shifted using one excitation winding powered by a single-phase inverter. The effect of PWM and inverter parameters on losses was investigated. However, this device cannot work at high power supply frequencies.

In [12], the simulation of losses in a magnetically soft composite core was carried out using experimentally measured results. The research indicates that soft magnetic composite components need to be processed differently than multilayer iron cores. Modeling of composite materials using the finite element method requires experimentally substantiated loss models to be able to accurately calculate power losses under variable magnetic flux density and frequency. An approach is proposed that can predict iron loss with an accuracy of 7 %, but has only been tested for component cross-sectional areas of 144 mm^2 or less.

Ferromagnetic cores of electric machines and transformers are made of charged electrotechnical sheets to reduce eddy current losses. Burrs are formed on the edges of electrical sheets during punching and cutting. These burrs deteriorate the insulation of adjacent sheets, create interlayer contacts and cause interlayer currents, additional losses and heating, reduce equipment reliability. The analysis of literary sources showed that currently insufficient attention is paid to the research of ferromagnetic charged cores at high frequencies. The study of high-frequency processes is the basis for the development of a methodological base for diagnosing and detecting defects in inter-sheet insulation. In order to reliably diagnose these defects, it is necessary to develop theoretical foundations based on the physical processes that occur in the layered magnetic core. Based on this, it is necessary to conduct a study of physical processes in the charged magnetic core at different frequencies of the power source.

3. The aim and objectives of the study

The aim of the study is to determine the characteristics of physical processes in the charged magnetic core at different frequencies of the power source. This will make it possible to take into account the effect of remagnetization in charged magnetic conductors at frequencies from 50 Hz to 100 kHz and higher, changes in magnetic permeability, magnetic delay and the effect of currents on adjacent magnetic conductor sheets.

To achieve the aim of the study, it is necessary to solve the following objectives:

– to develop a mathematical model of a single sheet and the interaction of several sheets of a charged magnetic conductor, taking into account changes in magnetic permeability, magnetic delay and the influence of currents in the COMSOL Multiphysics software environment;

– to analyze current distribution and magnetic induction in one plate;

– to analyze current distribution and magnetic induction in a package of several plates.

4. Materials and methods of the study

The object of the study: magnetic cores of electric machines.

The main hypothesis of the study is that the given eddy currents in the sheets of the charged package interact with each other and the nature of their distribution changes when the number of individual sheets changes. In this way, the so-called “proximity effect” is manifested, which can be useful for the development of a methodological basis for diagnosing the magnetic core of electric machines.

Assumptions adopted in the study: the material of the plates is isotropic; the change in temperature during the flow of eddy currents is not taken into account; temperature properties of materials are constant.

The simplifications adopted in the study are that a flat model is considered, and the active length is assumed to be constant. That is, the effect of longitudinal end effects is not taken into account in the work.

Research materials: sheets of a toroidal magnetic circuit of a general-purpose asynchronous machine, devices for creating different frequency of remagnetization. The data of the engine under study and the parameters of the magnetic core are given in [13].

Research methods: analytical methods of classical electrodynamics, the finite element method implemented in the software package Comsol Multiphysics (Sweden), graphic methods for building calculation models, methods for calculating the electromagnetic field.

5. Research results of the charged magnetic circuit

5. 1. Development of a mathematical model of individual sheets of a charged magnetic conductor in the COMSOL Multiphysics software environment

In order to study the magnitude of the magnetic flux and induced eddy currents induced in individual plates of the magnetic core by the external magnetic field, the calculation of the magnetic field using the finite element method was carried out in the work. The induced magnetic fluxes in individual sheets interlock with each other, while affecting the distribution of electromagnetic quantities within each individual sheet.

Well-known Maxwell’s equations [14, 15] are used to study the dynamic processes in individual sheets of a charged magnetic conductor.

$$rot(H) = J, \tag{1}$$

$$B = rot(A), \tag{2}$$

$$rot(E) = -\partial B / \partial t, \tag{3}$$

where γ – the specific electrical conductivity of the material under study, H and E – vectors of magnetic and electric field intensity, B – vector of magnetic induction.

The studied models are flat, which allows to consider the field problem as two-dimensional in the Cartesian coordinate system in the $x0y$ plane. In this case, the main field quantity is the vector magnetic potential A, which has a single z-component, i. e. $\mathbf{A}=(0, 0, A_z)$.

From the system of Maxwell's differential equations for a stationary magnetic field of the form (1)–(3), the following equation for the distribution of the vector potential is obtained:

$$\nabla \times \left[(\mu_0 \mu_r)^{-1} \nabla \times \mathbf{A} - (\mu_0 \mu_r)^{-1} \mathbf{B} \right] = \mathbf{J}_e, \tag{4}$$

where $\mathbf{H}$ – the strength of the magnetic field, $\mathbf{B}$ – the magnetic induction, $\mathbf{A}$ – the vector magnetic potential, $\mathbf{J}_e$ – the current density in individual sheets, μ_0 – the magnetic permeability of the vacuum, and μ_r – the relative value of the magnetic permeability of the material.

Fig. 1 presents a geometric model of a thin plate compared to its length.

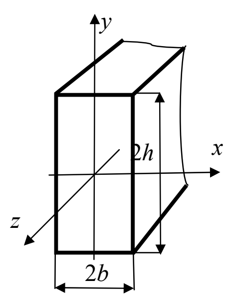


Fig. 1. Thin plate

The following designations are adopted: 2b is the width of the investigated plate, h is the height of the investigated plate. Input data for the model: width of the plate $2b=5\cdot10^{-4}$ m, height of the investigated plate $h=1.2\cdot10^{-2}$ m (h>>2b), axial length l=0.326 m (l>>h>>2b), the value of electrical conductivity for the selected material of electrical steel is 1.12·107 S/m, magnetic permeability μ=200 H/m. The magnet sheet of a general-purpose asynchronous motor is taken as a basis.

In practical activities, prefabricated busbars are often found, which have the appearance of thin, long conductive plates. If two thin plates of the magnetic conductor are considered, then they will have a significant magnetic permeability μ (H/m). The dimensions and relative position of the studied model for two plates are shown in Fig. 2.

The distribution of the electromagnetic field and eddy currents in the cross-section of a package consisting of three or more plates is significantly different from the case with one sheet and two. This is explained by the influence of the eddy currents given in the sheets on each other. The three-plate model is a prototype of a charged magnetic core. Fig. 3 shows the model of the three-plate package studied in this paper.

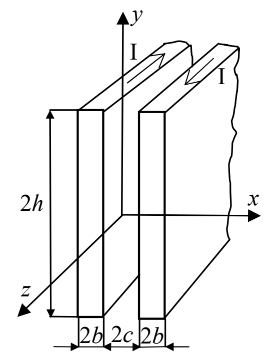


Fig. 2. Two thin conductive and magnetic conductive plates

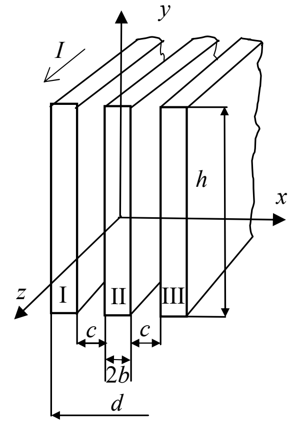


Fig. 3. Dimensions and shape of a package of three plates

In the case of a package of three plates, an analogy with the previous case for two thin plates is visible, but the pulsating flow Φ passes through the package in the direction of the z axis.

If the studied system has a known specific electrical conductivity γ (S/m), magnetic permeability μ (H/m) and the vectors of the magnetic and electric fields change with the angular frequency ω (rad/s), then Maxwell's equations are transformed and have the following form:

$$\frac{d^2 H}{dx^2} = k^2 \cdot H, \tag{5}$$

$$k^2 = j \cdot \omega \cdot \gamma \cdot \mu. \tag{6}$$

The depth of penetration (a) is determined by the well-known expression:

$$a = \sqrt{\frac{2}{\omega \cdot \gamma \cdot \mu}}. \tag{7}$$

With a change in the x coordinate, not only the value of the current density changes, but also its phase. Joule losses can be determined either using the Poynting vector or using the volume integral:

$$P = \frac{1}{\gamma} \cdot \int_V |J|^2 \, dv. \tag{8}$$

If to assume that $R_0=1/4\cdot b\cdot h\cdot\gamma$, [Ohm/m] is the resistance to direct current, then the effective resistance of the conductor to alternating current $R_{\sim}$ for the case when $2b>a$ can be written in the following form:

$$R_{\sim}=\frac{b}{a}R_0,\ \frac{\text{Ohm}}{\text{m}}. \qquad (9)$$

If the ratio $b \gg a$ is true for the conductor under study, then the resistance to alternating current, especially at high frequencies, will differ significantly from the actual value. In this case, the following expression is used to determine $R_{\sim}$ [1]:

$$R_{\sim}=\frac{1}{4\cdot a\cdot h\cdot \gamma}\cdot\frac{\operatorname{sh}\frac{2b}{a}+\sin\frac{2b}{a}}{\operatorname{ch}\frac{2b}{a}-\cos\frac{2b}{a}}. \qquad (10)$$

From the expression for the electric field strength E (V/m), it is possible to determine the value of EMF of self-induction and current density on the surface of the conductor at $x=\pm b$. Based on this, the total Z, the inductance x and the active resistance R are determined.

To obtain adequate results, it is necessary that $2h \gg 2b$. This is necessary in order to neglect the spatial dependence on the y-ordinate. Another condition of the task under consideration: the current on the plate passes in the direction of the z axis. In this case, the magnetic field strength has only one component (the other components will be relatively weak):

$$H=j\cdot H_y, \qquad (11)$$

and the electric field strength will also have only one component:

$$E=k\cdot E_z, \qquad (12)$$

$$H_{(+x)}=-H_{(-x)}, \qquad (13)$$

$$H_1=-H_2=H_0/2. \qquad (14)$$

For the analysis of high-frequency processes, a two-dimensional field mathematical model implemented in the COMSOL Multiphysics program is used. The distribution of the electromagnetic field and eddy currents is calculated by the finite element method using equations (4), (5). The assessment of the depth of current penetration into the conductive elements of the calculation model and the change in the active resistance of the investigated plates is modulated by expression (7) and formulas (9), (10). Losses in individual sheets of charged magnetic conductor are calculated according to expression (8). The magnitude of the current density and the induced EMF in the plates is calculated using expressions (11)–(14).

With the help of the model, it is possible to determine the depth of penetration of currents, calculate the change in the effective resistance to alternating current or the inductance of such a conductor.

5. 2. Analysis of current distribution and magnetic induction in one plate

In the Table 1 shows the results of calculating the resistance of a flat conductor to alternating current at a frequency of 50 Hz according to formulas (6), (8), (9).

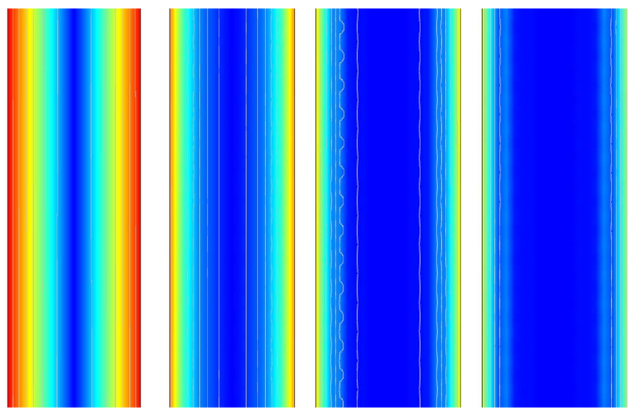
Fig. 4 shows the distribution of magnetic induction and vector potential in a thin plate (Fig. 1) at different values of the current frequency.

Fig. 5 shows the distribution of the current density in the cross section of the sheet at different frequency values.

Table 1

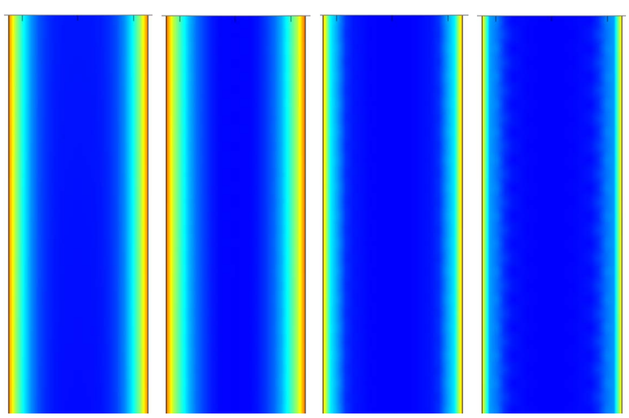
Dependence of the resistance of a flat conductor on alternating current

b/a	$R_{\sim}/R_0$
0.25	1.00034
0.50	1.0047
0.60	1.0124
0.70	1.029
0.80	1.038
0.90	1.062
1.00	1.091
1.25	1.24
1.50	1.52
2.00	2.04
2.50	2.63
3.00	3.12
3.50	3.73
4.00	4.18



a *b* *c* *d*

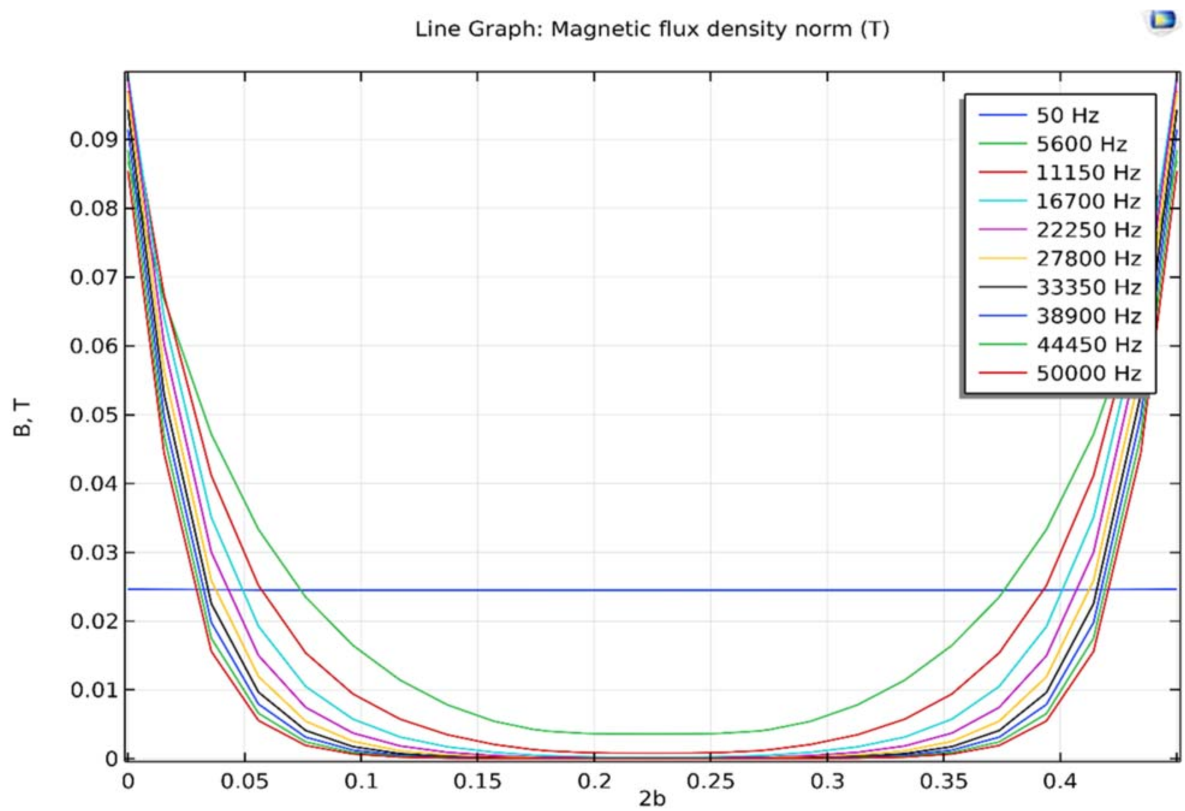
Fig. 4. Distribution of magnetic induction and vector magnetic potential in a steel sheet for different frequency values: *a* – 50 Hz; *b* – 10 kHz; *c* – 50 kHz; *d* – 100 kHz



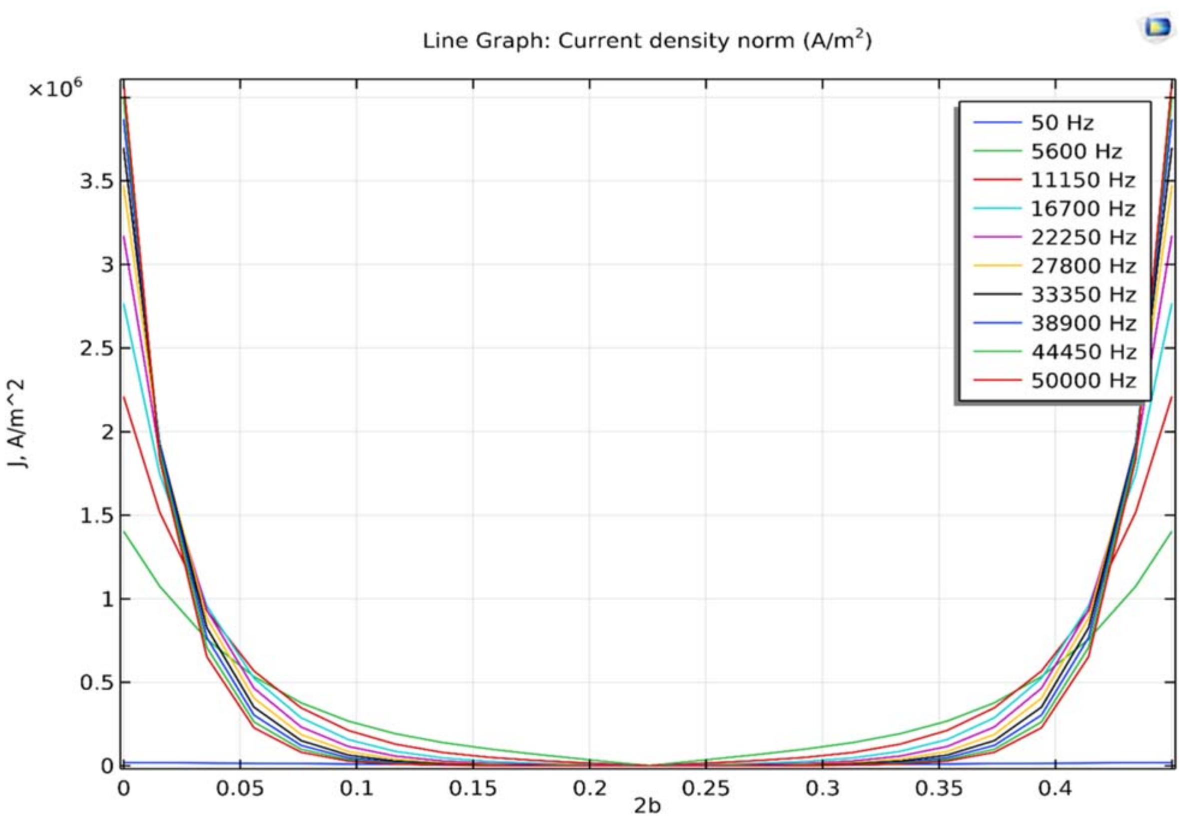
a *b* *c* *d*

Fig. 5. Distribution of current density in the investigated plate for different frequency values: *a* – 50 Hz; *b* – 10 kHz; *c* – 50 kHz; *d* – 100 kHz

Fig. 6 shows the distribution of magnetic induction and current density at different frequency values.



a



b

Fig. 6. Distribution of electromagnetic quantities: *a* — distribution of magnetic induction; *b* — current density in the cross section of the plate

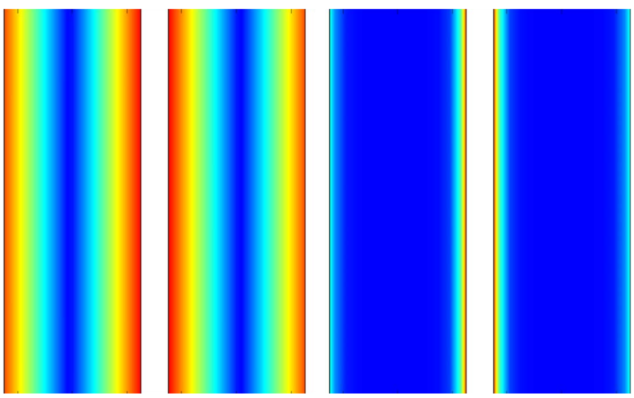
To calculate the distribution of magnetic induction and current density, the frequency range from 50 Hz to 100 kHz was chosen.

5. 3. Analysis of current distribution and magnetic induction in a package of several plates

The calculation is made for the case when in one plate the current flows in one direction, and the other conducts the current in the opposite direction. The plates are very long in the direction of the z axis, and the height of the plates $2h$ is several times greater than their width $2b$. Under such assumptions, it can be assumed that the magnetic field will have only the H_y component, and the electric field – only the E_z component.

Preliminary calculations of the effective resistance $R_{\sim}$ to alternating current for this problem showed that it will be twice as much as for a single plate. Therefore, the values in the table are also valid here. 2, if instead of the value of b/a, the value of $2b/a$ is understood.

Fig. 7 shows the distribution of magnetic induction for two current-conducting thin plates at different current frequencies.



a *b*

Fig. 7. Distribution of the electromagnetic field for two plates for different frequency values: *a* – 50 Hz; *b* – 100 kHz

Fig. 8 shows the distribution of eddy currents in an arbitrary section for two plates.

To analyze the current distribution and magnetic induction in a package of three wafers, the surface effect and the proximity effect in the package of insulated sheets of the type package were considered.

In well-known sources, for example [1], the nonlinear distribution of the current density in a conductor with a rectangular cross-section during the passage of an alternating current is considered. Related to this task is the determination of the surface effect in the package of plates, which conducts a pulsating magnetic flux Φ passing through the package in the direction of the z axis.

It is necessary to determine the interaction of letters I and III with letter II. The influence of other letters of the package can be neglected. It can be assumed that the influence of letters I and III will be completely compensated in the middle letter II. The symmetry conditions correspond to the following expression:

$$H_{(x=b)} = H_{(x=-b)}. \tag{15}$$

The distribution of the electromagnetic field and vector magnetic potential at a frequency of 1 kHz for three plates is shown in Fig. 9.

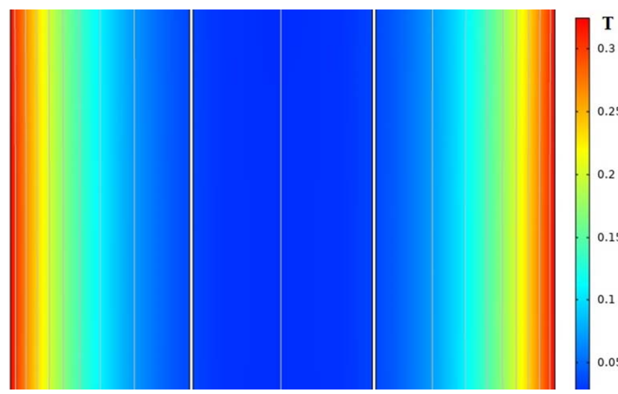


Fig. 9. Distribution of the electromagnetic field

The change in current density and the distribution of the average value of the magnetic induction across the cross-section of plate II are shown in Fig. 10.

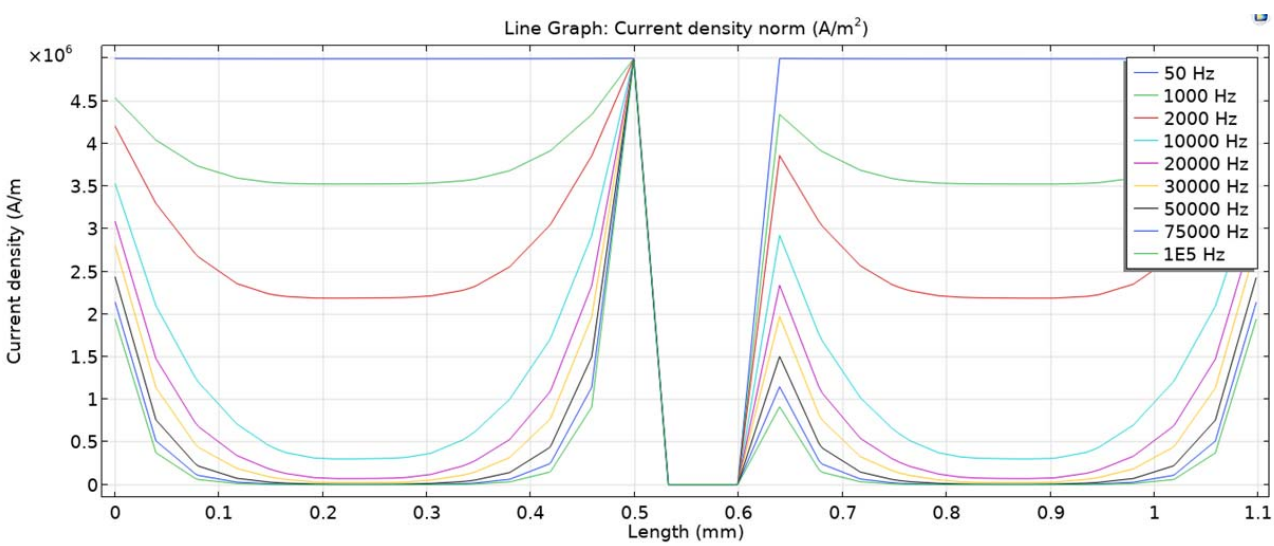
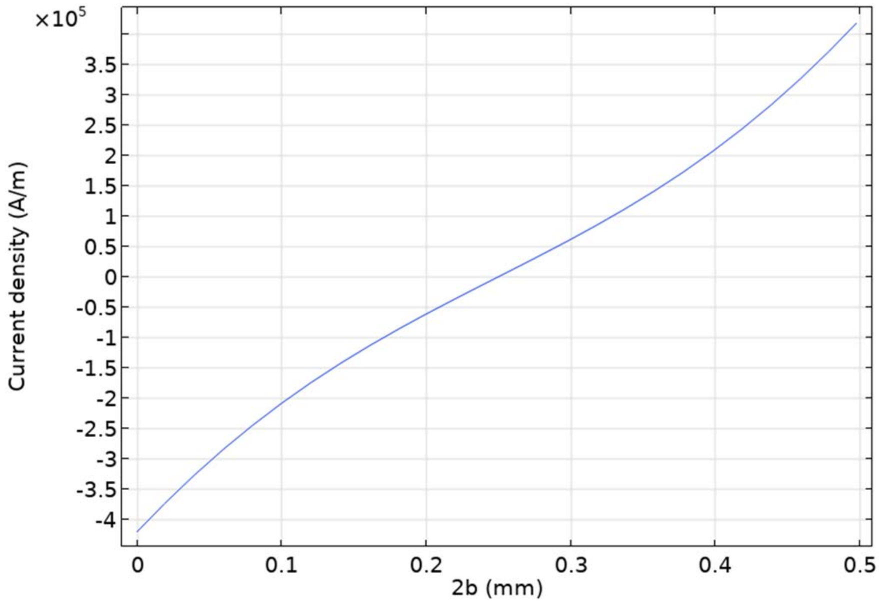
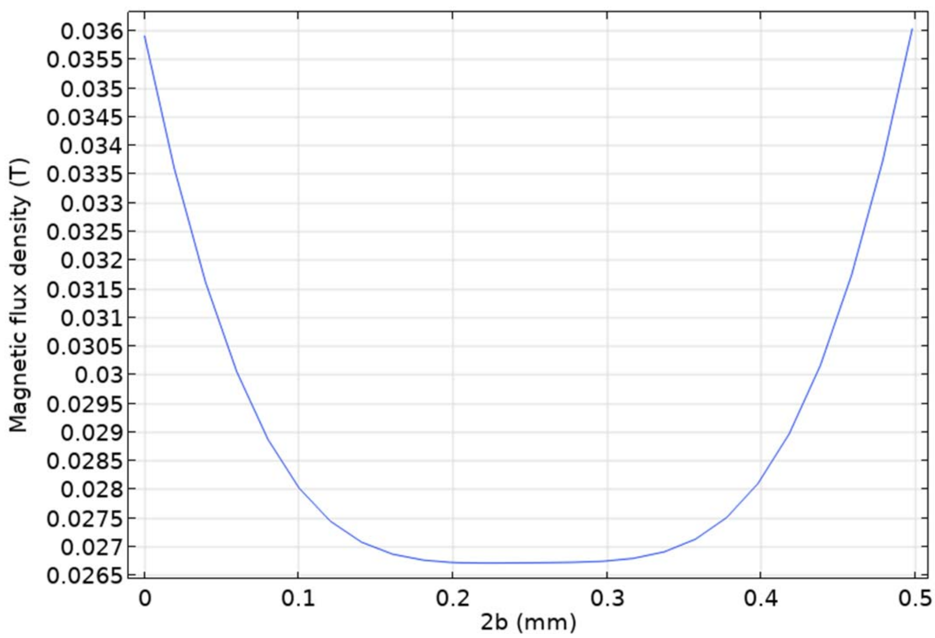


Fig. 8. Distribution of eddy currents in an arbitrary cross-section for two plates



a



b

Fig. 10. Distribution of electromagnetic quantities: *a* — current density in the cross section of the plate; *b* — distribution of magnetic induction

To calculate the distribution of magnetic induction and current density in the cross-section of plate II, a frequency of 1 kHz was chosen.

6. Discussion of the results of mathematical modeling of physical processes in a charged magnetic core at different remagnetization frequencies

A two-dimensional field mathematical model of a single plate and several plates was developed, which was implemented using the finite element method. The peculiarity of the model is that it takes into account the change in the active resistance of the plate when the frequency changes, the change in magnetic permeability, saturation and magnetic delay.

The mutual influence of separate packages of the magnetic field on the distribution of eddy currents is considered. It is shown that the distribution of the electromagnetic field and eddy currents in the presence of one, two, and three plates is phased. This allows to visually show the difference in processes and effects inside and on the surface of the plates for each case.

From fig. 4 shows that the maximum value of the induction at the industrial frequency is 0.6 T at the edges of the plate, the minimum value tends to zero in the middle of the plate at frequencies above 75 kHz. It can also be seen that the field penetration depth decreases with increasing frequency. This is explained by the fact that with an increase in the frequency of remagnetization, the wave of the electromagnetic field does not have time to penetrate into the middle of the sheet. The depth of field penetration depends on the frequency, magnetic permeability, magnetic and electrical conductivity of the core material. The penetration depth is determined by formula (7).

Fig. 5 shows the distribution of the current density in the cross section of the sheet at different frequency values. A decrease in the penetration depth of the magnetic field causes the effect of displacement of the current to the periphery of the plate, while the effective resistance of the plate increases accordingly.

From Fig. 6, *b* can be seen that with increasing current frequency, when γ, μ=const, the depth of current penetration decreases in the frequency range from 50 Hz to 100 kHz. Current density at a frequency of 50 kHz and higher, in the zone of penetration depth of $1 \cdot 10^{-5}$ m. This is correlated with the distribution of induction at the corresponding frequencies in Fig. 6, *a*.

From Fig. 7, it can be seen that in the presence of two plates with an increase in frequency relative to 50 Hz, the displacement effect is excellent compared to one plate. In addition, magnetic induction and eddy currents (Fig. 8) at the edges of the plates at different frequencies differ significantly. The total magnetic induction is created by two sources: the external field and the field of eddy currents, which are directed oppositely to each other in two adjacent plates. This is determined by the interaction of processes in adjacent plates by the mutual influence of eddy currents that flow on the periphery of the plates.

The distribution of the electromagnetic field and vector magnetic potential for three plates, shown in (Fig. 9, 10), will have the following pattern at a frequency of 1 kHz. It is obvious that the distribution of the electromagnetic field will differ from other values of the frequency. At the edges of the sheets, the value of induction will be the largest, in the middle of the sheets, the value of induction will decrease with increasing frequency. This distribution at a frequency of 1 kHz is explained by the corresponding value of the penetration depth, which is approximately $0.25 \cdot 2b$. As the frequency increases, the current density will be determined by a smaller penetration depth.

In contrast to works [3, 4, 8], in this study (Fig. 6, 8) the results were obtained, which show the mutual influence of individual sheets of the charged magnetic core on each other at different frequencies of remagnetization processes. In this way, the so-called "proximity effect" is manifested, in which the currents and magnetic fluxes of the extreme sheets exert an influence on the distribution of magnetic fluxes and currents of the middle sheet (Fig. 10).

The obtained results (Table 1, Fig. 6, 8, 10) are the theoretical and methodological basis for the development of systems for reliable diagnosis of damage to the inter-sheet insulation of the charged magnetic core. The results are based on physical processes that take place in a charged magnetic core at high frequency.

Implementation of the studied phenomena and principles in the form of diagnostic equipment operating at a high frequency is complicated. This is explained both by the shortage of powerful semiconductor equipment, that is, high-frequency generators, and by the sensitivity and selectivity of measuring equipment.

The difficulty of taking into account the processes of remagnetization (hysteresis), the manifestation of the inertia of magnetic domains at high frequency (>100 kHz) and the appearance of a significant measurement error is considered a disadvantage. However, there is an opportunity to take these processes into account in future research.

The issue of choosing the optimal diagnostic frequency, developing an automated diagnostic system, and assessing the quality of the charged magnetic core are urgent issues that require further research in this direction.

7. Conclusions

1. A two-dimensional field mathematical model of a single plate and several plates has been developed, which is implemented using the finite element method. The peculiarity of the model is that it takes into account the change in the active resistance of the plate when the frequency changes, the change in magnetic permeability, saturation and magnetic delay. The obtained results are clearly correlated with physical phenomena and processes that occur in real samples of charged magnetic conductors, which indicates the adequacy of the developed model.

2. The depth of magnetic field penetration into the plate and the corresponding distribution of eddy currents in the frequency range from 50 Hz to 100 kHz varied from $a=2b=5 \cdot 10^{-4}$ m to $0.02 \cdot 2b=1 \cdot 10^{-5}$ m. The distribution of the eddy current density is correlated with the distribution of magnetic induction at different frequencies, but the value of the eddy current density on the surface of the plate depends on the reduced active resistance (Table 1). According to calculations, at the lowest frequency of 50 Hz and at the highest frequency of 100 kHz, the current density on the plate surface is $0.018 \cdot 10^6$ A/m^2 and $4.2 \cdot 10^6$ A/m^2, respectively. At the same time, the integral value of the eddy currents remains constant when the frequency changes.

The complexity of the model, due to the use of modern methods and software products, made it possible to take into account magnetic nonlinearity and the effect of the proximity of adjacent sheets. Comparative analysis of numerical modeling with classical calculations shows the physical and mathematical coincidence of specific results. The compared results show the convergence of analytical and numerical calculations, but modern methods allow taking into account the nonlinearities of high-frequency processes in the laminated core.

3. Based on the analysis of the distribution of currents and the given magnetic induction in the package of plates, it was determined that the currents at a high frequency of remagnetization are distributed over the surface of the plates. But the proximity effect consists in the fact that the currents on the surface of adjacent plates have a different direction and therefore there is an effect of reverse displacement. In the middle sheet in a package of three plates, the value of the induced current changes both in magnitude (from $-4 \cdot 10^5$ to $4 \cdot 10^5$ A/m^2) and in direction.

The nature of the distribution of magnetic induction in the middle sheet in a package of three plates is parabolic in nature, the induction value varies from 0.035 T at the edges of the sheet to 0.026 T in the middle of the plate, which corresponds to the transition of the current through zero.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, including financial, personal, authorship or other, which could affect the research and its results presented in this article.

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Data availability

The manuscript has no associated data.

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