UDC 621.314.21
DOI: 10.15587/1729-4061.2018.140236

ENHANCING THE EFFECTIVENESS OF CALCULATION OF PARAMETERS FOR SHORT CIRCUIT OF THREE-PHASE TRANSFORMERS USING FIELD SIMULATION METHODS

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Проведено теоретичні дослідження електромагнітних процесів при випробуваннях силових трансформаторів в режимі дослідного короткого замикання на основі чисельної реалізації тривимірної моделі магнітного поля у частотному формулюванні. Шляхом верифікації даних розрахунків частотних і змінних у часі моделей магнітного поля обґрунтовано достовірність і точність визначення параметрів дослідного короткого замикання силового трансформатора у частотному формулюванні. Визначено основні закономірності розподілу магнітного поля в об'ємі активної частини трансформатора. В зонах локалізації магнітного поля 3D розподіл напруженості є рівномірним і визначається 2D розподілом у горизонтальному перерізі активної частини на середині висоти фазних обмоток. Значення осьової компоненти напруженості магнітного поля наближаються до 96–97 % від модуля вектора напруженості. Реалізовано ефективний підхід до польового моделювання на основі декомпозиції розрахункової області на просторові зони. Кожній розрахунковій зоні поставлено у відповідність електричний контур схеми заміщення. Розподіл електричних потенціалів у горизонтальних перерізах провідників між котушками або між витками обмоток прийнято рівномірним. Суперпозицію магнітних полів у просторових зонах здійснено засобами динамічного синтезу за критеріями мінімальної струмової похибки для електричних контурів схеми заміщення. Декомпозиція 3D області польового моделювання на центральну і торцеві зони здійснюється на відстані 10–15 % висоти фазних обмоток, що забезпечує високу точність розрахунку напруженості магнітного поля із похибкою не більше 1,62 %. Витрати часу для польового моделювання електромагнітних процесів у режимі дослідного короткого замикання зменшено у 5 раз, а вимоги до потужності обчислювальних апаратних ресурсів знижено у 4 рази. Високу точність ідентифікації параметрів дослідного короткого замикання трифазних трансформаторів підтверджено порівнянням даних розрахунків із результатами випробувань в умовах приватного підприємства «Елтіз» (Запоріжжя, Україна). Похибки розрахунків не перевищують 1,42 % для активних втрат і 1,39 % для напруги короткого замикання. Запропонований підхід із використанням методів декомпозиції та динамічного синтезу дозволяє значно підвищити ефективність попереднього етапу конструкторської підготовки виробництва і може бути використаний при реалізації задач оптимізації конструктивних рішень

Ключові слова: електромагнітне поле, трифазний трансформатор, дослідне коротке замикання, декомпозиція, динамічний синтез

1. Introduction

Power transformers are some of the most common electrical devices that play a major role in the transportation of electricity from the place of its generation to its users. The established capacity of power transformers can by order of magnitude exceed the capacity of electricity generation, the transformation multiplicity of which can be equal to 7–8 [1, 2]. That is why there are high requirements to technical and economic indicators and reliability of power transformers that must be provided even at the stage of design preparation of production [3].

Under the steady operating modes of power systems and distribution networks, the main effect of transformer equipment is determined by the parameters of the replacement scheme for the test short circuit (SC) [3–5]. Resistances of SC are calculated according by specifications of the transformer for voltage and short circuit losses [1, 2].

Engineering design techniques based on the methods for researching linear systems fragmentally take into consideration design features of the active part of power transformer and its other structural elements [1, 2]. This can lead to a distortion of real processes of electromagnetic conversion of AC energy in power transformers [4, 5]. Therefore, the accuracy of the design calculations of specifications of short circuit of the transformer is low, and permissible errors can approximate 10–15 % [3]. This causes the relevance of development of high-precision and high-performance methods for calculation of the transformer parameters in the mode of the studied SC.

2. Literature review and problem statement

To determine the parameters and characteristics of power transformers, the schematic models based on the theory of electric and magnetic circuits are normally used [6, 7]. Comparative simplicity of the algorithms of computer implementation caused the use of schematic models in engineering calculations at the stage of design preparation of production [4, 5]. However, a number of assumptions and simplifications, which laid the basis of schematic models, lead to deviations from the actual electromagnetic processes of energy conversion of AC during its transformations [8, 9]. Simplified descriptions of surface effects, nonlinear properties of active and structural materials [10], disregarding the peculiarities of a multi-component spatial structure of the active part of transformers [11] can lead to significant calculation errors [12–14]. It imposes a limitation to the application of these methods for calculation of currents, voltage and electrical resistance under the dynamic conditions of short circuit with the shock electro-dynamic efforts and thermal loads [15, 16].

It is possible to take into consideration the influence of structural factors on parameters of a short circuit of power transformers more completely, using field simulation [17–19]. 3D field simulation can ensure high accuracy in determining the parameters of power transformers. However, its computer implementation, based on the methods of finite elements in multi-component areas of the active part with non-linear electro-physical properties, is complicated by great consumption of time and requirements for computational resources [17]. Paper [20, 21] proposed the 3D model of electromagnetic processes to determine electrical and electro-power parameters of electro-technical systems of the AC transformation. However, its application is limited only to systems that have linear magnetic properties of materials. In papers [22–24], it is proposed to use the differentiation of dimensions of finite elements and approximation by Lagrange first order polynomials for effective numerous implementations of the field models. The application of this approach to power transformers is complicated by the significant nonlinearity of magnetic properties and the difference of geometric dimensions of separate elements [25–27]. Some authors try to introduce simplifications into the geometric model [28, 29], neglect nonlinearity of the magnetic properties of materials [24] or to apply 2D models [30, 31]. These assumptions and simplifications decrease the accuracy of results of simulation and in some cases can distort a real picture of electromagnetic processes. The field calculation model of the power transformer in the mode of the studied short circuit should in detail display the multi-component structure of the active part and take into consideration the nonlinearity of electro-physical and magnetic properties of the active materials. The effectiveness of the numerical implementation of the field model must meet the requirements of the problems of design parameters optimization. This causes the need for development of specific approaches that improve the computation accuracy and efficiency and ensure adaptation of 3D-field simulation to the tasks of optimum design of power transformers.

3. The aim and objectives of the study

The aim of this study is to develop an effective approach to field simulation of the electromagnetic processes of the three-phase transformer through the decomposition of the 3D area of the active parts into sub-areas for the synthesis of parameters of the corresponding electric circuits in SC parameters with high precision.

To accomplish the aim, the following tasks have been set:

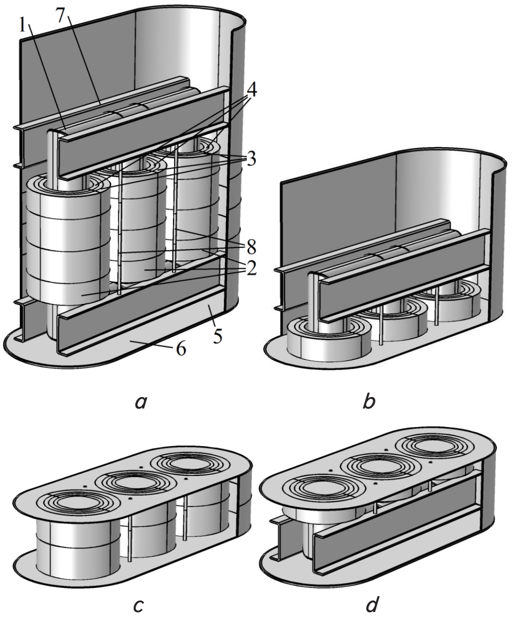
– to determine mathematical statement of the AC field model that reflects the features of electromagnetic energy conversion in the mode of the studied SC of the power transformer with the multicomponent active part of a complex structure;

– to determine parameters of decomposition of the calculation region of the active parts of the transformer in the spatial zones of the reduced volume in order to reduce the number of finite elements, to ensure the accuracy and effectiveness of the computation processes;

– to develop the method of synthesis of field zones into the electric circuit by the criterion of current error minimization for the refined determining of SC parameters.

4. Statement of the mathematical model of electromagnetic processes in the transformer for the mode of the studied short circuit

The 3D area of the field simulation of electromagnetic processes in the power transformer includes the active part, which is placed in the tank – 6 (Fig. 1, *a*). The active part consists of the systems of windings, the magnetic system, the systems of longitudinal and main electric insulation. The system of windings consists of the main and adjusted windings on the high voltage side (HV) – 1 and the winding on the low voltage side (LV) – 2 with coils, turns, layers, etc. [33]. In the charged magnetic system of the transformer – 3, one distinguishes limbs and yokes that are brought together by yoke beams. The system of electric insulation of the transformer consists of solid insulation from electric cardboard – 4, paper electric insulation and transformation oil – 5 (Fig. 1, *a*).



a *b*

c *d*

Fig. 1. Three-phase power transformer: *a* – calculation; *b*, *c*, *d* – upper, central and lower decomposition zones

According to data from [17], electro-physical processes in dielectric materials can be considered similar to the processes of electrical conductivity in materials with relatively low electrical conductivity. That is why electromagnetic fields in the calculation region Ω (Fig. 1, *a*) can be described by Maxwell equations in frequency statements [20, 21]:

$$\begin{cases}\nabla\times\left[\left(\mu_{\theta}\mu_{j}\right)^{-1}\nabla\times\mathbf{A}_j\right]=-\sigma_j\left(\theta_j\right)\left(j\omega\mathbf{A}_j+\nabla V_j\right);\\ \nabla\cdot\left[\sigma_j\left(\theta_j\right)\cdot\nabla\cdot V_j\right]=-j\omega\cdot\nabla\cdot\left(\sigma_j\left(\theta_j\right)\cdot\mathbf{A}_j\right),\end{cases}\qquad(1)$$

with potentiality conditions [20]:

$$\left\{\mathbf{E}_j=-\mathbf{grad}(V);\ \mathbf{B}_j=\mathbf{rot}\left(\mathbf{A}_j\right),\right.\qquad(2)$$

relationships of form [20]:

$$\left\{\dot{\mathbf{H}}_j=\left[\mu_0\mu_j\left(\left|\dot{\mathbf{B}}_j\right|\right)\right]^{-1}\dot{\mathbf{B}}_j;\ \dot{\mathbf{J}}_j=\sigma_j\left(\theta_j\right)\dot{\mathbf{E}}_j+\dot{\mathbf{J}}_{e_j},\right.\qquad(3)$$

where **A**, *V* are the vector and magnetic potentials, **B** is the induction of the magnetic field, **E**, **H** are the voltages of electric and magnetic fields, **J** is the density of current, σ(θ) is the temperature dependence of specific electric conductivity, θ is the temperature, μ_0 is the magnetic permeability of vacuum, μ(|**B**|) is the equivalent relative magnetic permeability, ω is the angular frequency.

The system of the field equations (1) is supplemented by conditions of combination of magnetic and electric fields on the boundaries of the cells with different electro-physical properties [21]:

$$\left\{\mathbf{n}\times\left(\mathbf{H}_{+}-\mathbf{H}_{-}\right)=0;\ \mathbf{n}\cdot\left(\mathbf{J}_{+}-\mathbf{J}_{-}\right)=0,\right.\qquad(4)$$

and homogeneous boundary conditions at the external surface of the tank [26] or impedance conditions [32] at its internal side.

For calculation region Ω, the temperature mode of the power transformer is accepted as stationary. The temperatures of the elements of the active parts are determined by the project or by the data, which are admissible for heating resistance A [1]. The anisotropy of magnetic properties of cold rolled electro-technical steel was taken into account according to [25].

For the elements of the power transformer in the 3D field Ω, densities of currents, active losses (for electrically conductive materials) and energy of the magnetic field are calculated [20]:

$$\begin{cases}W\big|_j=\dfrac{1}{4}\iiint\limits_{V_j}\left(\dot{\mathbf{H}}_{\mathrm{j}},\dot{\mathbf{B}}^{*}_{\mathrm{j}}\right)\Big/\mu_0\mu_j\left(\left|\dot{\mathbf{B}}_j\right|\right)\mathrm{d}x\mathrm{d}y\mathrm{d}z;\\ P\big|_j=\iiint\limits_{V_j}\sigma_j^{-1}\left(\dot{\mathbf{J}}_j,\dot{\mathbf{J}}^{*}_j\right)\cdot\mathrm{d}x\mathrm{d}y\mathrm{d}z;\\ \mathbf{J}_j=-\sigma_j\cdot\left(\mathbf{grad}\left(V_j\right)+j\omega\mathbf{A}_j\right),\end{cases}\qquad(5)$$

as well as currents in the phase windings of HV and LL.

Phase high-voltage windings are attached to the three-phase power supply source by scheme Y, and low-voltage windings, connected by scheme A, are shunted by branches with small active resistance. The restrictions for the power source of test voltage are taken into account using linear resistances between this source and the windings of the transformer. This will not lead to any significant increase in current error provided that these resistances are by several orders of magnitude lower than resistance of SC, determined by specifications. Under the mode of the studied SC, currents in the windings are equal to the rated values, in accordance with the phase voltage at the HV side $\left\{\Delta\dot{\mathbf{U}}_{\mathrm{k}}\right\}$, $k=1,2,3$:

$$\begin{cases}\Delta\dot{\mathbf{U}}_{\mathrm{k}}=-j\omega\dot{\Psi}_k+\dot{I}_k\cdot R_k, & k=1,2,3;\\ 0=-j\omega\dot{\Psi}_k+\dot{I}_k\cdot R_k, & k=4,5,6.\end{cases}\qquad(6)$$

Computer implementation of the field model (1) to (4) is carried out in the structure of the specialized software of field simulation COMSOL Multiphysics [33]. 3D area is divided into three-dimensional finite elements – tetrahedrons with edges, which are approximated by Lagrange second order polynomials. To increase effectiveness of the numerical implementation of the model, differentiation of dimensions of finite elements is performed. In sub-regions with distinctly pronounced nonlinearity of magnetic properties and localization of magnetic field, dimensions of finite element decrease and increase near the outer boundary of the calculation region.

5. Results of the study of magnetic fields of the transformer under the mode of test short circuit. Statement of criteria for the decomposition of active part and the synthesis of electric circuits of field zones

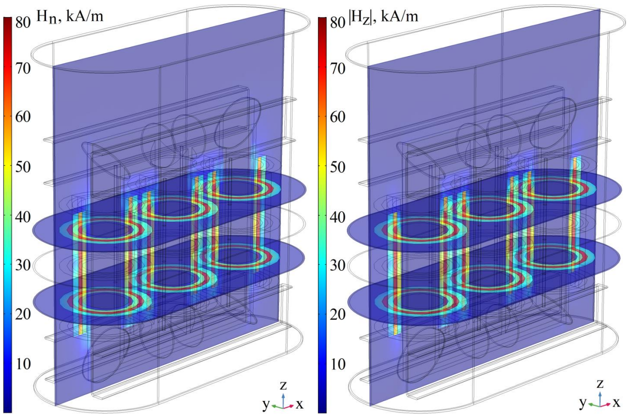
Field simulation of electromagnetic fields in the area of the active part was carried out for the three-phase power transformer of voltage class of 35 kV and power of 1,600 kWA. The windings are connected by Y/Y_0–0 circuit. Rated values of linear voltages on the side of HV and LV were 20 kV and 0.4 kV. For the mode of the test CS, the amplitudes of phase voltages were determined by specified value of SC voltage, which amounted to 6.5 % of the rated phase voltage from the HV side of the transformer. The symmetric three-phase system of electrical voltages with the phase shift vector [0; 2 π/3; 4 π/3] for frequency of 50 Hz of AC was used.

The results of 3D simulation are represented by distributions of voltage of the magnetic field and its axial components in vertical and horizontal cross sections of the active part of the power transformer (Fig. 2, *a*).

According to field calculations, it was determined that for the mode of the test SC the localization of the magnetic field occurs in the phase windings systems. In the determined localization areas, directions and module of vectors of magnetic field intensity almost never change. The biggest component is the projection of H_z, the value of which is 96–97 % of the module of magnetic intensity vector. This allows us to consider that the 3D distribution of the magnetic field intensity in the area of its localization is determined by the 2D distribution in the horizontal plane of cross section of the active part. The change in electrical potentials on the surface of horizontal cross-sections of the conductors between the coils or between the turns of the windings can be neglected and we can accept the assumption of the uniform distribution of electrical potentials.

The features of the magnetic fields distribution allow applying for calculation region Ω the principle of superposition of electromagnetic fields, calculated separately in the central (Fig. 1, *c*) and end zones (Fig. 1, *b, d*).

To reduce the number of finite elements and dimensionality of equations of the finite element model, it is advisable to apply the distribution of the active part structure into the subsystems with separate operating elements or components [33]. This will significantly reduce the number of functional relations between the parameters of each subsystem and the number of independently varied parameters to minimize current errors for phase currents of the studied SC.



a *b*

Fig. 2. Magnetic field of the active part of the power transformer: *a* — amplitudes of magnetic field intensity; *b* — amplitudes of the projection of magnetic field intensity onto the vertical axis of the transformer

Decomposition of the calculation region Ω implies the division into several calculation areas, each of which can be put in conformity with the circuits of the replacement scheme. These areas are separated from each other by horizontal cross sections that are perpendicular to axis 0z and pass through the axial insulating channels between the coils or between the turns of the windings. The distance of horizontal cross-sections from the upper and lower ends is 10–15 % of the height of the windings.

The central area includes the central part of phase windings of HV, LV and limbs, main insulation, transformer oil and the central part of the tank (Fig. 1, *c*). The end zones include the upper or the lower part of the tank, the upper or the lower yokes, relevant parts of HV, LV windings and limbs of different phases, solid insulation and transformer oil (Fig. 1, *b, d*). Division of the field of simulation Ω into the zones ensures a reduction of time of implementation of the field models due to the fewer number of finite elements in the zones of smaller volume.

It is possible to display the volume of the region of electromagnetic energy conversion Ω by the sum of the volumes of zones and to determine electrical losses and magnetic energy by the sum of values in the respective areas.

For the synthesis of electric circuits on the boundaries of connection of the areas of phase windings, we accept the conditions of the equality of electric potentials:

$$\left\{V_{j,i}=V_{j,i+1}\Big|_{\Gamma_{j,i+1}}=\mathrm{const}_{j,i},\Delta U_{i,j}=V_{j,i}-V_{j,i+1}\Big|_{\Gamma_{j,i+1}}\right.,\tag{7}$$

for which system of equations (6) will take the form:

$$\begin{cases}\Delta\dot{\mathbf{U}}_{BH,\mathrm{k}}=\sum\limits_i\left\{\Delta\dot{\mathbf{U}}_{i,j}\right\}_k\Big|_{k=1,2,3},0=\sum\limits_i\left\{\Delta\dot{\mathbf{U}}_i\right\}_k\Big|_{k=4,5,6},\\ \Delta\dot{\mathbf{U}}_{\mathrm{k,i}}=-j\omega\dot{\Psi}_{k,i}+\dot{I}_{k,i}\cdot R_{k,i},k\in(1,6),\end{cases}\tag{8}$$

where $\left\{\Delta\dot{\mathbf{U}}_{\mathrm{k,i}}\right\}$ is the voltage drop in the sections of phase windings; *i* is the number of sequential branches in the circuit of the phase winding, indices $k\in(1,2,3)$ belong to the HV windings of A, B, C phases, indices $k\in(4,5,6)$ belong to LV windings of A, B, C phases, respectively.

In conditions (7), each value of const is “free”. That is why a voltage drop in the section of phase windings $\left\{\Delta\dot{\mathbf{U}}_{i,j}\right\}_{\mathrm{k}\in(1.6)}$ cannot be assigned in advance and should be determined from the solution of the problem of current errors minimization. For the synthesis of electric circuits and superposition of magnetic fields, in the calculation region, it is possible to state objective function with the components that are determined by the sum of the squares of current errors for currents in the sections of windings:

$$\begin{cases}\min\left(M^2(\mathbf{D},\mathbf{R})\right)=\sum\limits_{k=1}^{6}\min\left(M^2(\mathbf{D},\mathbf{R})_k\right)=\\ =\sum\limits_{k=1}^{6}\min\left(\left(\sum\limits_i\dot{\mathbf{I}}_{i,k}-\dot{\mathbf{I}}_k\right)_j^2\right).\end{cases}\tag{9}$$

In the general case, component of the vector of objective function $M^2(\mathbf{D},\mathbf{R})_k$ is the function of vectors of independently varying **D** and dependent **R** parameters for each winding of the transformer. A voltage drop on the section of the circuit of the winding is considered as projections of the vector, irrespective varying parameters **D**. This makes it possible to convert the components of objective function $M^2(\mathbf{D},\mathbf{R})_k$ into components of function $\tilde{M}^2(\mathbf{D})_k$.

To implement conditions (9), it is advisable to apply the method of dynamic programming [34]. The vector of optimization parameters with components

$$\mathbf{D}=\left\{\Delta\dot{\mathbf{U}}_{\mathrm{i}}\right\}_{\mathrm{i}\in(1,3),\mathrm{k}\in(1,6)}$$

can be represented as the sum of vectors of initial approximation

$$\mathbf{D}_0=\left\{\Delta\dot{\mathbf{U}}_{0,i}\right\}\Big|_{\mathrm{k}\in(1,6)}$$

and its specification

$$\delta\mathbf{D}=\left\{\delta\Delta\dot{\mathbf{U}}_{1,i}\right\}_k\Big|_{\mathrm{k}\in(1,6)}.$$

That is why optimality conditions (9) can be put in conformity with the system of recurrent equations of Bellman [9] for each winding of the transformer:

$$\left.\begin{cases}\min\Delta\tilde{M}_\Sigma^2=\mathbf{\Phi}\left(\mathbf{D}_{0,\mathrm{k}}\right)=\\ =\min\limits_{\delta\mathbf{D}_1}\ldots\min\limits_{\delta\mathbf{D}_m}\left[\left(\Delta\tilde{M}_1^2\left(\mathbf{D}_{0,k},\delta\mathbf{D}_{1,k}\right)+\ldots\Delta\tilde{M}_m^2\left(\mathbf{D}_{m-1,k},\delta\mathbf{D}_{m,k}\right)\right)\right]\end{cases}\right|_{k\in(1,6)}.\tag{10}$$

Relations (9), (10) determine the conditions for dynamic connections of “free” parameters in equations (7) for the central and end 3D zones of region Ω. The iteration calculation process of the method of dynamic programming is implemented in the assigned limits for current $\varepsilon_I\leq0.1$ % and angular errors $\varepsilon_\varphi\leq0.5$ %.

For the mode of the studied SC, we applied the conditions that the sum of instantaneous values of voltage drop in the circuits of the parts of phase windings of each decomposition zone must be equal to instantaneous values of SC voltage for each phase. Spatial distribution of magnetic field intensity in sub-areas of the upper – I, central – II and lower – III zone of the decomposition was compared with the distribution of intensity in the 3D area of the active part (Fig. 3). For the decomposition method, the largest deviations of calculations of magnetic field intensity are characteristic of horizontal surfaces of the areas that cross windings (Fig. 3). However, the maximum value did not exceed 1.62 %.

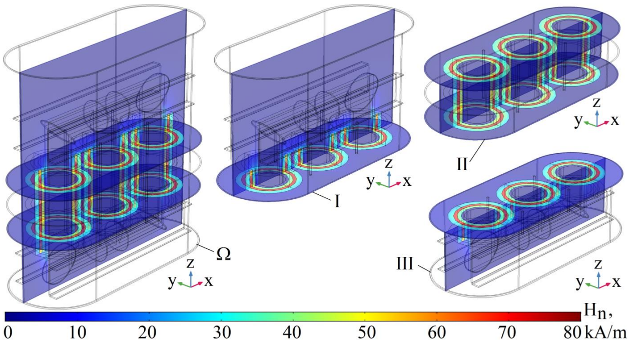


Fig. 3. Distribution of normal component of the magnetic field intensity in the calculation area and zones

6. Discussion of results of simulation of electromagnetic processes in the mode of the test short circuit of the three-phase transformer

Verification of SC parameters by the data of field simulation of the parameters of SC of the transformer was performed for SC voltage, the value of which was 740.2 V (6.41 %) for the frequency-domain model and 741.7 V (6.42 %) for the time-dependent model. Corresponding calculation values of SC losses were equal to 17.745 kW and 17.815 kW.

Thus, relative discrepancies in frequency calculations did not exceed 0.4 % for losses and 0.2 % for voltage of short circuit. The relative error in calculation of losses and short-circuit voltage did not exceed 1.5 %.

Errors of calculation of active power losses, magnetic field energy and voltage drops using the method of decomposition of the 3D area of the active part of the power transformer are shown in Table 1. The relative errors in the decomposition areas do not exceed: 0.47 % for magnetic field energy, 0.53 % for electric losses, 0.51 % for the voltage drop module, 0.29 % for the voltage drop phase. The relative errors of calculation of SC parameters make up 1.42 % for losses and 1.39 % for SC voltage. Validation of calculation parameters of the short circuit was carried out by comparing the calculation data using technique [26] with the results of tests, obtained at private enterprise "Eltiz" (Zaporizhye, Ukraine).

Reliability and accuracy of the results of simulation using the methods of decomposition and of dynamic synthesis of the windings sections circuits are ensured provided that the distribution of electrical potential in the connection boundaries approaches the uniform one. In this case, the sum of active losses and magnetic field energy in the calculation regions will correspond with high accuracy to active losses and magnetic energy for the 3D area of the active part.

The proposed combination of the methods of decomposition and of dynamic synthesis with "free" conditions of connection of electric circuits of phase windings sections ensures effective implementation of the 3D modeling of magnetic fields in the regions of a complex spatial form. High reliability and accuracy of the data of modeling and determining parameters of a short circuit are achieved thanks to taking into account of finite dimensions of the magnetic system, the winding system and features of reciprocal location. Time consumption decreases by 5 times, and requirements for capacity of computation resources for the refined calculation of the SC parameters decrease by 4 times.

The application area of the results of the conducted research is limited to the most common types of three-phase power transformers of voltage classes of up to 35 kV including the circuits of connection of windings Y/Y_0–0, Y/D–11, D/Y_0–11 [1]. For the transformers of voltage class of 110 kV and above, the linear input inside HV windings is applied, which is performed by an electric circuit with two parallel branches [1]. In addition, high voltage classes require a substantial increase in dimensions of axial insulation gaps in the middle of LV windings, which leads to a multiple increase in the number of decomposition zones for calculation of the SC of the transformer. That is why effective approaches to high-precision determining the SC parameters for transformers with voltage class of 110 kV and above require further development.

Table 1

Errors of the method of dynamic synthesis of field models for the criterion of minimum current error

Calculation regions (zones)	Upper zone	Central zone	Lower zone	Area of active part
Magnetic field energy	0.47 %	0.19 %	0.25 %	0.76 %
Active power losses	0.53 %	0.31 %	0.48 %	1.42 %
Voltage drop (module/phase)	0.51 %/0.29 %	0.38 %/0.18 %	0.46 %/0.28 %	1.39 %/0.78 %

In the future, the proposed methods of decomposition and of dynamic synthesis can be adapted for studying high-voltage reactors and rotating electric machinery and determining their parameters in test modes.

7. Conclusions

1. It was found that mathematical statements for the model of the magnetic field reflect the features of the electromagnetic energy conversion in the mode of the test SC of the power transformer with the multicomponent active part of a complex structure. Using the verification of the data of calculation of frequency-domain and time dependent models of the magnetic field, we substantiated validity and accuracy of results when using frequency statements for determining the parameters of the studied SC of the power transformer. The relative discrepancies of frequency calculations did not exceed 0.4 % for losses and 0.2 % for short circuit voltage. Comparison of calculation data with test results from the private enterprise "Eltiz" (Zaporizhye, Ukraine) is proved by high accuracy of identification of the parameters of the test SC. Relative error of calculation of losses and voltage of short circuit does not exceed 1.5 %.

2. It was established that in the test SC, the magnetic field is located in phase windings. In the localization areas,

directions and the module of the vector of magnetic field almost never change. The axial component, the value of which is 96–97 % of the module of the magnetic tension vector, is the largest. This makes it possible to determine the 3D distribution of the magnetic field intensity in the localization area according to the data of 2D distribution in the horizontal plane of the cross section of the active part in the middle of the phase windings height. The change in electrical potential on the surface of horizontal cross-sections of the conductors between the coils or between the turns of the windings can be neglected and the assumption of uniform distribution can be accepted. The calculation area is divided into the central and end zones. Each of the zones was set in compliance with the electrical circuit in the substitution scheme. Decomposition of the 3D area of field simulation into the zones at the distance of 10...15 % of the height of the phase windings from their ends ensures high precision of calculation of the spatial distribution of the magnetic field intensity with the error of not more than 1.62 %.

3. It was found that the dynamic synthesis of field areas with electric circuits in the substitution scheme by the criterion of a minimum current error significantly increases computational efficiency of determining SC parameters. In the set restrictions for current $\varepsilon_I \leq 0.1$ % and angular errors $\varepsilon_\varphi \leq 0.5$ %, relative calculation errors do not exceed 1.42 % for active losses and 1.39 % for SC voltage. Application of the methods of decomposition and of dynamic synthesis of electric circuits make it possible to decrease time consumption by 5 times and decrease the requirements for computing resources by 4 times.

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