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NUMERICAL SIMULATION OF LOSSES AND HEATING IN THE CONSTRUCTIONAL ELEMENTS OF TRANSFORMERS OF FERROMAGNETIC STEEL

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The application of the methods of calculation of surface and volume losses in the constructional elements of transformers of ferromagnetic steel is considered. A brief description of the developed practical procedures of their calculation using the ANSYS software is given. The testing results of the proposed procedures conducted on the known experimental studies TEAM21, as well as calculation samples of losses and heating in the constructional elements of a single-phase autotype transformer with capacity of 500 MVA and reactor of ROM type with capacity of 80 MVAr, are provided. References 16, table 1, figures 16.

Keywords: powerful electrical transformer, losses, heating, three-dimensional modeling.

1. Introduction. Additional losses in the constructional elements of power transformers with significant specific electromagnetic loads may lead to the unacceptable heating. That is why researchers and designers pay constant attention to the issues of local losses and heating calculation, as well as the total losses in transformers.

The experimental studies, using natural samples of the equipment and the corresponding to it physical models, were conducted and continue to be conducted. The mathematical models and methods of calculation of this problem class are constantly improved. Significant results have been achieved through the extensive use of such invariant systems of numerical finite-element analysis (FEA) as ANSYS, Comsol, ELCUT, ELEKTRA, FEMM, Infolytica, OPERA, etc. A systematic representation of the known publications on this problem is given, for example, in the following books: [1, 4−6, 13, 15, 16].

The issues related to the definition of magnetic field in the constructional elements of ferromagnetic steel with a pronounced nonlinear surface effect, are particularly complex when determining the local losses and heating, as well as the total losses in transformers. The known methods of research and calculations devoted to these issues in the power transformer equipment can be roughly classified into two groups of methods: surface and volumetric losses.

The method of surface losses is based on the fact that in the massive conductive bodies with a pronounced non-linear surface effect, the electromagnetic field is concentrated in a thin surface layer. [6]. In this case, the conductive body shows up as an equivalent impedance surface, and the losses are determined by using an input impedance (surface resistance) of the body and the value of the tangential component of magnetic field intensity on its surface [4, 5, 16].

However, the method of surface losses does not provide the calculations of the bodies of limited dimensions. For example, in the power transformers they are yoke beams, pressing metal rings, and lifting plates on the rods of magnetic system (MS). The losses calculation in the yoke beams is further complicated by the fact that they often have horizontal shelves of non-magnetic steel, and vertical walls from a ferromagnetic steel. Electric welding of such parts of the construction leads to the exchange of the eddy currents in their volumes. Such can be observed when realizing the inserts of non-magnetic steel in ferromagnetic caps and tank walls of transformers and reactors, that is used to reduce the local losses of the total magnetic fields of windings and taps with significant currents [8].

Additional losses in the constructional elements of transformers of ferromagnetic steel can be determined numerically by using the method of volumetric losses [2, 4, 5, 9−11]. This method provides a way to determine the field vectors and energy parameters directly in the volume of conductive bodies. The method of volume losses has been investigated numerically, and is represented in several publications of the authors of testing TEAM method (Testing Electromagnetic Analysis Methods) on physical models [9−11]. Numerous studies of a family of TEAM21 problems using Infolytica software are also given on the website [12]. The research of the problems for two plates with a section of nonmagnetic steel, and two plates of ferromagnetic steel are given in [14].

It should be noted that in the KEA ANSYS [7] software there are no standard procedures for calculating the losses in the bodies of ferromagnetic steel with a nonlinear surface effect. Therefore, the additional development and testing of these calculation procedures are needed when using ANSYS software.

The aim of this work is to represent the main methods and examples of losses calculation in the constructional elements of power transformer equipment of ferromagnetic constructional steel, and evaluate their heating on the basis of the developed additional procedures of numerical simulation using ANSYS software.

The main approaches to the calculation of electromagnetic field of transformers.

Electromagnetic processes in the power transformer equipment are described by the system of Maxwell's equations relative to the vectors of intensity and induction of magnetic field $\overline{H}, \overline{B}$, and intensity and induction of electric field $\overline{E}, \overline{D}$ [2, 4, 5, 13, 15, 16]

$$\nabla \times \overline{H} = \overline{j} + \partial \overline{D} / \partial t , \quad \nabla \times \overline{E} = -\partial \overline{B} / \partial t , \quad \nabla \cdot \overline{D} = \rho , \quad \nabla \cdot \overline{B} = 0 . \tag{1}$$

The ratio between the field vectors are determined by constitutive equations

$$\overline{j} = \overline{j}_{ces} + \sigma \overline{E} , \qquad \overline{D} = \varepsilon \overline{E} , \; \overline{B} = \mu \overline{H} , \tag{2}$$

where σ − electrical conductivity; μ − magnetic permeability; ε − dielectric permeability.

The bulk densities of electric charge ρ and current $\overline{j}$ are the sources of electromagnetic field, and are connected with the equation $\nabla \cdot \overline{j} + \partial \rho / \partial t = 0$.

In the ratios (2), the electrical conductivity σ and magnetic permeability μ for unisotropic mediums are tensor quantities [4, 5, 13, 15, 16]. In many problems the nonlinear dependence of electrical conductivity σ on temperature θ is taken. For ferromagnetic mediums the relation between $\overline{B}$ and $\overline{H}$ will be nonlinear [4, 5, 6]. At the industrial frequencies the displacement currents are neglected, which leads to the known ratios: $\partial \overline{D} / \partial t = 0$ and $\rho = 0$.

The harmonic change of the currents from equations (1) leads to the second-order differential equation with respect to the complex amplitudes $\overline{H}$ and $\overline{E}$ [2,4,16]

$$\nabla^2 \overline{H} - k^2 \overline{H} = -\nabla \times \overline{j} , \qquad \overline{E} = \sigma^{-1} \left(\nabla \times \overline{H} - \overline{j} \right), \tag{3}$$

where $k = \sqrt{-i\omega\sigma\mu}$ − phase constant.

Similar equations also determine the relationship between the amplitudes $\overline{E}$ and $\overline{H}$.

To reduce the number of equations (3), the auxiliary vector potential function $\overline{A}$ by definition $\overline{B} = \nabla \times \overline{A}$ is entered. In this case, instead of two equations (3) we get a single equation for the potential $\overline{A}$ [2, 4, 16]

$$\nabla^2 \overline{A} - k^2 \overline{A} = -\mu \overline{j} . \tag{4}$$

In this case the field vectors are

$$\overline{H} = \mu^{-1} \nabla \times \overline{A} , \qquad \overline{E} = i\omega \overline{A} - i\omega k^{-2} \nabla\nabla \cdot \overline{A} . \tag{5}$$

For the problems of determining the magnetic field of permanent currents $k = 0$ and equation (4) will be Poisson's equation at controlled currents of external sources $\overline{j}_{ces}$. For the problems of determining a variable magnetic field $k \neq 0$ and the equation (4) will be Helmholtz equation, at which the electromagnetic field is generated by external sources as well as eddy currents in the conductive bodies $\overline{j} = \overline{j}_{ces} + \sigma \overline{E}$.

There are also other problems solutions of electromagnetic fields with the use of other auxiliary potentials [2, 4, 16]. To solve the boundary problems, the Maxwell's equations are complemented by known boundary relations at the interface surface of mediums and boundary conditions at infinity. For electromagnetic fields that depend on time, the initial conditions must be given as well [2, 4, 16]. In analytic solutions when determining the field in the air near conducting medium with a strong surface effect, the so-called Leontovich approximate boundary conditions of impedance type are used [2, 4, 16].

In this paper, in order to conduct electromagnetic calculations of transformer equipment, the methods of stationary, harmonic and nonlinear harmonic analysis of ANSYS software [7] are used, and only necessary explanations to the practical procedures developed by means of ANSYS for certain problems and corresponding to them computational models and calculation methods are represented.

To achieve the aim of this work it is necessary to develop more specific procedures to calculate the energy parameters in ferromagnetic bodies. The main algorithmic features of these procedures are set out below.

The energy characteristics of electromagnetic field are expressed through dependencies [2, 4]

$$w_{\text{em}} = w_{\text{e}} + w_{\text{m}}, \quad w_e = \bar{E}\cdot\bar{D}/2, \quad w_m = \bar{B}\cdot\bar{H}/2, \quad p_{ces} = \bar{j}_{ces}\cdot\bar{E}, \quad p_j = \bar{j}\cdot\bar{E}, \quad \bar{\Pi} = \bar{E}\times\bar{H}. \quad (6)$$

They determine the bulk w_{em} density of electromagnetic energy as the sum of electric w_e and magnetic w_m components, bulk densities of loss power from eddy p_j currents and extraneous currents p_{ces}, as well as the energy flux density of electromagnetic field or Poynting vector $\bar{\Pi}$.

The features (6) are linked by Umov-Poynting theorem relative to surface density of energy power transferred by electromagnetic field through the surface S in the direction to the outward normal $\bar{n}$ and losses in the volume V

$$\frac{\partial}{\partial t}\int_V w_{em}dv = \int_V p_{ces}dv - \int_V p_j dv - \int_S \left(\bar{E}\times\bar{H}\right)\cdot\bar{n}ds. \quad (7)$$

On the basis of (7), the relationship between the Poynting vector and power densities of electric losses and magnetic energy in complex form is set, which in the absence of external currents in the constructional elements of transformers can be written as follows [4]

$$-\frac{1}{2}\oint_S \left[\bar{E}\times\bar{H}^*\right]\cdot\bar{n}\,ds = \frac{1}{2}\int_V \bar{j}\cdot\bar{E}^* dv - i\omega\int_V \frac{\mu\bar{H}\cdot\bar{H}^*}{2}dv. \quad (8)$$

The given equations allow to determine the similarity and differences of the methods for calculating surface and volumetric losses. Common to both methods is the need to determine the electromagnetic field vectors. The difference is that for the method of surface losses, the determination of the field vectors on the surface of bodies under review, and for the method of volumetric losses − within their volume, is necessary and sufficient.

The properties of structural steels. When determining the vectors of field and energy parameters taking into account the constitutive equations (2), it is usually assumed that the electrical conductivity of the constructional steels is a constant. Later, after the thermal calculation, this parameter can be updated. For nonmagnetic steels the magnetic permeability is a constant, which is slightly different from the magnetic permeability of air.

More complicated is the account of the nonlinear and hysteresis relationship between tension and induction in ferromagnetic steels. The known magnetic permeability along the normal induction curve is defined as the locus of the vertices of hysteresis symmetric loops. At the cyclic magnetization of ferromagnetic material from the demagnetized state, its magnetization occurs through the so-called ascending and descending parts of the hysteresis loops.

For the important in engineering practice case of harmonic field change $\omega = 2\pi/T$, a complex magnetic permeability $\dot{\mu}_I$ on the first harmonic is used.

A complex magnetic permeability $\dot{\mu}_I$ is determined by the complex amplitudes on the first harmonics B_1 and H_1 [4 – 6]

$$\dot{\mu}_I = B_I / H_I, \qquad B_1 = \frac{2}{T}\int_0^T B(t)e^{i\omega t}dt, \qquad H_1 = \frac{2}{T}\int_0^T H(t)e^{i\omega t}dt. \quad (9)$$

When integrating (9), the values of the area of hysteresis loops that determine the value $\dot{\mu}_I$, are determined numerically [4] or by planimetering [6] the area bounded by the descending and ascending loop branches with vertex H_m

$$\mathrm{S}(H_{1m}) = \int_{-H_{1m}}^{+H_{1m}} \left[B_D(H, H_{1m}) - B_A(H, H_{1m})\right]dH, \quad (10)$$

where $\mathrm{S}(H_{1m})$ – square of hysteresis loop.

The graphic representations $\dot{\mu}_I$ and analytical descriptions of the dependence $\dot{\mu}_I(H)$ for different parts of the magnetization curve are given in [4–6]. The introduction of $\dot{\mu}_I$ allow to trace the system of Maxwell equations to the equations of first harmonic, which differ from the equations (1), (2) with respect to the complex amplitudes of the field for a medium with constant parameters σ and μ only with μ for $\dot{\mu}_I(H)$ replacement.

The introduction of complex magnetic permeability $\dot{\mu}_I$ on the first harmonic enabled to solve several problems of electromagnetic field propagation in ferromagnetic half-space with a surface effect, without and taking into account the hysteresis loss [4, 6]. The obtained solutions allow to determine that at the "sufficiently strong fields H that exceed the intensity value at which μ has a maximum" of active losses in ferromagnetic with hysteresis, with more losses in ferromagnetic with a constant value of magnetic permeability of about 1.4 times [6]. The given ratio was also obtained by solving the problem using numerical method of grids, the results of which are described in [16]. To exclude the adopted in [6] reduction in [4, 5], the so-called equivalent magnetic permeability on the first harmonic $\dot{\mu}_{\text{Э}}$ was introduced. The analytical methods for calculating equivalent magnetic characteristics of the known static magnetic characteristics, and experimental methods for determining this characteristic are presented in [4, 5].

Fig. 1 shows the dependence of the modulus and argument of equivalent magnetic permeability on the first harmonic on the current value of the amplitude of first harmonic of the magnetic field intensity for the steel of Ст.3 mark and for the frequently used constructional steel of 09G2C mark.

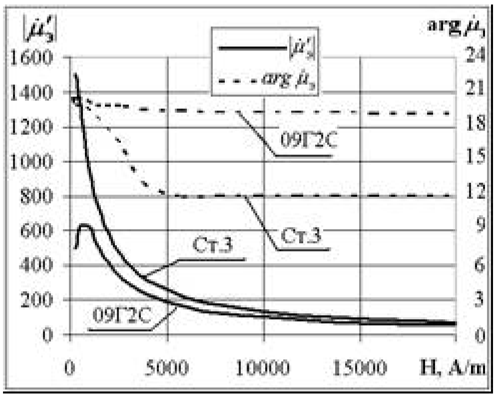


Fig. 1

The method of surface losses, as mentioned above, determines the specific surface losses w in ferromagnetic half-space as through the tangential components of the electric and magnetic fields intensity according to (7), (8) and through the known [2, 4−6] determination of the conventional surface impedance through the field vectors on the first harmonic $\dot{Z}(|H_1|) = \dot{E}_1 / \dot{H}_1$ and the square of the magnetic field intensity

$$w = \frac{1}{2} Re\left(\dot{E}_1 \dot{H}_1^*\right) = \frac{1}{2} Re\dot{Z}\left|H_1\right|^2 . \tag{11}$$

Using the equivalent magnetic permeability, the surface losses p_S are expressed through the tangential component of the magnetic field intensity H_τ on the first harmonic and surface impedance Z [4, 5]

$$p_S = \frac{1}{2}\mathrm{Re}\dot{Z}\left(H_\tau\right)H_\tau^2 , \quad \mathrm{Re}\dot{Z} = 2\sqrt{\omega\mu_0 \left|\dot{\mu}'_{\text{э}}(H)\right|\sigma^{-1}} \cos\left(\pi/4 - 0,5\arg\dot{\mu}_{\text{э}}\left(H\right)\right). \tag{12}$$

To calculate specific surface losses, the values of modulus and argument of equivalent magnetic permeability for the steel Ct. 3 and steel 09G2S provided in Fig. 1, can be used. The works [4, 5] also present the experimental dependence of surface losses on magnetic field intensity for steels Ст.2, Ст.3. The obtained values by (12) correspond to the conditions of massive conductive bodies. The shape and dimensions of the experimental samples have a negligible effect [4, 5].

The analytical method of the surface losses is used to calculate the field losses and losses in the tanks of transformers and electrical reactors [3, 4], as a closed surface of the tank to the maximum extent corresponds to the condition of the flat conductive half-space. Following the [4] method, on the first stage (using measurements, and calculations) the primary magnetic field H_τ^0 in the air along the contour coinciding with the tank surface (without tank) is determined. In the second stage the field is calculated directly on the tank surface using an influence coefficient of impedance type $H_\tau = H_\tau^0 k_\tau(Z)$, including taking into account the local placement of the magnetic screens on the tank surface [3]. At the same time the determining surface impedance and losses (12) nonlinear dependence of magnetic permeability on the magnetic field intensity of tank steel is installed using the method of successive refinements.

By numerical simulation in ANSYS, a computing model of transformer (reactor) with tank is formed. A ferromagnetic constructional steel of the tank is characterized by basic magnetization curve and electrical conductivity. By the method of nonlinear harmonic analysis, the tangential component of the magnetic field intensity directly on the tank surface H_τ is calculated. Developed by means of ANSYS additional procedure implements the algorithm (12) for determining the local losses. The total losses in the tank are calculated by integrating the local losses of its surface.

The method of volumetric losses according to (6) determines the losses as the total of ohmic losses on the eddy currents and losses on alternating magnetization of constructional steel with a nonlinear magnetic characteristic and with hysteresis [2, 4, 5, 9–11]

$$p_v = p_j + p_h . \tag{13}$$

Power density of electrical losses is $$p_j = \bar{j} \cdot \bar{E} . \tag{14}$$

The losses $p_h(B_m)$ spent on alternating magnetization with a frequency f in the body with the density ρ are proportional to the area of hysteresis loop $S(B_m)$ [2, 4 – 6]

$$p_h(B_m)=f\rho^{-1}S(B_m). \qquad (15)$$

The area of hysteresis loop $S(B_m)$ is defined as in (10) on the amplitude of the magnetic field induction B_m

$$S(B_m)=\int\limits_{-|B_m|}^{+|B_m|}\left[H_D(B,B_m)-H_A(B,B_m)\right]dB\,. \qquad (16)$$

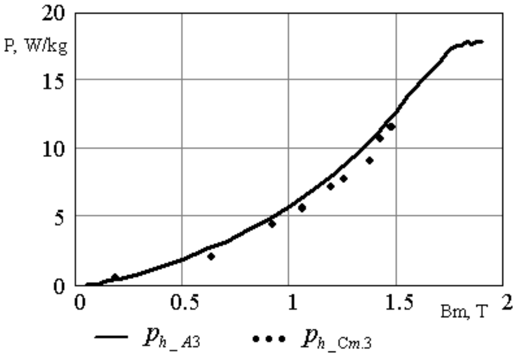


Fig. 2

In particular, for steel Art.3 the family of static hysteresis loops for a range of values B_m is graphically represented in [4]. With their use by the expressions (15) and (16) at a frequency of alternating magnetization 50 Hz, the values of losses of alternating magnetization shown in Fig. 2 by points are obtained. There's also a solid line, which represents almost identical losses values for steel with the $A3$ designation from the work [11].

The use of the above-mentioned algorithms for calculating the losses by means of ANSYS requires the performance of a series of actions. The calculation is performed by using a nonlinear harmonic analysis. The time dependence of the harmonic currents changes of the specified sources (windings, bends) is given. Instantaneous values of losses in ferromagnetic bodies are calculated by integrating on the total volume (13) of specific eddy and hysteresis losses, and in those construction parts which are of nonmagnetic steel, the losses are determined only on account of eddy currents. When reaching a steady-state process, the non-linear functions of losses are averaged over a period of a given harmonic change of current. These procedures are implemented by specially designed macros for ANSYS.

The testing of the developed procedures was performed on a family of TEAM21 problems [9 – 11]. As is known, for TEAM21 problems the experimental installation of transformer type, containing two identical windings of rectangular cross-section with oppositely directed currents and frequency supply of 50 Hz, is used. At the outer surface of the windings there are plates of nonmagnetic (N) and/or ferromagnetic (M) steels, including those with cross-sectional cut or direct-axis cuts.

The calculations results of the mentioned test models TEAM21 with the use of the developed procedures are given in the **Appendix** of this paper. The obtained results confirm the accuracy of the developed practical procedures of simulation of electromagnetic fields and losses in the nonmagnetic and ferromagnetic bodies in the ANSYS, and the possibility of their application for the relevant calculations of transformer equipment.

Heating calculation. The basis for calculating the heating of the constructional elements of transformers and reactors are the values of volume losses. Thermal processes in the power transformer equipment with oil cooling are characterized by complex heat-exchange conditions of constructional elements with internal oil coolant and ambient air. The processes of losses and heating resolution are paired into the force of interdependence of thermal and electrical parameters. However, as previously mentioned, for the practice of engineering calculations, the execution of sequential calculations with iterative refinement of necessary parameters such as electromagnetic and thermal problems is valid.

With a known bulk density of losses Q in order to determine the body temperature θ with a thermal conductivity λ and heat-exchange coefficient α on the surface it is convenient to use the available procedures FEA of the thermal problem modeling in the form of Poisson's equation and with the boundary conditions on the surface with normal n

$$div(\lambda grad\theta)=-Q, \qquad -\lambda\,\partial\theta/\partial n=\alpha(\theta-\theta_0), \qquad (17)$$

where θ_0 − ambient temperature. If $\theta_0=0$, then the problem determines the increase of body temperature above the external medium.

In the practical calculations the heat-exchange coefficients α included in the boundary conditions (17) in the oil and air medium are determined by engineering dependencies of the form $\alpha=mq^n$ [1]. The surface density of the losses q can be both balanced, and/or on sites. The coefficients m and n depend on the body position (vertical, horizontal), type of cooling, parameters of the radiation and convection in the air [1].

Example of transformer calculation. Fig. 3 shows the computing model of single-phase autotype transformer with a tank capacity of 500 MVA, and Fig. 4 shows its active part. Three-dimensionality and finiteness of the sizes of MS, windings, constructional elements, magnetic shielding system are taking into account.

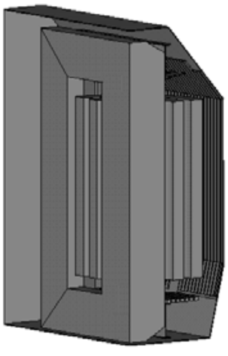


Fig. 3

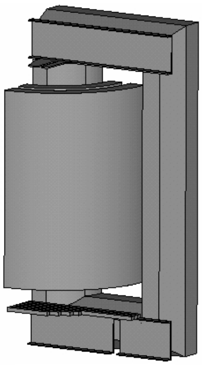


Fig. 4

For simplicity, MS is represented as a homogeneous body without special features simulation in the parts of burden revision of plates of electrotechnical steel. The rods and yokes are characterized by basic magnetization curve of electrotechnical steel. Along the normal to the flat surface of plates MS the magnetic permeability is determined by with consideration of the filling coefficient of steel, and is a constant.

The windings are represented with the actual distribution of magnetizing forces along their height in the form of zones of equal density of ampere turns. In the justified cases, equilibrium distribution of magnetizing forces is defined in the windings.

Upper and lower yoke beams have horizontal shelves of non-magnetic steel, and walls of ferromagnetic steel. The lower shelf of the upper beam has protrusions for winding pressing. The lower beams have vertical sections between the rod and side yokes.

Longitudinal and transverse shunts on the lower yoke beams are made of electrotechnical steel package. On the tank surface vertical magnetic shunts are mounted (see Fig. 3). Magnetic and electrical properties of computational models of shunts are described by magnetization curve of steel and its electrical conductivity.

When carrying out the calculation the symmetry property of construction relative to the vertical planes along the longitudinal and transverse axes of MS is used. The calculation is performed according to the method of volumetric losses.

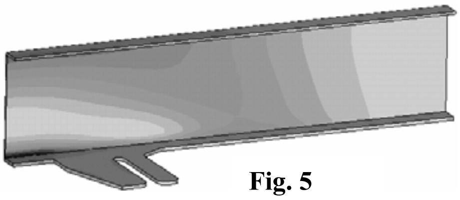


Fig. 5

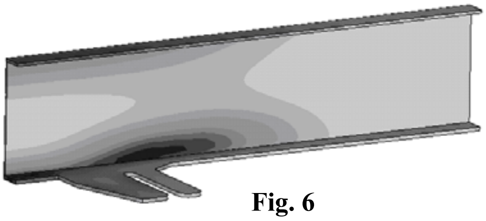


Fig. 6

The pattern of distribution of losses and temperature rises of parts of upper yoke beams above the ambient oil are shown in Fig. 5 and Fig. 6. The existence of notch in the protrusion of the lower shelf ensures the concentration limitations of eddy currents and losses in it..

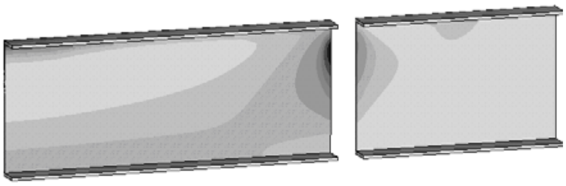


Fig. 7

Distribution of volumetric losses in the surface layer of lower yoke beams is shown in Fig. 7.

Lower loss rate can be seen on the part of lower yoke beam under the side yoke. Major losses are released in the beam under the rod. The presence of the vertical section of beam promotes the losses reduction.

The distribution of volumetric losses in the surface layer of tank without shunts is shown in Fig. 8. As shown in Fig. 9, the degree of local and total losses in the tank decreases at the presence of shunts. The obtained heat patterns of tank surface temperatures at the heat tests of transformer showed a close match of the results of calculations and measurements.

Calculations also determined that the calculated elementwise total additional losses in the construction of this transformer are close to the measured values.

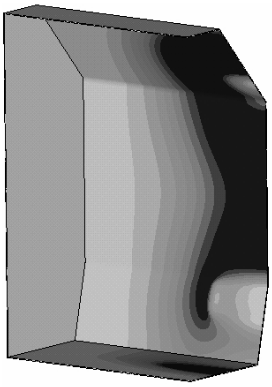


Fig. 8

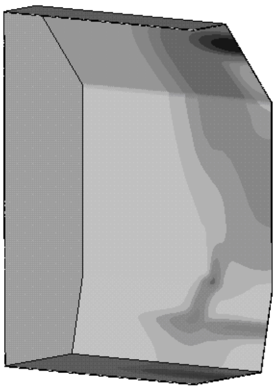


Fig. 9

Example of reactor calculation. The structures of electrical shunt reactors of ROM type with capacity of 80, 110 and 120 MVAr with gaps in the core of MS are studied by means of developed methods. As an example, Fig. 10 shows the calculating model of the 80 MVAr reactor. In the actual structure of reactor on the longitudinal walls of the tank the vertical shunts are mounted. To compare calculations results by means of the method of surface and bulk losses, the calculations are carried out for the model without magnetic shunts. The distribution of surface losses is shown in Fig. 11. Fig. 12 shows the distribution of volumetric losses in the surface layer of the tank walls. The calculations are qualitative and quantitative close to each other according to both methods.

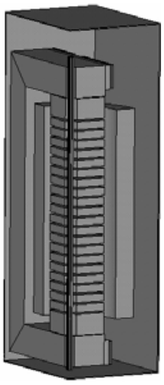


Fig. 10

Fig. 11

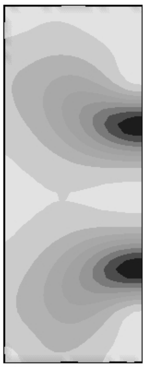


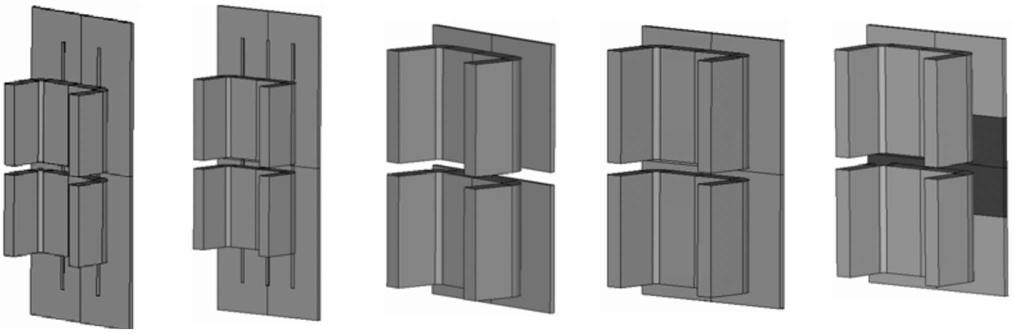
Fig. 12

For the actual structure, the total losses are determined in MS, in the tie rods of MS cores, in windings, in yoke beams, in the beams of given reactors, which showed close fit between the results of calculations and measurements.

Conclusion. The practical procedures for calculating the parameters of electromagnetic field, losses in the limited details of construction of computational models of transformer equipment of nonmagnetic and ferromagnetic steel, are developed by means of ANSYS software tools. The methods and software procedures verified on test experimental and computation data of the known family of TEAM21 problems are developed. The examples of practical calculations of transformers and reactors show that the developed procedures provide necessary accuracy of calculation of the local and total losses in the constructional elements, their heating, and are also applicable to elementwise calculation of total additional losses in construction.

Appendix. Verification of numerical procedures in TEAM21problems.

This article presents numerical models for continuous non-magnetic plate (P21^a-0), non-magnetic plates with one, two and three longitudinal cuts (P21^a-1, P21^a-2, P21^a-3), continuous ferromagnetic plate (P21-B), two plates of nonmagnetic and ferromagnetic steels (P21^b-2N, P21^b-2M), a combination of three welded plates: nonmagnetic-magnetic-nonmagnetic (P21^b-NMN) and welded plates in a different order (P21^b-MNM). These given models designation correspond to the models taken from works [9–11].

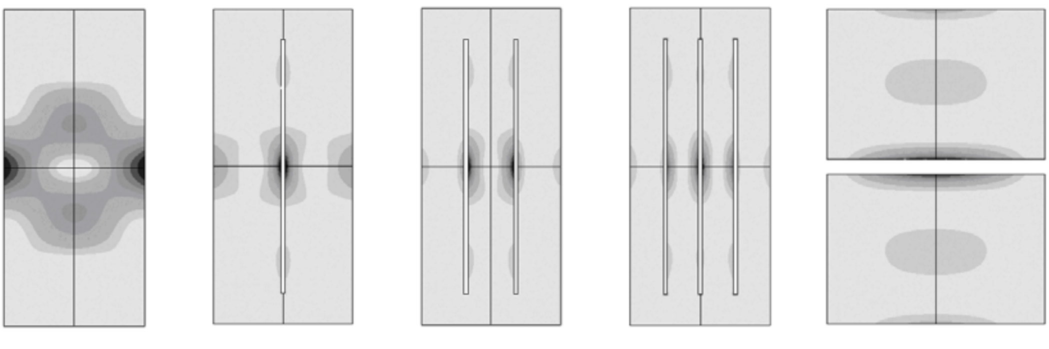


a) P21^a-2 **b) P21^a-3** **c) P21^b-2N, P21^b-2M** **d) P21-B** **e) P21^b-NMN, P21^b-MNM**

Fig. A.1

Fig. A.1 a) – e) shows the geometry of the basic computational models.

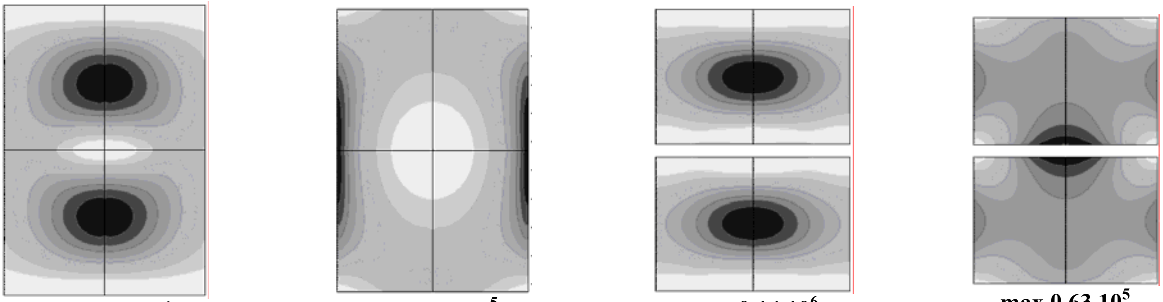
Calculation of the magnetic field, the bulk eddy losses in the models containing only non-magnetic plate is formed in ANSYS using the method of linear harmonic analysis. The distribution of volumetric losses (W/m^3) in non-magnetic plates of different configura-



max $0.18.10^5$ a) P21^a-0 **max $0.18.10^5$ b) P21^a-1** **max $0.14.10^5$ c) P21^a-2** **max $0.87.10^4$ d) P21^a-3** **max $0.10.10^5$ e) P21^b-2N**

Fig. A.2

ferent configuration is shown in Fig. A.2 a) - e). Under the figures, the maximum values of losses given to compare the results of models calculation instead of the usual scale in ANSYS are given.



max $0.23.10^6$
a) P21-B
front surface

max $0.62.10^5$
b) P21-B
back surface

max $0.14.10^6$
c) P21^b-2M
front surface

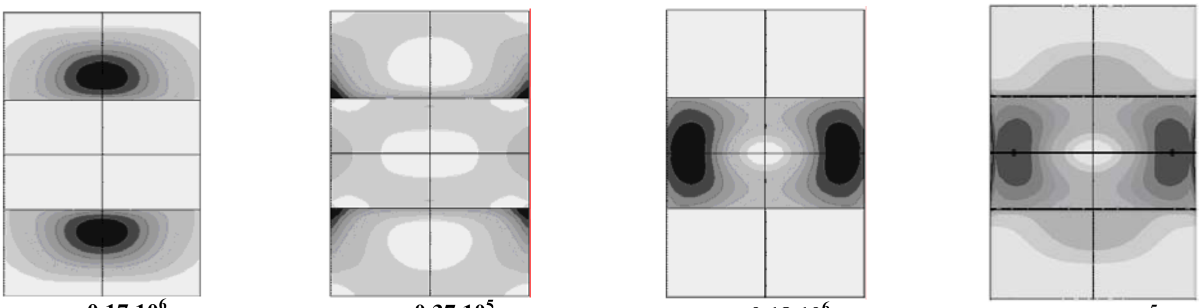
max $0.63.10^5$
d) P21^b-2M
back surface

Fig. A.3

In particular, the comparison of Fig. A.2 a) - d) shows a known fact of a significant reduction of losses in non-magnetic plates (for example, on lifting plates of MS cores of transformers) by performing longitudinal cuts.

The calculation of magnetic field, volumetric eddy and hysteresis losses in the models with magnetic plates is performed in ANSYS using nonlinear harmonic analysis and using practical procedures of calculation of volumetric eddy losses and hysteresis losses represented in the main part of this work. The distribution of volumetric losses (W/m^3) in the surface layer for the magnetic plates is shown in Fig. A.3 a) - d). The major part of the distributed losses is centered on the front surface facing to the windings, and on the back surface of plates there is a current "wicking" on the small area at the edge of plates.

Calculation of the combined models of plates with magnetic and non-magnetic elements is also performed by using a nonlinear harmonic analysis ANSYS. The distribution of volumetric losses on the front and back surfaces of the plates is shown in Fig. A.4 a) - d).



max $0.17.10^6$
a) P21-MNM
front surface

max $0.37.10^5$
b) P21-MNM
back surface

max $0.18.10^6$
c) P21^b-NMN
front surface

max $0.16.10^5$
d) P21^b-NMN
back surface

Fig. A.4

Model	Fig.	Eddy current calculated losses (P_e), hysteresis (P_h), total P_Σ , W				Measured total losses [9–11], W	Calculation error, %
		Nonmagnetic plate	Ferromagnetic plate		Total losses		
		P_e	P_e	P_h	P_Σ ,	$P_{изм}$	ε
P21^a-0	P.2	9.39	-	-	9.39	9.17	2.4
P21^a-1	P.2	3.18	-	-	3.18	3.40	-6.5
P21^a-2	P.2	1.67	-	-	1.67	1.68	-0.6
P21^a-3	P.2	1.04	-	-	1.04	1.25	-16.8
P21^b-2N	P.2	1.34	-	-	1.34	1.38	-2.9
P21^b-2M	P.3	-	6.69	2.16	8.85	9.34	-5.2
P21-B	P.3	-	8.58	2.74	11.32	11.97	-5.4
P21^b-MNM	P.4	4.62	3.16	1.07	8.85	10.53	-16.0
P21^b-NMN	P.4	1.90	3.47	1.10	6.47	7.44	-13.0

On the front surfaces of magnetic plates, the surface densities of volumetric losses are much greater than the density of losses in the non-magnetic plates. On the back surfaces of welded plates, the surface densities of losses in the plates of non-magnetic and magnetic steel are comparable with each other. The mentioned features must be considered, for example, when calculating the losses in composite yoke beams, the parts of which are welded together from the parts of different types of steel.

The comparison of the total measured and calculated values for the TEAM 21 problems is shown in Table.

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ЧИСЕЛЬНЕ МОДЕЛЮВАННЯ ВТРАТ І НАГРІВІВ В ЕЛЕМЕНТАХ КОНСТРУКЦІЇ ТРАНСФОРМАТОРІВ З ФЕРОМАГНІТНОЇ СТАЛІ

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В роботі розглянуто застосування методів розрахунку поверхневих і об'ємних втрат в елементах конструкції трансформаторів з феромагнітної сталі. Подано короткий опис розроблених практичних процедур їхнього розрахунку із застосуванням програмного забезпечення ANSYS. Наведено результати тестування запропонованих процедур на відомих експериментальних дослідженнях TEAM21, а також приклади розрахунку втрат і нагрівів в елементах конструкції однофазного автотрансформатора потужністю 500 МВА і реактора типу РОМ потужністю 80 МВАр. Бібл. 16, табл. 1, рис. 16.

Ключові слова: потужний трансформатор, втрати, нагрів, тривимірне моделювання.

ЧИСЛЕННОЕ МОДЕЛИРОВАНИЕ ПОТЕРЬ И НАГРЕВОВ В ЭЛЕМЕНТАХ КОНСТРУКЦИИ ТРАНСФОРМАТОРОВ ИЗ ФЕРРОМАГНИТНОЙ СТАЛИ

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В работе рассмотрено применение методов расчета поверхностных и объемных потерь в элементах конструкции трансформаторов из ферромагнитной стали. Дано краткое описание разработанных практических процедур их расчета с применением программного обеспечения ANSYS. Приведены результаты тестирования предложенных процедур на известных экспериментальных исследованиях TEAM21, а также примеры расчета потерь и нагревов в элементах конструкции однофазного автотрансформатора мощностью 500 МВА и реактора типа РОМ мощностью 80 МВАр. Библ. 16, табл. 1, рис. 16.

Ключевые слова: мощный трансформатор, потери, нагрев, трехмерное моделирование.

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