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METHODS VERIFICATION FOR ELECTROTHERMAL CALCULATIONS OF ELECTRIC REACTORS WITHOUT STEEL

Based on the example of the reactor without steel, type ROM-510/26 with electromagnetic shields, verification of analytical and numeral finite-element methods is carried out by the calculation results comparison. For the purpose of corrected analytical calculation, horizontal and vertical shields of the reactor are represented by the system of short-circuited elements to consider their final dimensions. Calculation is performed as to their inductances, distribution of currents and losses in the shields, magnetic-field and losses in winding, calculation of winding heating by means of the «overheating» empirical method. It is illustrated that analytical calculations correspond to the researches using numeral methods of the electromagnetic and thermal CFD-analysis with sufficient accuracy. For the purpose of practical application in industrial designing of the equipment, the methods with approved and checked measurement results are recommended.

Key words: *reactor, electromagnetic shields, electro-thermal calculations*

INTRODUCTION

Power electrical reactors for AC and DC HV transmission lines are distinguished by a great variety of design selected with consideration of their functional purpose, required capacity and voltage class [1]. In particular, three-phase and single-phase smoothing shunt and current-limiting ironless reactors equipped with electromagnetic shields are widely used. In case of three-phase reactor, shielding is performed for each of the windings, so the main features of electromagnetic and thermal processes could be analyzed using the single-phase reactor as an example, particularly the reactor type ROM-510/26.

The reactor winding is subdivided by vertical cooling channel into inner cooling channel (IC) and outer (OC) concenters designated in Fig. 1a as (1-1) and (1-2). The reactor comprises the top (TS) and the bottom (BS) horizontal (2) and vertical (3) shields. Steel clamping plates (4) and cylindrical tank (5) are manufactured from structural ferromagnetic steel. Oil flowing is directed by winding cardboard cylinder (6). The winding end faces are equipped with cardboard supporting (7-1) and pressing (7-2) rings. Transformer oil is employed for cooling purpose together with external natural cooling system.

The simplified analytical calculation methods of a series of ironless (air-core) reactor parameters are widely known - inductance, magnetic field, currents distribution and losses in the shields, representing them not as the limited-size bodies, but in terms of boundaries of the design model [1]. Thermal calculations of structural elements are not considered.

The evaluation **relevance** of complex refined analytical-empirical and numerical finite-element method (FEM) of electromagnetic and thermal calculations of the reactors is determined by necessity of development of competitive equipment having ultimate electromagnetic and thermal loads not compromising their operational reliability.

The aim of the work is to verify the operational analytical methods more laborious numerical approaches in order to establish the practical guidelines for their application within industrial designing of the equipment. This also set the verification challenge for both recognized analytical methods and practical procedures of numerical model analysis, in particular, during calculation of the losses and temperature rises of the reactor structural elements.

BASIC EQUATIONS AND APPROACHES TO ELECTRO-THERMAL CALCULATIONS OF THE REACTOR

Calculation of electromagnetic processes in the ironless reactors, as well as in other types of power transformer equipment based on the solution of Maxwell's equations with respect to the magnetic H, electric E fields, magnetic flux density B and total current equals to the sum of the extraneous (given) currents J_{ces} and eddy currents J_σ in the conductive bodies (bias currents at power frequency voltage supply are neglected)

$$\nabla \times H = J_{ces} + J_\sigma, \qquad \nabla \times E = -\partial B / \partial t, \qquad \nabla \cdot B = 0. \quad (1)$$

Equations (1) are supplemented by material equations $B = \mu H$, $J_\sigma = \sigma E$, in which the field parameters linked through the values of magnetic inductive capacitance μ and electric conductivity σ, are considered for anisotropic media such as tensors. Electrical conductivity is nonlinearly dependent upon the temperature $\sigma(\theta)$. The relationship between induction and magnetic field strength for ferromagnetic media is nonlinear, and it is actually hysteresis of nonlinearity.

Solutions of these equations are limited by analytical methods to rather simple cases of design models geometry and finite values of constructive parameters [1-3].

In particular, for analytical electromagnetic calculation of the reactor [3], the cylindrical model (Fig. 1b) is used, in which horizontal boundaries (the reactor tank bottom and cover) are perfect ferromagnetics $\mu = \infty$. The outer cylinder (tank wall) is characterized by finite values μ and zero conductivity σ. From (1), for electromagnetic field model the respective boundary value is generated Poisson's equation with respect to the component value of magnetic vector potential $A_\varphi(r,z)$, to be introduced into (1) according to definition $B = rot\,A$. Its solution is obtained in terms of Fourier-Bessel series [3]. Using the known definitions of the vector magnetic potential terms, the flux linkages ψ_{nj} ($n = 1,...,N,\ j = 1,...,N$), the self-inductions L_{nn} and mutual inductances L_{nj} of the element, radial B_r and axial B_z components of the field density are calculated

$$\psi_{nj} = \frac{2\pi}{S_n}\int\limits_{S_n} A_{\varphi,j}(r,z)\,r\,dr\,dz, \quad L_{nj} = \frac{\psi_{nj}}{I_j},$$

$$B_r = -\frac{\partial A_\varphi}{\partial z}, \quad B_z = \frac{1}{r}\frac{\partial}{\partial r}(rA_\varphi). \tag{2}$$

At the moment the practical FEM-procedures of numerical simulation of equations (1) for the calculation of the magnetic field, inductance, losses in the conductive structural elements of nonmagnetic and ferromagnetic steels of the transformers and the reactors are developed and tested [4]. Since the inductance of the reactor is determined via the energy W of the magnetic field and the current I in winding

$$L = \frac{2W}{I^2} = \frac{2}{I^2}\int\limits_V \frac{B_v^2}{\mu_v(B_v)}\,dv, \tag{3}$$

where V is three-dimensional volume of the reactor design model, including in the structural parts with nonlinear relationship $\mu(B)$.

In elementary volumes v of the shields FEM-models are calculated as eddy-current losses $p_{v,j}$ averaged within T period, and in the ferromagnetic clamping plates and in the tank, hysteresis losses $p_{v,h}$ are added to them

$$p_{v,j} = \frac{1}{\sigma}\frac{1}{T}\int_0^T j_v^2(t)\,dt, \quad p_{v,h} = \frac{1}{T}\int_0^T p_h\left(B_{m,v}\right)dt, \tag{4}$$

where $p_h\left(B_{m,v}\right)$ - specific volumetric losses determined by the area of hysteresis loop, which depends upon crest value of field density.

The results of loss calculation in the reactor windings and structural elements are the foundations for calculation of their heating (temperature rise).

For the purpose of analysis of thermal processes in transformers and reactors with oil cooling as referred to the most complete formulation, Navier-Stokes equations of motion and continuity of the cooling liquid should be employed [5]

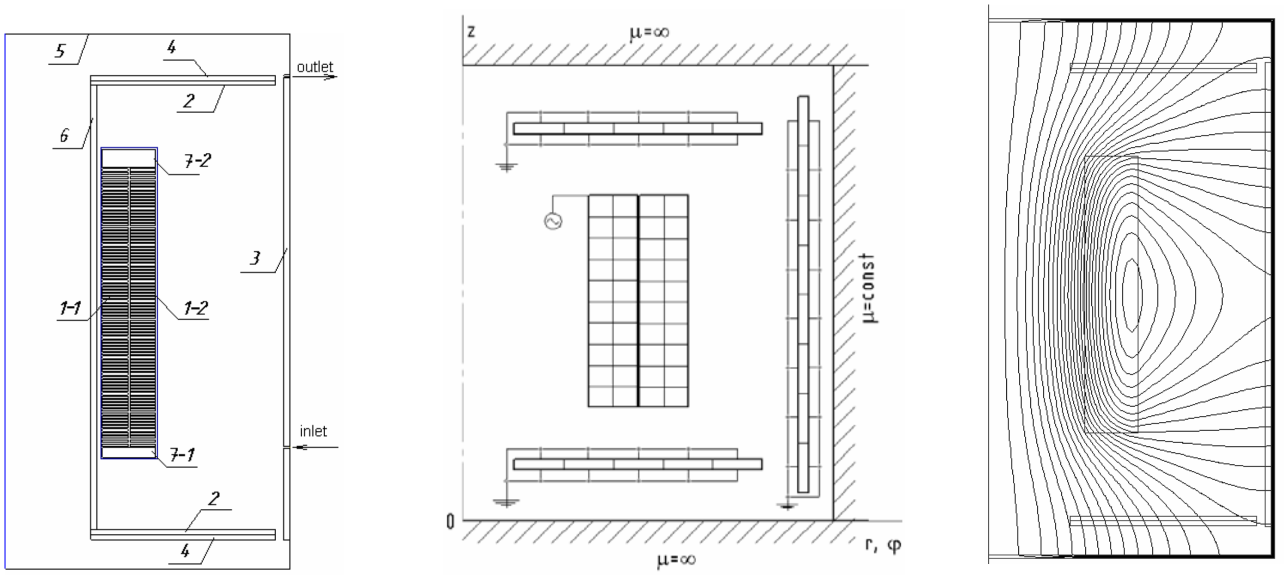
$$\nabla\cdot(\rho\vec{v}\vec{v}) = -\nabla P + \nabla\cdot(\bar{\tau}) + \rho\vec{g},$$

$$\bar{\tau} = \mu\left[\left(\nabla\vec{v} + \nabla\vec{v}^{\,T}\right) - \frac{2}{3}\nabla\cdot\vec{v}\,\hat{I}\right], \quad \nabla\cdot(\rho\vec{v}) = 0, \tag{5}$$

to be added by energy conservation equation

$$\nabla(-\lambda\nabla\theta) = Q_v - \rho C(\vec{v}\cdot\nabla\theta), \tag{6}$$

where θ, P and $\vec{v}$ - volumetric distribution of temperatures, powers and velocity vectors in cooling liquid (in transformer



a) b) c)

Figure 1 - Air-core reactor: a) design sketch; b) analytical model with system of short-circuited shield elements; c) numerical electromagnetic model and magnetic field lines

oil), Q_v - volumetric densities of heat sources; ρ, μ, C and λ - density, dynamic viscosity, thermal capacitance and oil thermal conductivity; $\vec{g}$ - vector of gravitational acceleration vector, matrix $\hat{I}$ determines direction of unit vectors of selected coordinate system.

To study the problems of heat and mass transfer in oil-cooled transformer equipment the well-known methods of Computational Fluid Dynamics (CFD) of numerical simulation of equation system (5), (6) are employed. Currently, the practical experience as to CFD-modeling of transformers and reactors have been obtained [5]. The assumptions are adopted that actual designs of magnetic systems, windings, tank and external cooling system could be calculated reduced by means of axially symmetrical design models. Nonlinear relationship between the parameters of oil and the temperature given in [6] are considered. Nonlinear relationship between the losses and the temperature is taken into account approximately. The calculation results contain the fields of the temperatures and velocities of oil in the analyzed model.

In the practice of industrial designing purposed for determination of winding temperature rises, the problems (5), (6) solution is replaced by empirical study. The so-called "overheating" calculation and empirical method are widely used [7], which based on application of empirical factors of heat transfer in averaged-surface coils of windings with simplified consideration of oil temperature at the location of coils. Resulting temperature rise of the coil above oil is the sum of temperature rises above coil surface oil, temperature gradient as to conductor strand insulation thickness and total insulation of the conductor. As a result, average winding temperatures and hot spot temperatures (HST) of the coils are determined.

Specified basic equations and methods are employed at calculation of the reactor under consideration.

ANALYSIS OF ELECTROMAGNETIC PARAMETERS BASED ON REACTOR TYPE ROM-510/26

For the purpose of more precise ***analytical calculation*** of the reactor electromagnetic calculation, the cylindrical model [2] (Fig. 1b) is used, which has the shields with finite sizes represented by a system of short-circuited elements connected in parallel with common grounded units. The winding is subdivided into the elements with a uniform density of turns. Total number of equivalent circuit is N. Taking into account the material conductivity of the winding conductors and the shields, the resistances of R_{nn} elements are assessed. Equivalent electric circuit of winding and shields parts is plotted. Voltage source U_0 with specified circular power supply frequency $\omega = 2\pi f$ is applied to the winding. Using Kirchhoff law, the matrix system of equations for voltage drop currents in the elements is formed

$$i\omega L\dot{\vec{I}} + R\dot{\vec{I}} = T\dot{\vec{U}} + T_0 U_0; \qquad T^{*}\vec{I} = 0; \qquad i = \sqrt{-1}, \quad (7)$$

where $L = \{L_{nj}\}$ – matrix of self and mutual inductances of the elements; $\vec{I} = \{I_{ai} + iI_{ri}\}$ - complexes vector of active (a) and reactive (r) current components of the elements; $\vec{U} = \{U_{am} + iU_{rm}\}$ - complexes vector voltages in $m = 1,...,M$ units equivalent circuit as referred to grounded units; $T = \{T_{nm}\}$ - matrix of elements connection; $T^{*} = \{T_{mn}\}$ - matrix transposed to T; $T_0 = \{T_{0n}\}$ - vector of elements connection with power source; $R = \{R_{nj}\}$ - matrix of elements resistances (at $n \neq j$ $R_{nj} = 0$).

As a result of the equation (7) solution, the vectors of active $\vec{I}_{an} = \{I_{an}\}$ and reactive $\vec{I}_r = \{I_{rn}\}$ currents in the elements compose $I_a = (\vec{I}_a, T_0)$, $I_r = (\vec{I}_r, T_0)$ and module of input current $I = \sqrt{I_a^2 + I_r^2}$, input impedance $\vec{Z} = U_0/\vec{I}$ of the reactor.

Using appropriate software and methodical complex (SMC) with reference designation RLI [8], the following is calculated and determined: induction parameters, automatic generation of Kirchhoff equations system and its solution, distribution of the currents and losses in the shields; determination of the reactor input impedance and calculation of magnetic field induction components in the winding for reactive component of the current.

By means of SMC RST [8] ohmic resistance is also evaluated, and using known magnetic field the stray losses in the winding conductors due to eddy currents are determined with calculation of the winding electrodynamic strength.

Results of electrodynamic calculations of the reactor type ROM-510/26 are given in Fig. 2 and Table 1.

Electromagnetic ***numerical*** calculations of the reactor is carried out using the methods of [4] in the harmonic setup taking into account the currents inverse effect in the conductive shields. FEM-model of the reactor and distribution of the magnetic field lines is shown in Fig. 1c. Comparison of calculation results of the magnetic field induction components at the winding elements by means of analytical and numerical methods was shown their complete match.

For the reactor under consideration the additional eddy current losses at the winding edges are approximately equal to ohmic losses, thus distribution of volumetric losses q in the coils throughout of the height H of winding concenters has strongly uneven nature – Fig. 2a.

Along the width of horizontal shields, distribution of current density is essentially uniform. In the vertical shield with height h the density of current j from the inner to the outer shield surface is almost twice reduced – Fig. 2b. Such unevenness is represented especially strongly in the middle part, and virtually invisible on the edges of the shield.

To improve the accuracy of the analytical calculation the vertical shield is represented by four layers, and this allows to consider the field attenuation along shield thickness and approaches the values of currents and losses to FEM-calculation – Fig. 2b. By vertical shield height for RLI model, the densities of the layers I, II, III, IV and average values RLI-avr are shown. Solid line is the result of FEM-calculation of averaged densities across the shield thickness.

Curves of current density j distribution across the width b of the top shield are shown in Fig. 2c. At internal edge of the shield the surge of the current density is observed, which could not be determined by the simplified calculations [1].

Calculation results of the input resistance (impedance) and the losses in the reactor as well as measured values are shown in Table. 1. In Calculation column the losses in vertical shield for two of RLI models are shown: made of four layers and one layer.

The Table columns Measurements and FEM, the winding losses are assigned on the basis of RLI, RST. As usual, by subtraction of winding losses from the total measured losses of the reactor, the measured losses in structural elements are determined. As can be seen from the Table 1, the calculated losses are close to the measured values. In ferromagnetic clamping plates and in the tank the losses are almost negligible.

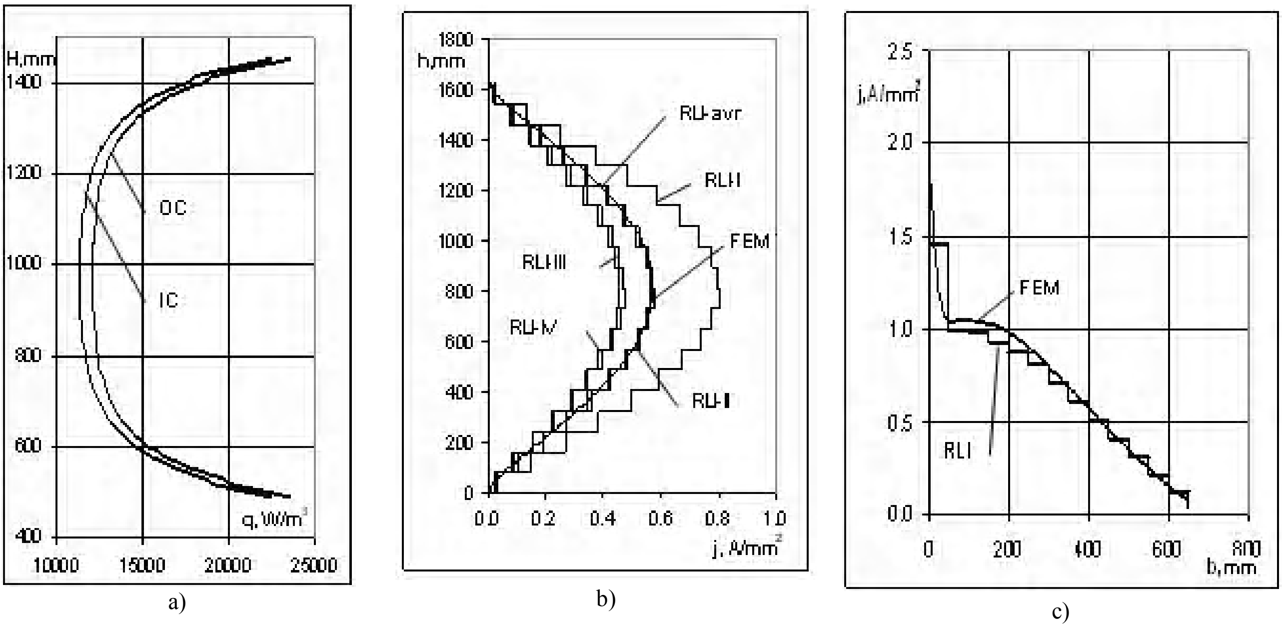
STUDY OF THERMAL MODELS

During ***analytical*** calculations based on known losses in the winding coils and oil temperature in the tank using empirical method of "overheating" [7], the winding average temperature rise and HST of the most heated coil above ambient cooling temperature (ACMT) is performed. To calculate winding temperature rise, SMC TKL is employed, and SMC RCO is used to determine the parameters of cooling system and oil temperature in the tank [8]. Calculation results for the reactor under consideration are shown in Table 2.

Axially symmetrical ***numerical*** model for calculation of the reactor thermal calculation according to method [5] corresponds to Fig. 1a. Heating elements are winding, shields, clamping ferromagnetic plates, and tank. Cardboard cylinder adjacent to the winding, supporting and pressing rings are taken into account. The geometry of the model is limited to the surface of the tank.

Winding concenters are represented by the coils with anisotropic factors of thermal conductivity both in axial and radial directions defined by conductor type. Within each coil the losses are assigned as uniform, along the concenters height - according to Fig. 2a.

Losses in the shields are assigned as averaged values as to their thickness according to distribution in FEM-calculations (Fig. 2b, 2c). Losses in the clamping plates and the tank are uniformly applied in their volume due to their small size. The factors of heat transfer to air and ambient air temperature are assigned at the tank surface. External cooling system is represented by boundary conditions at oil inlet to the tank bottom part according to bottom oil temperature and oil flow velocity at its inlet obtained by testing (or by RCO calculations), which ensures measured temperature of top oil.



a) b) c)

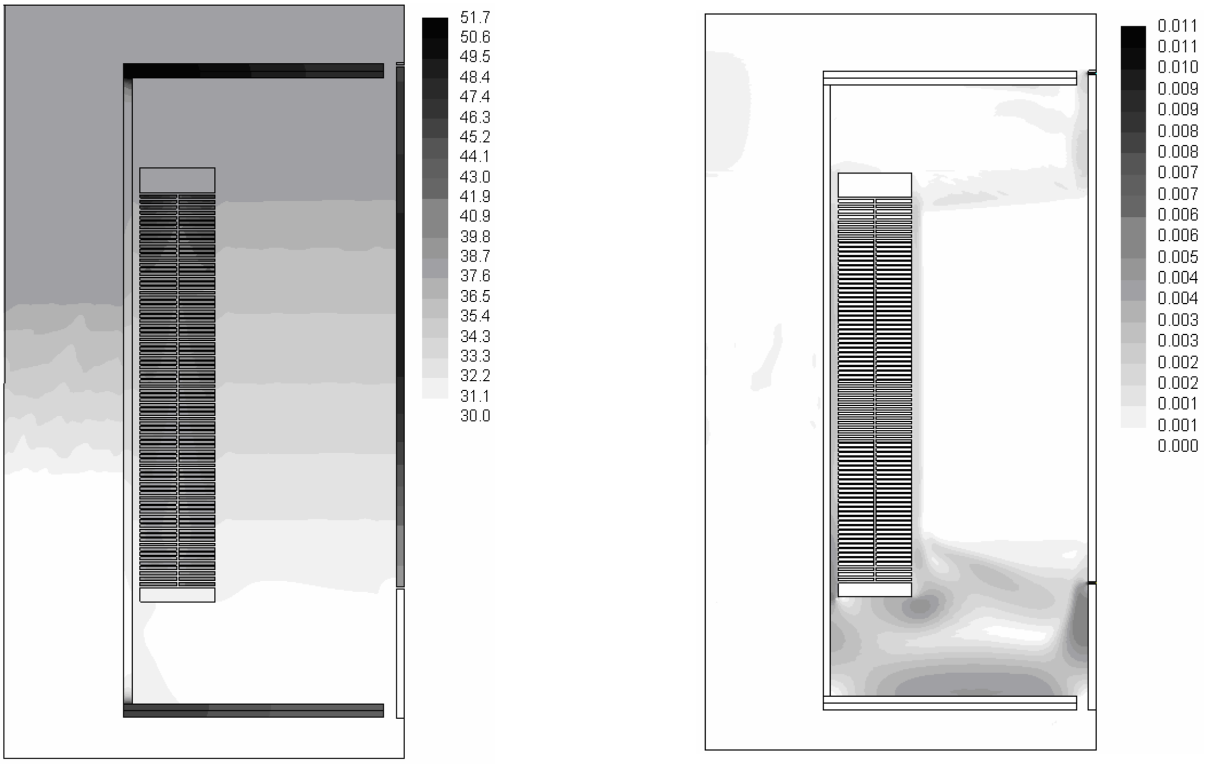
Figure 2 - Distributions: a) of volumetric losses in the coils by height of winding concenters; b) of current densities in vertical shield; c) in top horizontal shield

Distribution of heating in absolute temperatures and oil flow velocity field (m/s) in the reactor volume obtained by means of CFD-simulation (modeling) is shown in Fig. 3.

More details of temperatures distribution and the fields of oil flow velocity at the concenters' upper part are shown in Fig. 4. Uneven heating of the coils as to radial size is due to higher velocities oil flow in the inner vertical axial cooling channel. Area of oil flow adjacent to outer surface of the coil takes about 30 mm according to the picture of velocity distribution (Fig. 4b).

Table 1 – Calculated and measured values of input resistance and losses

	Measurements	RLI, RST	FEM
1 Input resistance, Ohm	1311	1319,9	
– reactive component	–	131,9	1318,5
– active components	–	14,53	-
2 Load losses, kW			
2.1 Winding – basic	3,737	3,737	3,737
– stray losses	–	0,797	,797
– total losses	4,534	4,534	4,534
2.2 Horizontal shields	–	0.658	0.727
2.3 Vertical shield – 1st layer	–	0,520	–
– 2nd layer		0,258	–
– 3rd layer		0,182	–
– 4th layer		0,171	–
– sum of four layers		1,131	1,154
– RLI model of one-layer shield		0,826	–
2.4 Clamping plates	–	–	0,016
2.5 Tank	–	–	0,010
Total losses in structure	1,881	1,789	1,907
Total losses in reactor	6,415	6,324	6,442



a) b)

Figure 3 - a) temperature field; b) oil flow velocity field

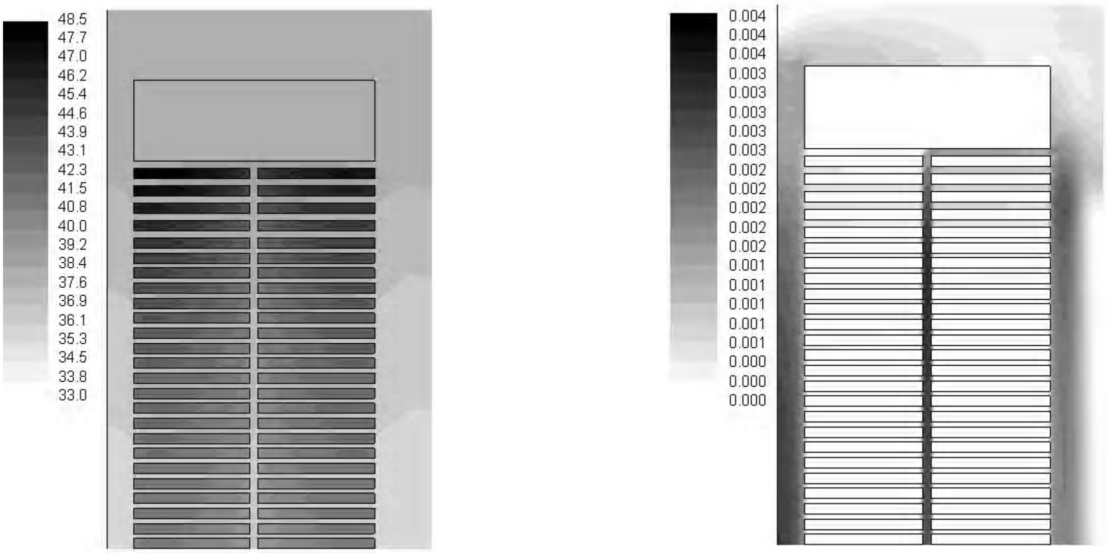
To calculate the temperature rises Δt (K) of the coils above ACMT 20 °C. Oil temperature at the level of each coil is determined by averaging of oil temperatures along the perimeter, which is separated from the coil surface by half of the horizontal channel height. Calculation results are shown in Fig. 5.

Uneven distribution of average temperature rises of coils and their HST along the height of winding above ACMT is determined by uneven values of applied losses according to Fig. 2a, as well as by almost linear increase of oil temperature throughout the tank height, Fig. 3a. Heating of external concenter is less if compared with internal concenter due to better oil cooling of external concenter uncovered by the vertical cylinder.

Distribution of the loss volumetric densities and temperature rises of the shields are presented in Fig. 6.

In temperature rises of the vertical shield, the calculated temperature jumps are observed in lower and upper parts being «cut» in the design model, at the area of oil inlet and outlet in the tank. Such matter is conditioned by representation in the model of actual holes in the shields by means of calculated circular slits, which ensure oil inlet and outlet in the tank. At the same time, the model ensures assessment of maximum temperature rises $\Delta t_{\max} = 29$ K at the shield medium part with required accuracy, at $q_{\max} = 12$ kW/m^3.

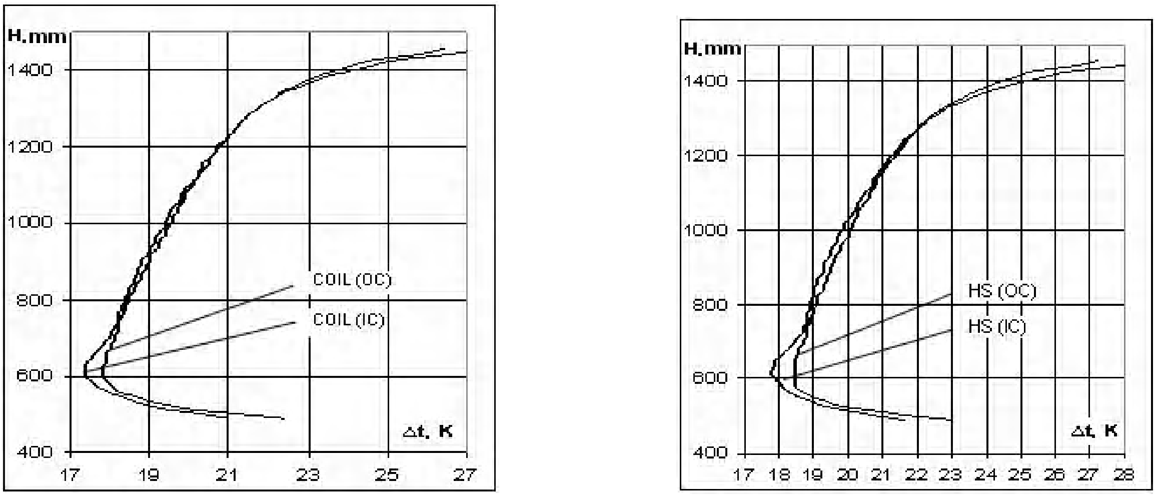
Due to finite size of upper horizontal shield, the maximum losses $q_{\max} = 87$ kW/m^3 are localized at its internal edge in



a)

b)

Figure 4 - a) temperatures field at upper group of winding coils and in ambient oil; b) oil flow velocity field in vertical and horizontal channels of upper part of winding



a)

b)

Figure 5 - Distribution of temperature rises above ambient air of average temperatures (a) and hot spot temperatures (b) in winding coils

the region of maximum magnetic field of the winding. At the same time, owing to perfect thermal conductivity of aluminum, the temperature rises have almost uniform nature, $\Delta t_{\max} = 32\ \mathrm{K}$.

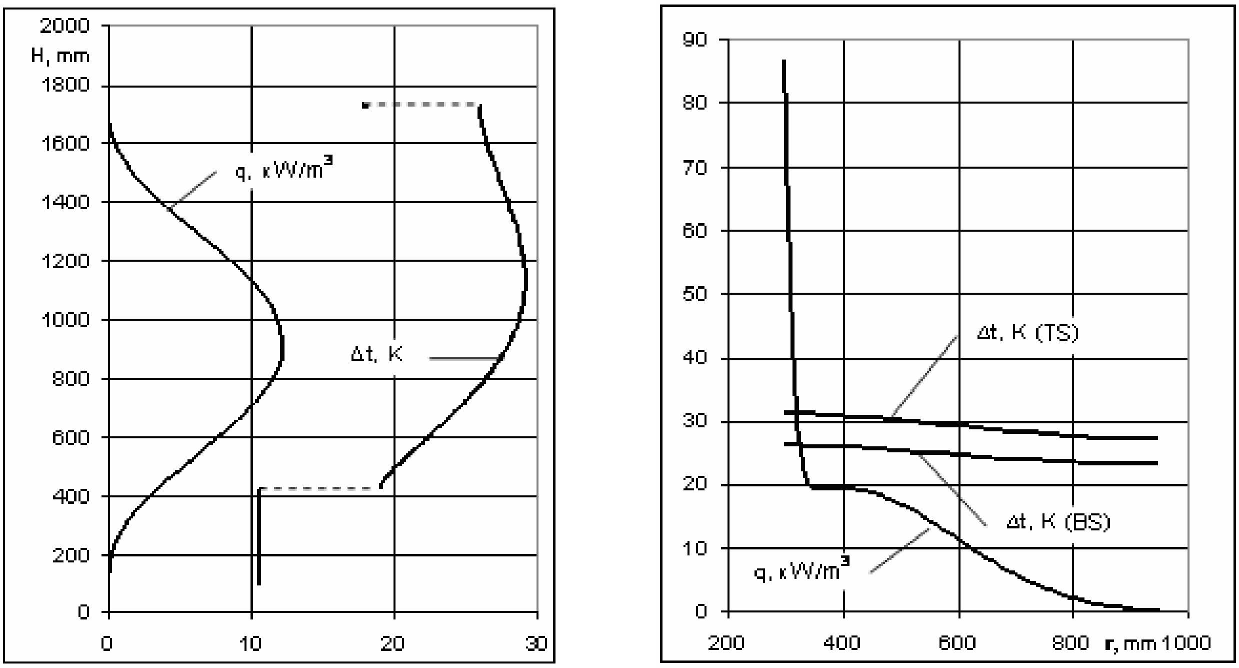
In the above formulation, the reactor numerical model reactor has ***academic novelty*** in terms of joint electromagnetic and thermal CFD-analysis. The well-known works represent simplified calculation of structural elements heating using empirical averaged heat transfer factors (constants) from the surfaces of the elements to the cooling oil. In the model under study, heat transfer from the surface of finite sizes of horizontal and vertical shields is determined by the numerical solution of heat and mass transfer equations (5), (6), taking into account the uneven distribution of volumetric heat sources Q_V.

The test results and the calculation of temperature rises above ACMT are given in Table 2. Rather sufficient agreement between the test results and CFD-calculation results as referred to temperature rises of medium and bottom oil in the tank, and average winding temperature were obtained.

The obtained temperature rises of the windings and the shields confirm the validity of selection of electromagnetic loads, cooling system parameters and reliability of the reactor operation, including those at possible long-term fault currents.

Table 2 – Temperature rises (K) above ACMT in the reactor design

Structural part	Testing	CFD (TKL)
Oil – top	20,7	18,0
– medium	15,5	14,8
– bottom	10,3	10,3
Internal/external concenter	–	19,9 / 20,0 (20,4 / 21,0)
Winding	19,7	20,0 (20,8)
HST: internal/external concenter	–	28,6 / 27,2 (28,1 / 28,7)
Shield – upper	–	31,7
– lower	–	26,2
– vertical	–	29,3



a) b)

Figure 6 - Distribution of the loss volumetric densities and temperature rises above ambient temperatures: a) in vertical shield; b) in upper and lower horizontal shields

CONCLUSIONS

1 The compliance degree of calculation and measurements of the losses and temperature rises obtained using the example of the reactor ROM-510/26 is sufficiently verify the analytical-empirical and the numerical methods of calculation of electromagnetic and thermal parameters of ironless reactor with the shields, and provision of the recommendations as to their practical application.

2 It should be considered that simplified representation using analytical method for the vertical shield without separation as to thickness could lead to assessment of reduced losses in the shield by 10–15%, that is essential for total losses used to determine the necessity of external cooling system utilization, and evaluation of its parameters. Numerical studies also demonstrate that in spite of considerable concentration of the losses at the edges of horizontal shields, their heating is even enough owing to high thermal conductivity of the shield metal.

3 The numerical model of the reactor under consideration possesses academic novelty as referred to electromagnetic and thermal analysis of structural elements temperature rises has heat transfer. CFD-model under study from the surface of horizontal and vertical shields finite sizes, clamping plates is determined by means of numerical solution of heat and mass transfer equations with consideration of uneven distribution of volumetric sources of heating, unlike the conventional simplified estimates using the empirical factors of heat transfer.

4 In the cases of direct measurement of hot spot temperatures in windings, or structural parts, using for example, up-to-date system of fiber-optic sensors, it is recommended to carry out numerical simulation (modeling) for the purpose of calculation justification of the locations and the values of maximum temperatures. Obtained values could also be used for the purpose of adjustment of the equipment monitoring systems within operation.

BIBLIOGRAPHY

1. Бики М. А. Проектирование электрических реакторов для высоковольтных линий электропередач на постоянном и переменном токе / М. А. Бики. – Днепропетровск: «Монолит». – 2014. – 164 с.
2. Иванков В. Ф. Модели и методы расчета электромагнитного поля электрического реактора с проводящим экраном / В. Ф. Иванков, Н. В. Рапцун, А. К. Мовсесян, Г. И. Калайда, А. А. Кобылецкий // Генерирование, преобразование, потребление электроэнергии: Сб. науч. тр. / Ин–т пробл. Энергосбережения АН УССР; Редкол.: В. Е. Тонкаль (отв. ред) и др. – К.: Институт проблем энергосбережения АН УССР, 1989. – С. 86–92.
3. Иванков В. Ф. Исследование плоскомеридианных полей рассеяния трансформаторов и реакторов / В. Ф. Иванков. - В кн.: Электроэнергетика и магнитная гидродинамика. Киев: Наук. думка, 1974. – С. 121-128.
4. Ivankov V. F. Numerical simulation of losses and heating in the constructional elements of transformers of ferromagnetic steel / V. F. Ivankov, A. V. Basova, I. V. Khimjuk // Технічна електродинаміка. – 2014. – № 3. – С. 19–27.
5. Круковский П. Г. Методические подходы к CFD-моделированию тепловых режимов силовых масляных трансформаторов / Круковский П. Г., Яцевский В. Ф., Конторович Л. Н., Иванков В. Ф., Юрченко Д. Д. // Промышленная теплотехника. – 2008. – Т. 30. – № 6. – С. 57–66.
6. Киш Л. Нагрев и охлаждение трансформаторов. / Л. Киш. – М.: Энергия. Трансформаторы; Вып. 36. Пер. с венгерского. Под ред. Г. Е. Тарле. – 1980. – 208 с.
7. Воеводин И. Д. Методы расчета превышений температуры обмоток силовых трансформаторов / И. Д. Воеводин, Ю. А. Михайловский, В. М. Черноготский, А. Б. Швидлер, Г. Е. Тарле, И. Ш. Люблин // Трансформаторы: Перенапряж. и координация изоляции. Пер. докл. Междунар. конф. по больш. электр. системам СИГРЭ–84. – М.: Энергоатомиздат, 1986. – С. 190–198.
8. Іванков В. Ф. Розрахункова підсистема автоматизованого проектування трансформаторів і реакторів / В. Ф. Іванков, Ю. Н. Шафір // Праці Ін–ту електродинаміки НАН України. Збірник наукових праць. – К.: Ін–т електродинаміки НАН України. – 2008. – № 18. – С. 123–131.

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ВЕРИФІКАЦІЯ МЕТОДІВ ЕЛЕКТРОТЕПЛОВИХ РОЗРАХУНКІВ ЕЛЕКТРИЧНИХ РЕАКТОРІВ БЕЗ СТАЛІ

На прикладі реактора без сталі типу РОМ-510/26 з електромагнітними екранами порівнянням результатів розрахунків проведена верифікація аналітичних і чисельних скінчено-елементних методів. Для уточненого аналітичного розрахунку горизонтальні і вертикальний екрани реактора для врахування їх кінцевих розмірів представлені системою короткозамкнених елементів. Виконується розрахунок їх індуктивностей, розподілу струмів і втрат в екранах, магнітного поля і втрат в обмотці, розрахунок нагріву обмотки емпіричним методом «перегрівів». Показано, що аналітичні розрахунки з достатньою точністю відповідають досл-

іdженням чисельними методами електромагнітного і теплового CFD-аналізу. Апробовані і перевірені результатами вимірів методи рекомендовані для практичного застосування при промисловому проектуванні устаткування.

Ключові слова: *реактори, електромагнітні екрани, електротеплові розрахунки*

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ВЕРИФИКАЦИЯ МЕТОДОВ ЭЛЕКТРОТЕПЛОВЫХ РАСЧЕТОВ ЭЛЕКТРИЧЕСКИХ РЕАКТОРОВ БЕЗ СТАЛИ

На примере реактора без стали типа РОМ-510/26 с электромагнитными экранами сравнением результатов расчетов проведена верификация аналитических и численных конечно-элементных методов. Для уточненного аналитического расчета горизонтальные и вертикальный экраны реактора для учета их конечных размеров представлены системой короткозамкнутых элементов. Выполняется расчет их индуктивностей, распределения токов и потерь в экранах, магнитного поля и потерь в обмотке, расчет нагрева обмотки эмпирическим методом «перегревов». Показано, что аналитические расчеты с достаточной точностью соответствуют исследованиям численными методами электромагнитного и теплового CFD-анализа. Апробированные и проверенные результатами измерений методы рекомендованы для практического применения при промышленном проектировании оборудования.

Ключевые слова: *реакторы, электромагнитные экраны, электротепловые расчеты*

REFERENCES

1. Biki M. A. Proektirovanie elektricheskikh reaktorov dlia vysokovoltnykh linii elektroperedach na postoiannom i peremennom toke. Dnepropetrovsk: «Monolit», 2014, 164 s.
2. Ivankov V. F., Raptsun N. V., Movsesian A. K., Kalaida H. I., Kobyletskii A. A. Modeli i metody rascheta elektromahnitnoho polia elektricheskoho reaktora s provodiashchim ekranom. Henerirovanie, preobrazovanie, potreblenie elektroenerhii: Sb. nauch. tr. In–t probl. Enerhosberezheniia AN USSR; Redkol.: V.E. Tonkal (otv. red) i dr. Kiev, Institut problem enerhosberezheniia AN USSR, 1989, S. 86–92.
3. Ivankov V. F. Issledovanie ploskomeridiannykh polei rasseianiia transformatorov i reaktorov. *Elektroenerhetika n mahnitnaia hidrodinamika*, Kiev, Nauk. dumka, 1974, S. 121–128.
4. Ivankov V. F., Basova A. V., Khimjuk I. V. Numerical simulation of losses and heating in the constructional elements of transformers of ferromagnetic steel. *Tekhnichna elektrodinamika,* 2014, No 3, S. 19–27.
5. Krukovskii P. H., Yatsevskii V. F., Kontorovich L. N., Ivankov V. F., Yurchenko D. D. Metodicheskie podkhody k CFD-modelirovaniiu teplovykh rezhimov silovykh maslianykh transformatorov / Krukovskii P. H., // Promyshlennaia teplotekhnika, 2008, T. 30, No 6, S. 57–66.
6. Kish L. Nahrev i okhlazhdenie transformatorov. Moscow, Enerhiia. Transformatory; Vyp. 36. Per. s venherskoho. Pod red. H.E. Tarle, 1980, 208 s.
7. Voevodin I. D., Mikhailovskii Yu. A., Chernohotskii V. M., Shvidler A. B., Tarle H. E., Liublin I.Sh. Metody rascheta prevyshenii temperatury obmotok silovykh trans-formatorov. Transformatory: Perenapriazh. i koordinatsiia izoliatsii. Per. dokl. Mezhdunar. konf. po bolsh. elektr. sistemam SIHRE–84, Moscow, Enerhoatomizdat, 1986, S. 190–198.
8. Ivankov V. F. Shafir Yu. N. Rozrakhunkova pidsistema avtomatizovanoho proektuvannia transformatoriv i reaktoriv. Pratsi In–tu elektrodinamiki NAN Ukraini. Zbirnik naukovikh prats, Kiev, In–t elektrodinamiki NAN Ukraini, 2008, No 18, S. 123–131.