УДК 621.314

LOSSES, HEATING IN TANK COVERS OF TRANSFORMERS

[1] **A.V.Basova,** [1]**V.F.Ivankov,** [2]**I.V.Khimjuk**
[1] – PJSC "Zaporozhtransformator",
Dnipropetrovske shose, 3, Zaporizhia, 69600, Ukraine.
[2] – Institute of Electrodynamics of National Academy of Science of Ukraine,
Peremogy, 56, Kyiv-57, 03680, Ukraine,
e-mail: vsi@ied.org.ua

The main approaches to analytical estimations and three-dimensional modeling by finite element method of electromagnetic and thermal processes in the tank covers using ANSYS software are presented. The results of an investigation of three-dimensional constructions of tank covers of three-phase transformers taking into account not only the magnetic fields in taps, but also the leakage fields in windings, are provided. Referances 6, figures 16.

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

1. Introduction. Up to date in the development of powerful transformers the problems of tanks protection from the intensive leakage magnetic fields in the windings and taps remain urgent. To reduce the losses in the tanks' zones of structural ferromagnetic steel, the electromagnetic screens of copper and aluminum, the magnetic screens of electrical steel packages (shunts) are traditionally used [1].

The detailed analysis of the papers devoted to the problems of experimental investigations and the development of methods for calculating losses and heating in tanks and other parts of transformers is presented in [2]. Thus the problem of designing an optimal structure of tank cover in the zone, where the taps with considerable currents are located, is one of the most complex problems so far.

In [3] it is shown that under the existing overall restrictions the combination of measures is effective. These are the optimal construction execution of windings and taps, the application of electromagnetic screens, the development of tanks' covers and walls of non-magnetic steel, the optimal taps location relative to the holes in input boxes' covers. Also, the effectiveness of eddy currents reducing is demonstrated by arranging the electrical steel package on nonmagnetic cover. The packages are perpendicular to the taps, and their length is less than the width of cover. This is the difference between these packages and traditional shunts on the ferromagnetic tank walls.

Results given in [3] are based on the data received from transformers testing, experimental investigations of physical analogues, and design analysis of basic computable models [4].

The models that allow the analytical solutions are plate models of nonmagnetic steel in the preset field of free taps that contact with ferromagnetic electrical steel packages periodically distributed on the plate surface with circular cutouts to output the taps from the tank.

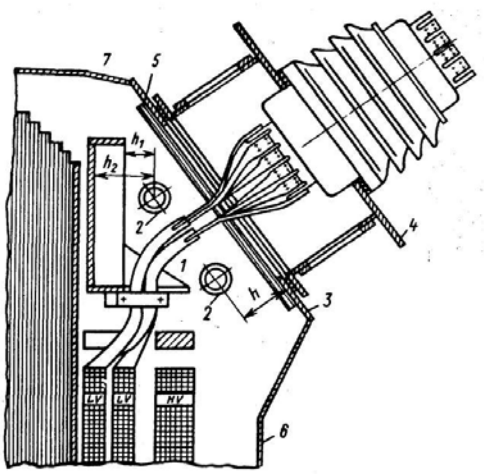


Fig. 1

In order to define the main factors influencing the problem statement of complex analysis using finite element method (FEM) a brief description of the mentioned models is provided in the paper. Also the investigation results of electromagnetic and thermal processes in the three-dimensional construction of transformer's tank cover taking into account either the magnetic field in taps and the leakage fields in windings are given. When investigating the FEM-modeling represented in [5] was used.

The cross-section of the top of high-power transformer is shown on the Fig. 1, where: *1* – winding taps' sections of lower voltage (LV) perpendicular to the tank cover; *2* – horizontal sections of LV taps of adjacent phases; *3* – non-magnetic insert; *4* – LV bushing box; *6* – ferromagnetic tank wall; *7* – ferromagnetic tank cover. When doing an analytical analysis a given construction determines the necessity of consideration of several boundary problems for infinite plates with different conductivities; plates contacting with ferromagnetic ones; rectangular plate with discrete packages of silicon-sheet steel; plates with circular holes; and so on.

2. Mathematical statement of analytical problems. In [4] for the nonmagnetic plate with thickness d, electrical conduction σ and tangent to plate surface of electric field component $\dot{\vec{E}}_{\tau}$, the surface current density is determined as $\vec{j}_\tau = d\sigma\vec{E}_\tau$, and for ferromagnetic plate it is determined as $\vec{j}_\tau = \dot{\vec{E}}_\tau / \dot{Z}$, where $\dot{Z}$ is the surface impedance. To determine the eddy currents, the potential U is introduced to $\vec{j}_\tau = rot(\bar{n}U)$, where $\bar{n}$ is plate normal. From Maxwell equations at excitation with a circular frequency $\omega = 2\pi f$ and $\partial/\partial t = -i\omega$ the U will get such Poisson's equations as: in nonmagnetic plate – $\Delta U = -i\omega d\sigma B_n$, in ferromagnetic – $\Delta U = -i\omega B_n / \dot{Z}$, where B_n is normal magnetic field component of plate surface.

For the basic models under consideration the boundary conditions are determined. At the outer contour l that conducts bodies the normal eddy current component is missed, i.e. $\partial U / \partial l = 0$. If there are cutouts with contour L, the tangent integral to the contour of electric field intensity component is linked in the nonmagnetic plate with the external field flow Φ_n, that enters this contour area by normal $\oint_L (\partial U/\partial n) dl = i\omega d\sigma\Phi_n$. On the line l of the contact of nonmagnetic plate with ferromagnetic continuity regarding the field E_l, the condition for potential $d^{-1}\sigma^{-1}\partial U / \partial n\big|_{l+0} = \dot{Z}\partial U / \partial n\big|_{l-0}$ is determined.

Contacting infinite plates. The draft of a computing model is shown on Fig. 2.

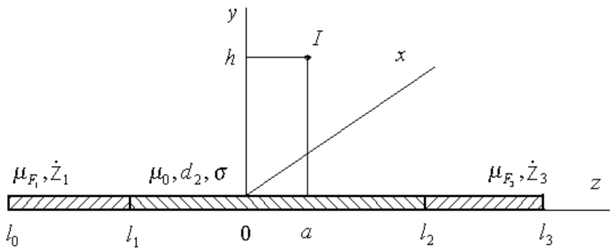


Fig. 2

The nonmagnetic plate with d, σ parameters contacts in a butt joint with two parts of constructional ferromagnetic steel with impedances $\dot{Z}_1$, $\dot{Z}_3$. The tap field with the current I at the plate surface $y = 0$ is $B_n(z)2\pi = I\mu_0 z_a / (h^2 + z_a{}^2)$, where $z_a = z - a$.

On the basis of mathematical statement in the p. 2.1 the solution of one-dimensional boundary-value problem for this model is given in [4]. The particular case of this model is the model of infinite free plate.

2.1. Eddy currents in the nonmagnetic plate with the electrical steel packages on its surface. In [3] by physical model investigations it is shown that in this case directly on the plate the exciting filed between the packages insignificantly differs from the tap's primary field, while under the packages the field reverses its direction to an opposite one. It can be explained by an edge effect of discrete pack, the length of which is less than width l of nonmagnetic plate (Fig. 3). Thereby, the field on the plate in the areas $k = 1,...,K$ can be represented as a piecewise constant function $B_n(x,z) = B_{n,k}(z)$.

For potential U the equation $\Delta U = P$ with conditions on the outer boundary $U\,|_\Gamma = 0$ takes place. In the areas between the packages and under them $t_k = (x_{1,k}; x_{2,k})$, $P_k = -i\omega d\sigma B_{nk}(z)$. It is assumed that the field distribution in each area can be represented as a periodic function, that is why in [4] the problem solution is represented as $U = \sum_{m=1}^{\infty} U_m(x) \sin \nu_m z$, where $\nu_m = m\pi / l$.

The coefficients U_m are the problem solutions

$$\frac{d^2 U_m}{d x^2} - \nu_m^2 U_m = \begin{cases} 0, & x \notin t_k \\ -i\,\omega d\sigma B_{m,k}, & x \in t_k \end{cases}; \qquad U_m\big|_{x=0,b} = 0,$$

where $B_{m,k}$ are the expansion coefficients in Fourier series of the distribution $B_{n,k}(z)$. The components of the eddy current are defined by $j_x = \partial U / \partial z, \quad j_z = -\partial U / \partial x.$ ratios.

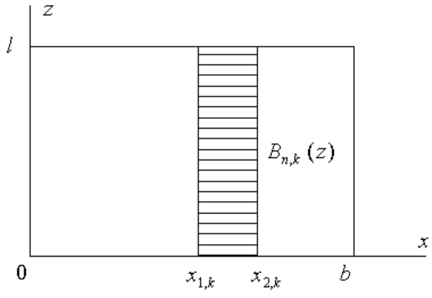


Fig. 3

2.2. Nonmagnetic plate with circular cutout. For the purpose of assessment of the circular cutouts influence on the eddy current distribution in nonmagnetic plate the model showed in Fig. 4 is considered. Following the statement from p. 2.1, the boundary-value problem for the potential U can be represented as $\Delta U = -i\omega d\sigma B_n$, $U\,|_\Gamma = 0$, $U\big|_L = \breve{C}$, $\int_L (\partial U / \partial n) dl = -\sigma d \int_S i\omega B_n\, ds$. Its solution is represented as the sum of $U = U^{(0)} + W$ where $U^{(0)}$ is the problem solution for infinite nonmagnetic plate and is a particular case of

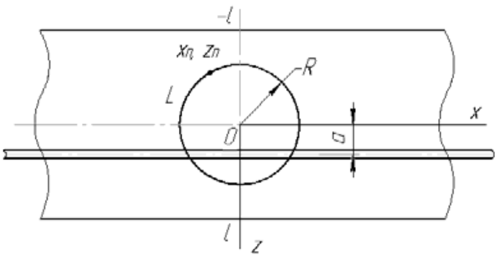


Fig. 4

the p. 2.1 model. An additional potential W is defined from the solution of boundary-value problem such as Laplace's equation $\Delta W = 0$ with boundary conditions on the plate sides $W\big|_{z=l,-l} = 0$, with symmetry conditions $\partial W / \partial x\big|_{x=0} = 0$, and with conditions on a contour L of the internal cutout $W\big|_L = \breve{C} - U^{(0)}$, $\int\limits_L \frac{\partial W}{\partial n} dl = 0$. The value of additional potential is represented as the sum of $W(x,z) = \sum\limits_{n=1}^{N} A_n G(x,z,x_{n,} z_n)$, where the Green function $G = \sum\limits_{m=1}^{\infty} m_l^{-1} S_m(z) S_m(z_n) \exp(-m_l |x - x_n|)$, when $m_l = m\pi/(2l)$, $S_m(z) = \sin m_l(z+l)$, $S_m(z_n) = \sin m_l(z_n + l)$, $m_l = m\pi/(2l)$. The coefficients A_n and constant $\breve{C}$ are found with collocation method at the x_n, z_n points of the *R* circumference. The eddy currents in the plate with a cutout are $j_x = j_x^{(0)} - \partial W / \partial z$, $j_z = \partial W / \partial x$.

In [4] the statements and numerically-analytical solutions of boundary problems for rectangular insert-plate in the tank cover with a circular cutouts system, for the plate with cutouts and packages of silicon-sheet steel, and for the specified plates that additionally contact with ferromagnetic tank parts, were also considered.

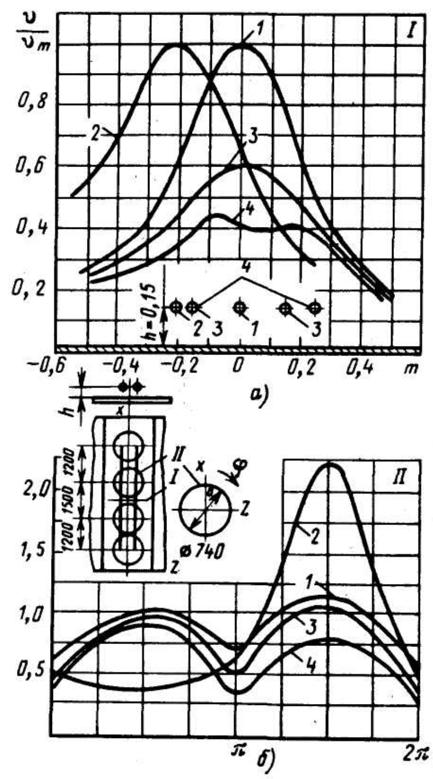


Fig. 5

3. Investigation of eddy currents and taps' losses on the full-scale model in the tank For the purposes of investigation of tank cover heat for different variants of high-current taps locations, the experimental investigations on the full-scale model of transformer tank cover with 1000 MVA power were conducted. The model corresponded to the draft on Fig. 1, but without the imitation of magnetic system and windings. The tap current was 14 kA. The distance from tap axis to the cover surface was 0.15 m.

Measured by thermocouple the heats of non-magnetic plate inserts along the line I between two pairs of holes are shown on the Fig. 5,*a*). The graphs and draft signs correspond to four variants of taps implementation and location: *1* – the tap passes above the axis of holes, *2* – the tap is shifted 0.15 m to the left, *3* and *4* – two split taps with the half-current in each one pass above the plate. The overheating of the cover's non-magnetic area over the ambient temperature relative to the most heated spot of the area between cutouts (ϑ = 93°C) is shown on the graphs.

The temperatures' distribution along the perimeter of circular hole II for the given cases of taps' implementation and location is shown on the Fig. 5, *b*).

As the non-magnetic steel used for making the tank cover insert possesses a low thermal conductivity, the heat distribution has a sharply non-uniform nature that corresponds to the eddy currents distribution.

In case of tap shifting the heating between holes and on the edge of the hole redoubles as compared to the case, when the tap passes above the hole axis – see the graphs *1* and 2, Fig. 5. The nature of losses' distribution similar to the temperatures' distribution mentioned above was obtained [7] by calculation using analytical models from p.2.3.

4. Investigation of specific physical models. It should be mentioned that full-scale model investigations under the weight of all influence factors, didn't allow differentiating the influence degree of main factors, that required the experimental investigations on specific physical models.

4.1. Model of contacting plates. On the Fig. 1 it is shown that the non-magnetic steel insert is welded into ferromagnetic conductive tank wall. The influence of ferromagnetic areas of the tank wall was determined on the model on Fig. 6, in which the ferromagnetic plates were welded to non-magnetic sheet. On the Fig. 6 the line with points corresponds to the field of surface in the air corresponded to the plates' location.

The measured value of normal component of magnetic field induction to the plate surface is shown by solid line. The local field jump is observed on the contact border of non-magnetic and ferromagnetic plates. The calculation results using the model from p.2.1 are shown on the Fig. 6 by dashed line. The differences between calculations and measurements are determined by simplifications of the ferromagnetic plate model, particularly of its magnetic parameters.

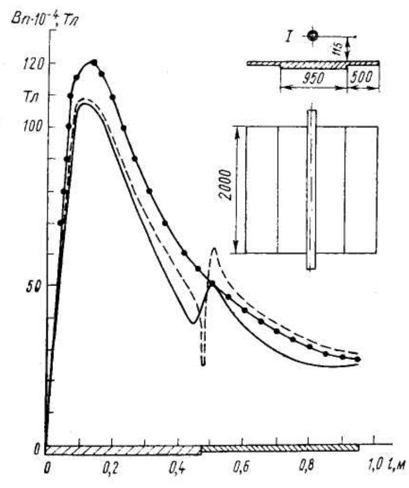


Fig. 6

4.2. Plate model with silicon-sheet steel packages. A physical model on the Fig.7 is investigated. According to the investigations the main effect consists in particular formation of magnetic field on the plate surface by means of finite sizes and discrete location of ferromagnetic packs on this plate [1].

The field on the plate surface depends on the packages sizes, their mutual location between each other, the correlation between package length and distance to the tap, and also on the magnetic condition of packages steel. The measurements by the gaps t between packages 0; 0,1; 0,16; 0,3 m are shown by solid lines *0*, *1*, *2*, *3*. The data describing normal component of magnetic field induction to the plate surface is shown on the Fig. 7: for the upper package surface B_{nH} faced to the tap (on the top of the figure); in the gap between packages B_{n3} (in the middle of the picture); under packages B_{nH} (in the lower part). The normal component of magnetic induction that is on the surface of non-magnetic insert under the packages gets the direction opposite to the direction of induction between packages.

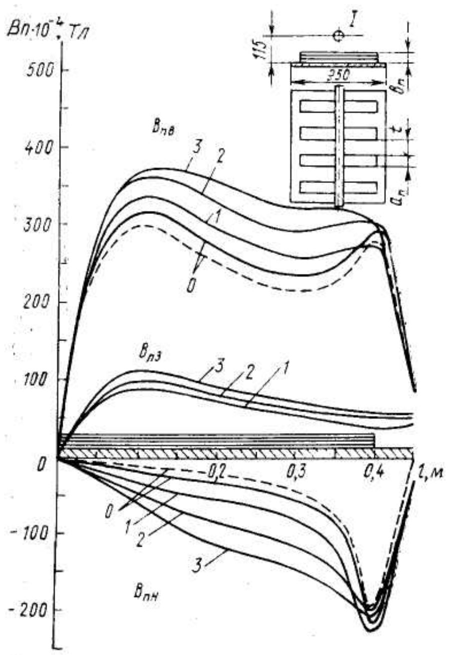


Fig. 7

Thereby, the magnetic field on the surface of insert with the packages obtains an alternating-sign behavior along the tap axis that results in the splitting of eddy currents, and, finally, in reducing the losses and heating in the middle of the plate. The insignificant concentration of field and losses can be found on the packages' ends.

For the analytical analysis of the distribution of eddy currents and losses the calculation model from p. 2.2 is used.

5. Problem statement for the computational investigations of FEM. The transformers electromagnetic processes, neglecting the shift currents, are described by the system of Maxwell's equations [5, 6, 8] $rot\overline{H} = \overline{j}$, $rot\overline{E} = -\partial B/\partial t$. The vectors of electric and magnetic fields, magnetic induction $\overline{E}, \overline{H}, \overline{B}$, and current density vector $\overline{j}$ are bounded to each other by constitutive equation $\overline{j} = \sigma\overline{E} + \overline{j}^{cm}$, $\overline{B} = \mu\overline{H}$, where σ is electrical conductivity, $\overline{j}^{cm}$ is a vector of extraneous currents density (of windings and taps), μ is magnetic conductivity. The relationship between $\overline{B}$ and $\overline{H}$ is complex, non-linear, and hysteresis for ferromagnetic mediums, and anisotropic for laminated ones.

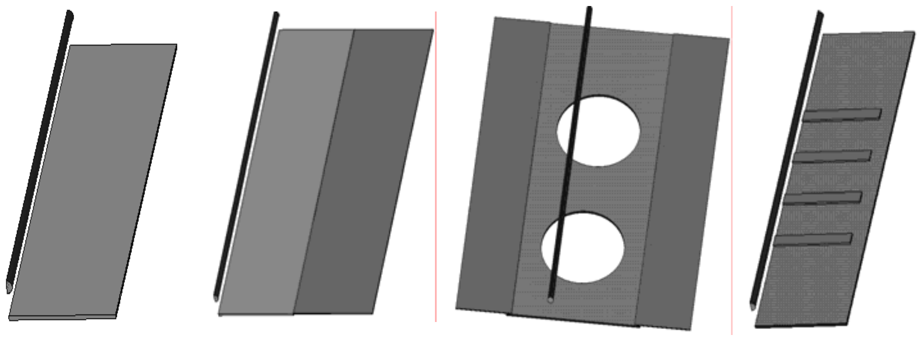
The computational modeling of considered electromagnetic problems was made by means of ANSYS software [9] using magnetic vector potential $\overline{A}$ defined by $\overline{B} = rot\overline{A}$ equation.

Heating calculation problem is a complex problem of conjugate analysis of electromagnetic processes and heat-and-mass transfer processes in cooling oil medium in tank, as well as from the ambient air side. In the current paper a slightly simpler heating analysis based on the empirical coefficients of heat transfer into the cooling medium of oil and air is considered. In this case the heat problem to determine a body temperature θ with bulk loss power Q, thermal conductivity λ, surface heat-emission coefficient α, and ambient temperature θ_0 can be formulated as Poisson's equation $div(\lambda grad\theta) = -Q$ with inhomogeneous surface conditions $-\lambda\partial\theta/\partial n = \alpha(\theta - \theta_0)$. The iterative refinement of the scale of electrical conductivity of steel of non-magnetic insert and heat-transfer coefficients of temperature provides the cohesion of numerical analysis of electromagnetic and thermal processes in the covers of transformers tanks.

The obtained variational statements of proper elliptic equations, their finite-element approximation; assignment of boundary conditions; solution of systems of finite-element equations, including non-linear ones are described in detail in the manuals [6]. Therefore, this research represents only necessary explanatory notes to computable models developed by using ANSYS resources.

6. Computational investigations of physical models. The full-scale and physical models, which were previously considered, are investigated to verify the developed by ANSYS procedures of modeling magnetic field, losses, and heating in transformer tank covers. The drafts of computational models in ANSYS are shown on Fig. 8.

6.1. Model of non-magnetic plate. The physical model from the Fig. 8, *a*) is considered. The distribution of $\mathrm{Im}\,\dot{\delta}$ component of eddy currents in plate (real component is negli-gibly small) is shown on the Fig.9, *a*). The measured (solid lines) and estimated values of magnetic induction modules $\left|\dot{B}_m(x)\right|$ and eddy currents density $\left|\dot{\delta}(x)\right|$ on the middle of the half of non-magnetic plate are shown on the Fig. 9, *b*).

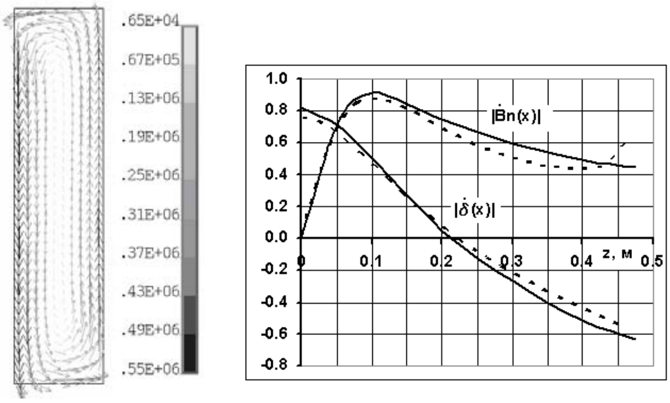


a ***b*** ***c*** ***d***

Fig. 8

6.2 Plate model contacting with ferromagnetic ones. The physical model from the Fig. 8, *b*) is considered. The distribution of eddy currents in plate is shown on the Fig. 10.

When calculating the ferromagnetic plate was divided non-uniformly in thickness to provide computational modeling of surface effect. The non-linear magnetic characteristic of structural steel was taken into account. The calculation was made by using transient analysis [6].



a ***b***

Fig. 9

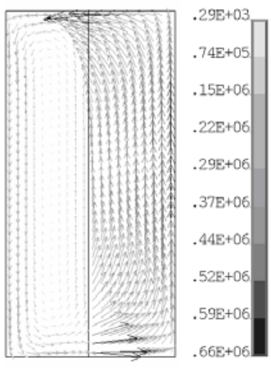


Fig. 10

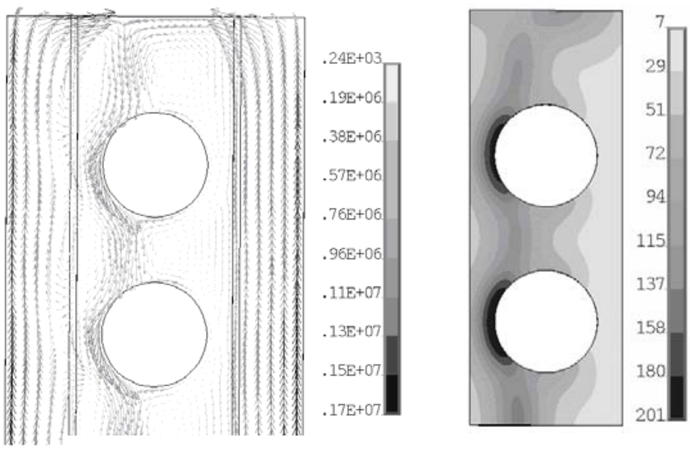
6.3. Plate model with cutouts. The symmetric half of the full-scale model from the Fig. 5 is shown on the Fig. 8,*c*). The axis projection of current distributor to plate is shifted relative to the holes centers in non-magnetic plate, contacting with ferromagnetic ones.

The vectors of eddy currents on non-magnetic part of model, and on two parts conjugated with non-magnetic plate of ferromagnetic steel are shown on the Fig.11, *a*). The eddy currents are concentrated non-uniformly under projection shift of current distributor relative to the centers of circuit cutouts. The estimated distribution of temperature excursions shown on the Fig. 11, *b*) also has a sharply non-uniform character. The heating distribution practically corresponds to the measurements shown on the Fig. 5. The calculation of eddy currents, and losses is made by a harmonious analysis [6], whereas the heating calculation is made according to the algorithms specified in p. 5.

6.4. Model with silicon-sheet steel packages. The physical model from the Fig. 7 is considered.

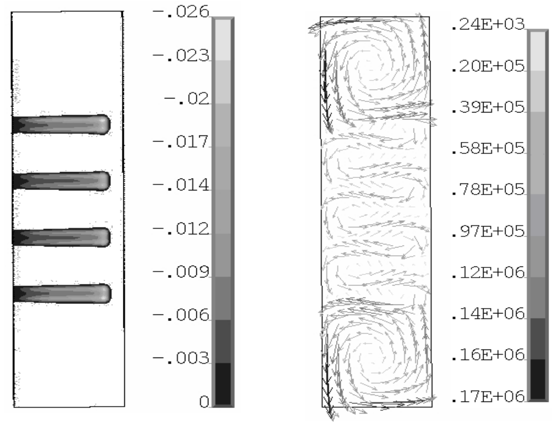
The draft of computational model for one of the variants of packages location is shown on the Fig. 8,*d*). ANSYS calculations are carried-out using harmonic analysis method. The anisotropy of silicon-sheet steel packages located flat wise on the plate is taken into account.

The normal component of magnetic induction that is under the packages obtains the direction opposite to the direction of induction between the packages. The field on plate with a positive direction of induction, is filled with white color, and the shaded areas correspond to the field with reverse direction (see Fig. 12, *a*)). The given character of the field alteration under packages is shown by measurements (see Fig. 7). Local field alteration results in subdivision of eddy currents and, finally, in reduction of losses and heating in the middle of plate.



a *b*

Fig. 11



a *b*

Fig. 12

The distribution of eddy currents $\mathrm{Im}\,\dot{\delta}$ is shown on the Fig. 12, *b*).

The modeling results of magnetic fields, eddy currents, losses, heating in the investigated full-scale and physical models confirmed the reliability of approaches and procedures, developed by ANSYS, and the validity of theirs application for transformers complex models investigation.

7. Computational modeling of the unifying three-dimensional models of transformers. Let's describe a practical methodology based on the application of ANSYS software by an example of unifying three-dimensional model of 630 MVA three-phase transformer. Because of symmetry, the model is designed for ¼ part of the structure obtained from the dissection of the transformer's longitudinal axis and in the middle of the windings' height. The view from the outside of the tank is shown on the Fig. 13.

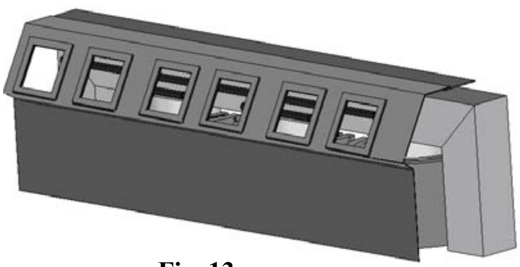


Fig. 13

The model consists of nonmagnetic tank part and adjacent ferromagnetic parts of the tank cover and walls. The model contains geometry of the taps' level sections, simplified model of three-rod magnetic system with the windings of lower and upper voltage on each bar. In the areas against the windings the tank vertical wall is closed with three groups of vertical magnetic screens in the forms of local shunts of electric steel packages. The model contains the geometry of cutouts, and flanges for the fastening of inlet boxes.

The input parameters are the density of magnetizing ampere-turns by winding sections with the connection to the phase shifts of three-phase excitation. The winding currents only have a circular component in the system of cylindrical coordinates of each bar. The currents in the taps, also with connection to the phases of windings excitation are oriented relative to the specified current phases in windings. The features of magnetic system are taken into consideration as a near-constant value of magnetic permeability (as of electric steel magnetizing in nominal operating mode). Also the magnetic permeability of each of the shunt packages with account taken of their anisotropy and preliminary estimate of their magnetizing, are specified in the form of constants. According to the results of preliminary calculations the specific conductivity value of the cover areas of nonmagnetic steel with account taken of expected temperature level in these areas is specified.

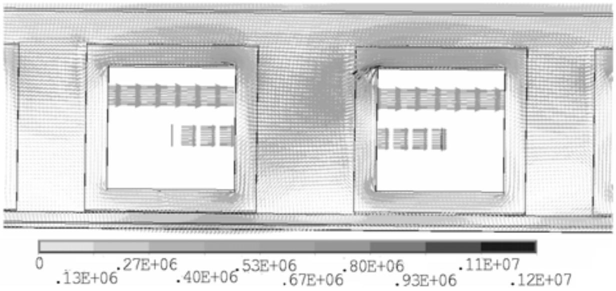


Fig. 14

The ferromagnetic areas of cover and tank walls are simply modeled with account taken of surface effect. On the strained areas of cover the necessity and optimal number, and the sizes of electric steel packages served for local limitation of losses and heating at nonmagnetic areas of cover are specified by preliminary calculations.

Thereby, the complex model takes into consideration the combined eddy currents in nonmagnetic and contacting with them ferromagnetic areas of tank cover and walls, the availability of local packages on nonmagnetic area of the cover, and the availability of the cutouts.

The calculation in ANSYS was made by using harmonic analysis method. The vectors distribution of imaginary component of eddy currents in non-magnetic insert of tank is shown on the Fig. 14.

The temperatures' distribution of non-magnetic insert to the transformer tank is presented on the Fig. 15. The computational modeling results satisfy the temperatures distribution patterns, obtained from thermal imager during thermal tests of transformer (Fig. 16).

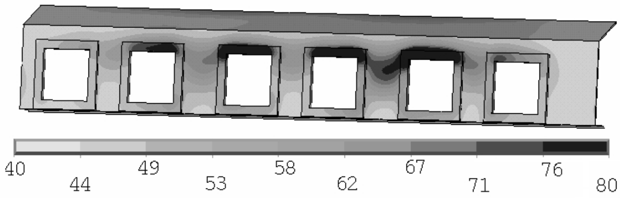


Fig. 15

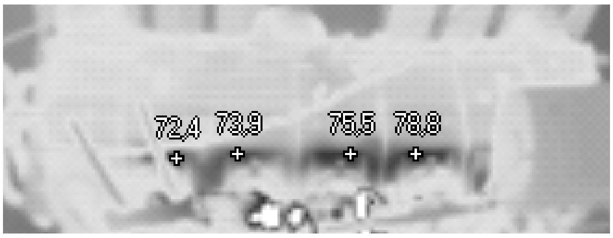


Fig. 16

Conclusion. The carried out investigations describe the main factors, which were studied experimentally on full-scale, and physical models. These investigations also show the influence of such factors on electromagnetic and thermal processes in tank covers of power transformers. The reliability of developed methods of analytic analysis and procedures of ANSYS computational modeling of magnetic field, eddy currents, losses, and heating of transformer tank covers, caused by the currents of windings, outlets and taps is shown.

1. *Turowski J.* Obliczenia elektromagne-tyczne elementow maszyn i urzadzen elektrycznych. − Warszawa, 1982. − 316 p.

2. *Kulkarni S.V. Khaparde, S.A.* Transformer Engineering. Design and Practice. − Marcel Dekker, Inc., New York 0 Basel, 2004. – 477 p.

3. *Furman Ja.I., Bereza V.L., Ivankov V.F., Nizhnik L.P.* Losses in tanks of large power transformers. caused by magnetic field and methods of their reduction // CIGRE 1988, Paper No. 12−07.

4. *Nizhnik L.P., Bereza V.L., Ivankov V.F., Furman Ja.I.* Vortical currents and losses in the tank of transformer from magnetic-field of taking. − Kyiv: Instytut matematyky AN USSR .– 1985. − 46 p. (Rus.)

5. *Basova A.V., Ivankov V.F., Kokoshyn S.S., Khimjuk I.V.* Numerical research of the electromagnetic fields in powerful transformers and reactors // Przeglad Elektrotechniczny, CPEE 2007. − No 2. − Pp. 261−264.

6. ANSYS software // http://www.ansys.com.

УДК 621.314

ВТРАТИ, НАГРІВ У КРИШКАХ БАКІВ ПОТУЖНИХ ТРАСФОРМАТОРІВ

[1]Басова А.В., [1]Іванков В.Ф., [2]Хімюк І.В.
[1] ПАТ "Запоріжтрансформатор",
Дніпропетровське шосе, 3, Запоріжжя, 69600, Україна;
[2] Інститут електродинаміки НАН України,
пр.Перемоги, 56, Київ-57, 03680, Україна. e-mail: vsi@ied.org.ua

Представлено основні підходи до аналітичних оцінок і тривимірного моделювання методом скінчених елементів електромагнітних і теплових процесів в областях кришок бака з використанням програмного забезпечення ANSYS. Наведено результати досліджень тривимірних конструкцій кришок баків трифазних трансформаторів, що враховують не лише магнітні поля відведень, але і поля розсіювання обмоток. Бібл. 6, рис. 16.

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

ПОТЕРИ, НАГРЕВ В КРЫШКАХ БАКОВ МОЩНЫХ ТРАНСФОРМАТОРОВ

[1]Басова А.В., [1]Иванков В.Ф., [2]Химюк И.В.
[1] ПАТ "Запорожтрансформатор",
Днепропетровское шоссе, 3 Запорожье, 69600, Украина;
[2] Институт электродинамики НАН Украины,
пр.Победы, 56, Киев-57, 03680, Украина. e-mail: vsi@ied.org.ua

Представлены основные подходы к аналитическим оценкам и трехмерному моделированию методом конечных элементов электромагнитных и тепловых процессов в областях крышек бака с использованием программного обеспечения ANSYS. Приведены результаты исследований трехмерных конструкций крышек баков трехфазных трансформаторов, учитывающих не только магнитные поля отводов, но и поля рассеивания обмоток. Библ. 6, рис. 16.

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

Надійшла 13.12.2012
Received 13.12.2012