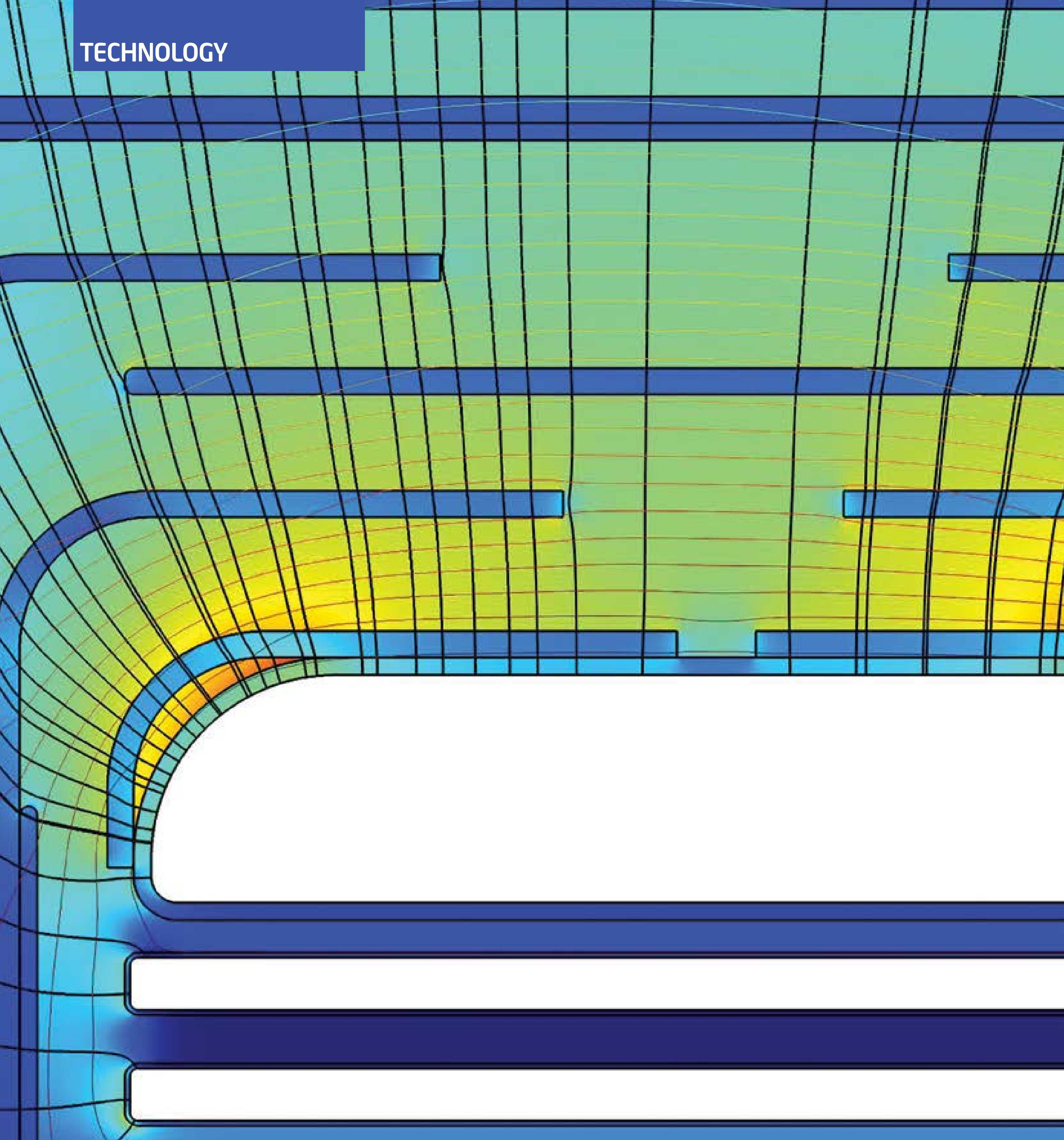
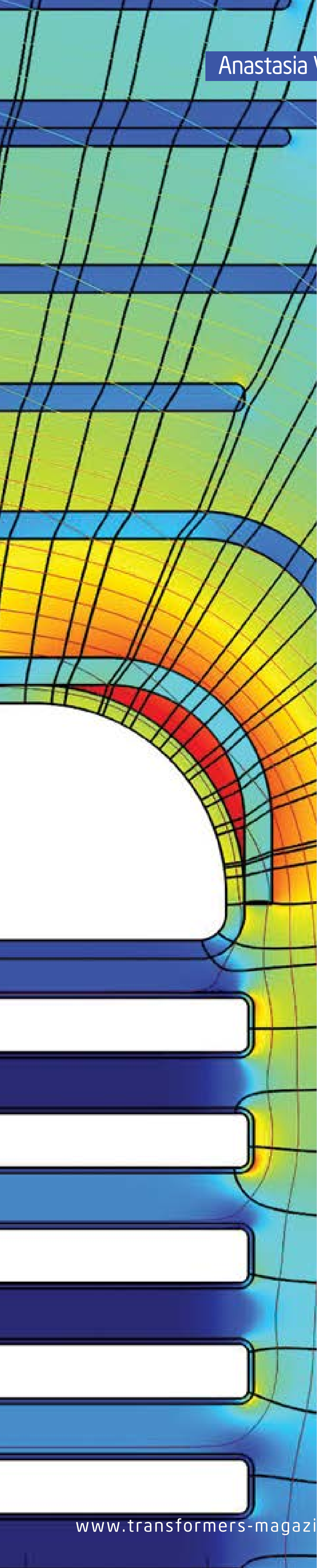


ABSTRACT

A preprocessor with unified elements and positioning in relative and symbolic coordinates is proposed for Finite Element Analysis (FEA) of electric fields. The preprocessor automates the preparation of two-dimensional (2D) data models for the calculation of electrical strength in the main insulation of transformer and reactor windings. Examples of the formation of 2D models and numerical calculation of electric fields using invariant software are presented. The use of graphic editors for building 2D&3D models of bushings and taps is ap-proved. Post-processors for determining 90% “stressed” volume and trajectories of electric field lines of force in three-dimensional (3D) models of windings and bushings are developed.

KEYWORDS:

transformer equipment, electric fields, 2D&3D numerical models, finite element analysis



Anastasia V. BASOVA, Olena V. SHINKARENKO, Viktor F. IVANKOV, Anatoliy I. SAVCHENKO

Technical and economic characteristics of high-voltage power transformers and electric reactors largely depend on the configuration and dimensions of winding insulation, bushing insulation, and taps

2D&3D models for numerical calculation of electric fields in high-voltage transformers and reactors

1. Introduction

Technical and economic characteristics of high-voltage power transformers and electric reactors largely depend on the configuration and dimensions of winding insulation, bushing insulation, and taps [1]. Such power equipment contains a magnetic core structure with oil cooling.

When defining the electrical strength of transformer equipment, there are three stages: calculation of emergency voltage actions, calculation of associated electric fields, and assessment of insulation strength.

Emergency actions depend on equipment voltage classes and operating conditions. Insulation coordination accounts for voltage type, level, and form, such as working low-frequency long-term voltage, quasi-stationary voltages, switching, and lightning overvoltages (full and chopped impulses). Therefore, in the first stage of work, transformer windings are modeled with lumped parameters for resistance, inductance, and capacitance to facilitate transient analysis. In particular, the matrix method for linear inductive-capacitive circuits is used [2]. The dissipation of thermal energy in active resistors is accounted for by empirical dependencies. In work [3], complex systems of equations model active resistances of windings dependent on displacement and proximity effects. Usually, calculated voltage distribution in windings is checked experimentally on active equipment. As a result of the specified calculations, time dependences of impulse currents and voltages are determined for emergency actions such as full and truncated lightning impulses and oscillating switching impulses. The specific results are necessary and sufficient for calculating electric fields of windings, bushings, and taps and for further determination of electrical strength.

Internal insulation strength in transformer equipment is determined by the following [4]:

- turn-to-turn and inter-coil (longitudinal) winding insulation
- oil barrier insulation between adjacent windings of one phase (main insulation of windings)
- insulation external to windings: e.g., to rods and yokes of the magnetic system,

The strength of turn and inter-coil winding insulation is determined by the breakdown potential of oil channels in the windings

to windings of other phases, and to the tank
- isolation of bushing settings
- insulation of taps

An insulation system formed of liquid petroleum transformer oil and solid cellulose structural parts is defined as "combined." In such composite insulation, under the action of industrial frequency voltage and emergency impulses, the electric field strength in oil channels is higher than in solid insulation due to the lower dielectric permeability of oil. In addition, the electrical strength of oil is lower than that of solid insulation. Therefore, the electrical strength of transformer equipment is dominated by the oil channel, which is most "stressed." First of all, the channels are adjacent to windings. A significant increase in electric field intensity exists due to inhomogeneity formed by radial channels between coils, rails between winding and insulating cylinders, corner washers, and container rings.

The strength of turn and inter-coil winding insulation is determined by the breakdown potential of oil channels in the windings. Therefore, the calculated voltage across winding insulation [2] and experimental data [4] on voltage-dependent breakdown voltage, the thickness of winding insulation, and the size of the oil channel between the wires (coils) are used as criteria for evaluating insulation strength.

The remaining tasks for determining the internal insulation strength of transformer equipment require detailed analyses of electric field parameters in two-dimensional and three-dimensional (2D&3D) models by numerical methods and specialized software.

Currently, no quantitative physical theory for pure transformer oil breakdown exists. This means that there is no theoretical approach to substantiate criteria for the electrical strength of oil gaps. Therefore, known methods for electrical strength assessment are based on a comparison of statistically sufficient empirical quantities from physical models of structural fragments. Electric fields are quantified by average field strength along the length of the power line in adjacent channels, stress at the middle of its length, distribution of field strength over the surface of solid insulation, and distribution of strength along the power line (Weidmann curves) [4]. The so-called 90% "stressed" volume (Wilson's hypothesis) is estimated as an integral characteristic for large oil spaces near bushings and taps.

A significant number of works by researchers, software developers, and practicing engineers are devoted to this complex problem. In this work, questions are limited to the important issues of forming 2D&3D models for calculating electric fields in transformer equipment.

Traditionally, 2D plane-parallel and axisymmetric models are used to study windings' main insulation [4-6]. The software is based on numerical methods of finite element analysis (FEA) and has specialized preprocessors for forming electrode models and winding insulation elements. Electric fields in the bushings and taps regions are not modeled. Post-processing of results and corresponding assessment of windings' main insulation electrical strength are provided. The work [6] also presents a 3D model of electric fields around windings and bushings. However, model formation issues and margins of safety assessment are not covered. Software in reference [7] (method of integral equations) can be considered invariant because it assumes a 2D model of computational bodies "by segments" or from a limited set of elementary structural elements of high-voltage devices. Model formation in 2D&3D and application of the well-known invariant FEA systems of ANSYS and COMSOL for calculation of transformer equipment electric fields are considered in [8].

Electric field calculation in transformers and reactors is time-consuming due to the complexity of multi-element calculation geometries, even by specialized software. Such models are defined as "edge" or "middle" winding models. Electrode surface models and insulation in 2D are usually modeled by basic elements: lines, arcs of a circle, and arcs of an ellipse. Significant time is spent on the transition from design data of calculation notes and drawings to parameters of calculation bodies. Therefore, the labor cost of building calculation models by appropriate preprocessors should be minimized. And field parameter calculations must be post-processed in order to assess the electrical strength of insulation. These issues are of particular interest when using such modern, widely developed invariant software as ANSYS or COMSOL for the calculation of electric fields.

This article proposes an algorithm for implementing a preprocessor for unified elements and their positioning with relative and symbolic coordinates. The algorithm prepares data from 2D models of the main insulation of the transformer and reactor windings. Examples are given for 2D model formation and numerical calculation of electric fields by invariant software. The 2D&3D model construction of bushings and taps directly by means of calculation software was tested. Developed post-processors for determining 90% "stressed" volume and trajectories of electric field lines in 3D models of windings and bushings are demonstrated.

Electric field calculation in transformers and reactors is time-consuming due to the complexity of multi-element calculation geometries, even by specialized software

2. 2D models of main winding insulation with the positioning of unified elements by relative and symbolic coordinates

A preprocessor was developed [8] to minimize labor costs and automate data preparation during numerical 2D modeling of the main insulation of windings. It uses a unified structure of electrodes and insulation parts which are positioned by relative and symbolic coordinates. Data for the preprocessor is provided in tables of general data and parameters of unified models of electrodes, capacitive rings, insulating barriers, corner washers, taps, and transposed wire.

Coils with rectangular cross-sections, capacitive rings, metal pressing rings, and electrostatic screens are recorded as winding parameters in the “Electrodes” table. The geometry of unified electrodes is shown in Fig. 1(a).

The body (electrode) number order is arbitrary. The body with the number “zero” is the contour of the calculation area. Each subsequent body is described after the reference body is used to describe radial and axial gaps. Depending on the height of the electrode, the potential can be set with either a linear distribution $Q_1 \neq Q_2$ or a constant $Q_1 = Q_2$ one.

Preprocessors are used to minimize labor costs and automate data preparation during numerical 2D modeling of the main insulation of windings

The relative geometric position of bodies is determined by so-called symbolic coordinates and relative radial and axial gaps between the nearest internal and external surfaces of bodies from insulation to insulation. Internal surfaces are those that are located closer to the coordinate axes — viz., the inner surface in the radial direction and the lower one in the axial direction.

For example, the notation in radial space is: *_# Nr. The first symbol * is written with the letters “I” or “O” for inner or outer surfaces, respectively, of the calculated body for which the data line in the table is filled. The inner and outer surfaces of the previously described support body are identified by the number Nr in place of “#”. The next column of the table defines the relative radial distance $<\Delta r>$ between specified surfaces in the symbol interval. A positive value of the interval corresponds to the displacement from the reference body to the calculated body along the positive direction of the coordinate axis. Axial spaces are similarly described: number *_# Nz and relative distance $<\Delta z>$. Axial a and radial b dimensions of the electrode begin at the surface, including the thickness t of its insulation. The radius of rounding r_C is indicated on the metal surface of the electrode. If there is insulation on the electrode, its relative permittivity and thickness are recorded. The radius of rounding of the insulation is calculated by the preprocessor program using that of the electrode and the insulation thickness. For the capacitive ring, the radius of “large rounding” R_C is also specified.

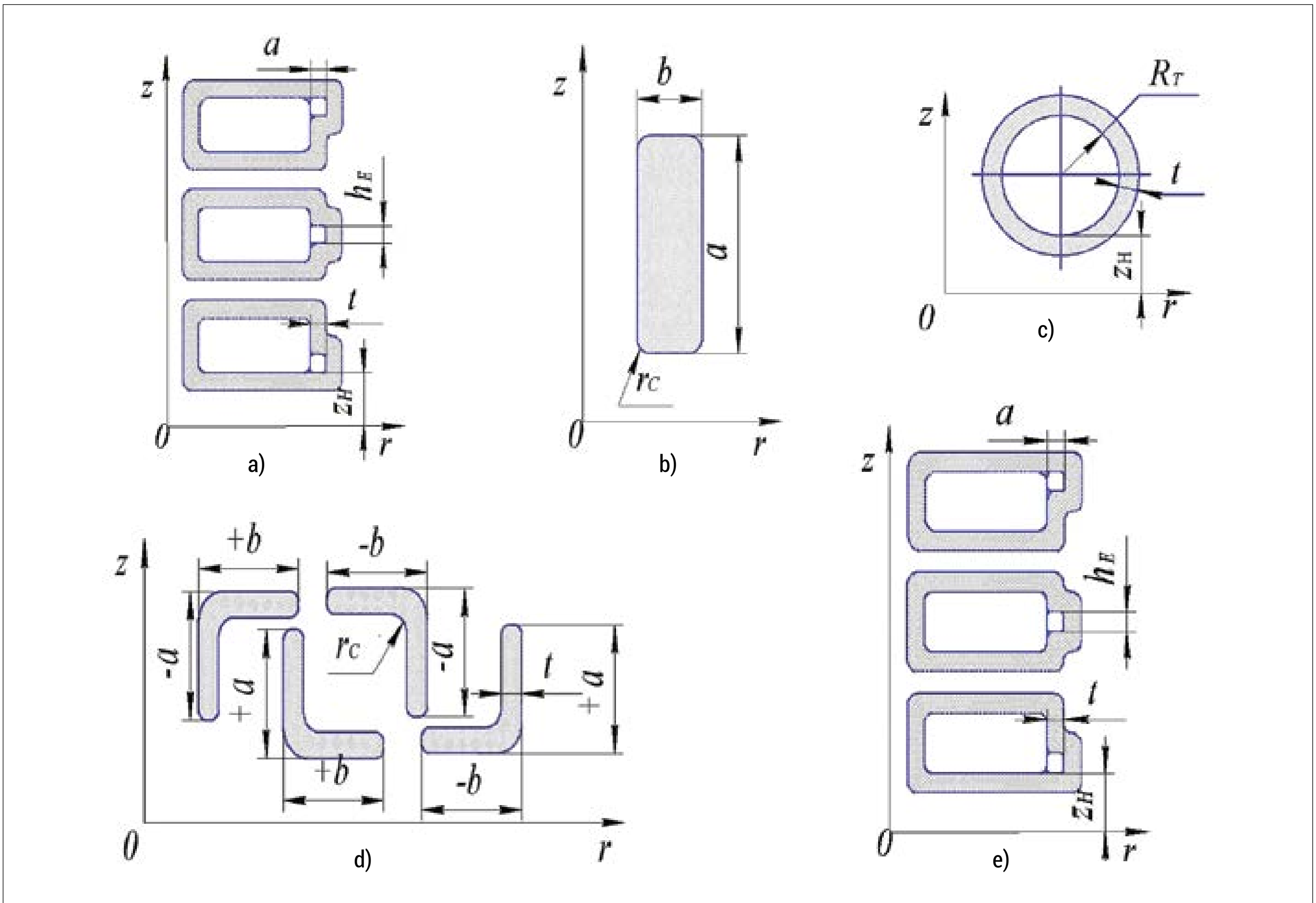


Figure 1. Unified structure of electrodes and insulation parts:
(a) electrodes, capacitive rings, (b) barriers, (c) taps, (d) corner washers, (e) transposed wire

The relative geometric position of bodies is determined by so-called symbolic coordinates and relative radial and axial gaps between the nearest internal and external surfaces of bodies from insulation to insulation

Insulation barriers include cardboard cylinders, flat washers, and non-metallic pressing rings. The unified barrier model geometry is shown in Fig. 1(b). Data is prepared, and tables are filled in screen form for insulating cylinder barriers the same as for electrodes. The one difference is that insulating barriers do not have insulation thickness parameters and potentials. Dielectric permeability characterizes the insulating material of the barrier.

Corner washers made of electrical cardboard are placed in separate rows due to their position and geometry peculiarities - Fig. 1(d). It is assumed that inner and outer surfaces in radial coordinates refer only to vertical parts of the washer. Inner and outer surfaces in axial coordinates are similarly assumed to refer only to the horizontal shelf. Data also quantify the height a and radial b dimensions of the washer. Height is the entire axial dimension, including the height of the vertical part and the thickness of the horizontal shelf. Positive height indicates that the shelf is placed below the vertical part. When the horizontal shelf is placed higher, and the vertical part goes down due to the rounding radius, height is negative. The radial dimension is recorded according to the same rule. Positive direction indicates the respective direction of the radial coordinate axis (to the tank wall). The negative direction indicates the opposite (toward the rod). Insulation is characterized by relative dielectric permeability and washer thickness t.

Toroidal elements model capacitive rings and circular cross-section taps (Fig. 1(c)). Their positions among calculation model bodies are described similarly to that of rectangular electrodes using symbolic and relative coordinates. Toroid metal radius, relative dielectric constant, insulation thickness, and the potential are illustrated.

The model shown in Fig. 1(e) is used for coils with transposed wire. Its feature is the location of the extreme elementary wire at the edges or in the middle of a coil's axial dimension. Therefore, in addition to axial and radial distances from other bodies, coil height, width, insulation thickness, and other information are specified: h_E height and d_E thickness of the elementary wire and M_E a conventional sign for location. The preprocessor builds wire geometry with the outermost wire of the inner winding on the outer surface of the coil transposed with the outer winding on the inner surface of the coil.

The preprocessor automatically divides the contours of calculated bodies into segments for detailed field calculation and analysis. A plot with the maximum contour curvature (with the minimum radius r_{min}) is determined from the curvilinear contours of calculated elements. The distance between calculation points (calculation interval) on all curved plots is assumed to be equal r_{min}. On rectilinear body contour plots, points are chosen so that the lengths of adjacent intervals differ by no more than 5 times.

Depending on invariant programs' capabilities, appropriate pre- and post-processors have been developed for receiving external information and issuing calculation data.

For example, AXIAL software is able to read input data in text format in a defined sequence for creating elementary geometry. The process of transforming the unified structure into text format may be implemented in different ways. The authors used Borland Developer Studio and the Delphi and Fortran programming languages. AXIAL calculates force line length and the average strength along them at specified points. Accordingly, no special post-processors for calculation results were developed. There are no functions for calculating stressed volume in the program.

COMSOL software directly constructs geometry through Java class libraries and Matlab scripts, in addition to reading parameter information from text lists. The preprocessor of the unified structure transformation in COMSOL was imple-

The preprocessor of the unified structure transformation in COMSOL was implemented in Embarcadero RAD Studio and programmed in C++ by means of Matlab scripts

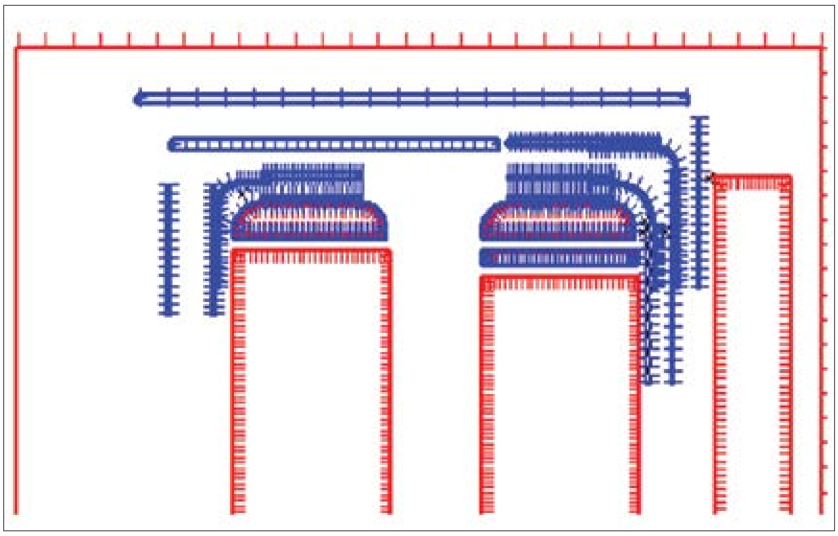


Figure 2. Estimated 2D model of the "edge" of the windings of a 500/220 kV autotransformer rated 167 MVA

mented in Embarcadero RAD Studio and programmed in C++ by means of Matlab scripts. COMSOL constructs streamlines from the specified surface (curve) to the outer boundary of the model, but there is no automated process for determining line length in oil gaps or the average stress along a line. Therefore, it was expedient to create post-processor tools to determine the characteristics of oil gaps and the corresponding reserve coefficients. Restructuring of geometry with streamlines in the most loaded areas and with minimal reserves has also been implemented. Standard COMSOL tools can be used to calculate the stressed volume around a given point.

There are no standard ANSYS tools for analysis of oil gap electrical strength and no functions to construct streamlines. However, the program includes the built-in APDL programming language, which provides a wide range of opportunities for geometry construction and analysis of results. APDL macros enable communication to a unified structure through files in text format and subsequent construction of geometry. APDL tools include macros for constructing power lines and evaluating the strength of oil gaps. Calculation of the stressed volume is only possible via special APDL macros.

An example of the calculation model is shown in Fig. 2. The preprocessor for AXIAL [7] formed "edges" of three windings of a 500/220 kV autotransformer rated 167 MVA. The left border of the model coincides with the surface of a magnetic system rod. Capacitive rings are located above two windings. In the middle winding, the outermost coil is selected. Thus, the model includes six electrodes with insulation, vertical insulating cylinders, and flat and angular washers for a total of 15 elements. The preprocessor segmented the contours for the approximation of secondary charges. Segmentation points are marked by dashes.

A 765/400 kV autotransformer rated 500 MVA was also modeled by AXIAL. The gap between the lower voltage windings and the regulating winding on the side shaft is modeled in Fig. 3, which shows the distribution of streamlines. Note that all coils of both windings are made of transposed wire. The wire model is shown in Fig. 1(e) and used by the preprocessor when forming the calculation model of the windings.

As a result of calculation from breaking points, the program produces streamlines and their parameters (length and average tension)

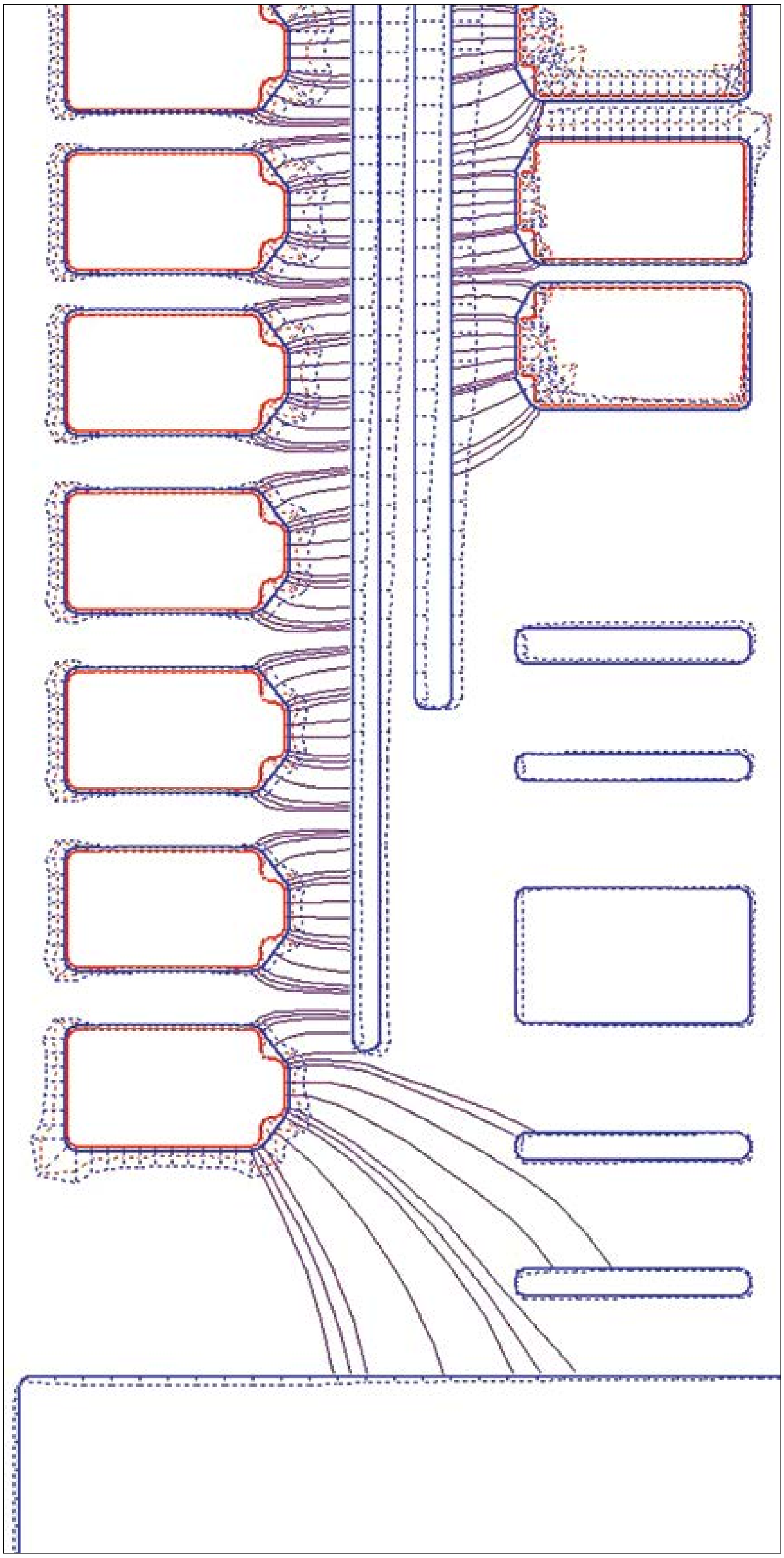


Figure 3. Calculated 2D model and distribution of power lines between lower voltage and regulating windings of a 765/400 kV autotransformer rated 500 MVA

The presented preprocessor created a calculation model of the “edge” of a general winding and a two-layer regulating winding of a 400/230 kV autotransformer rated 200 MVA

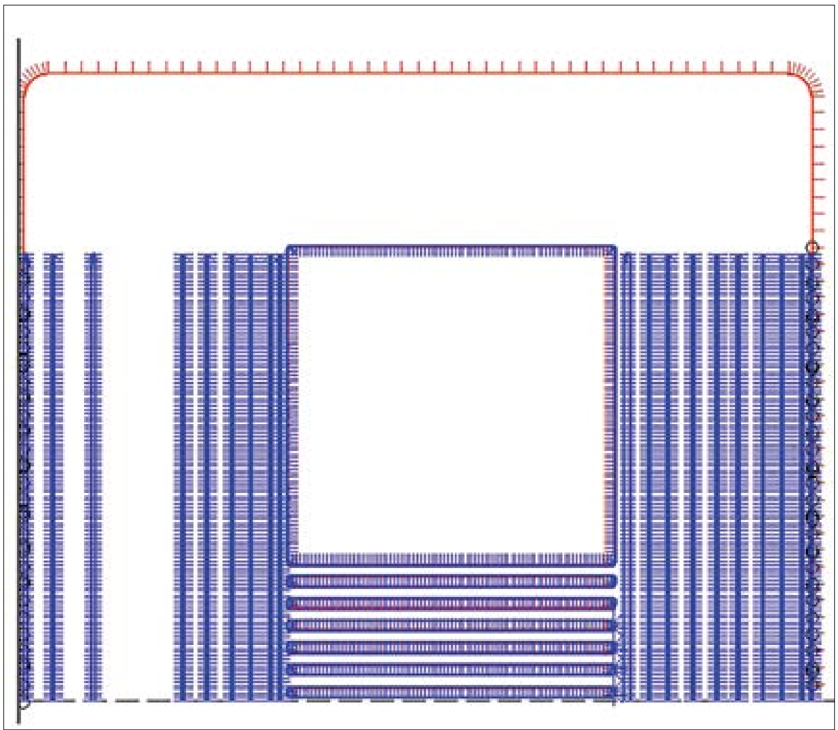


Figure 4. Estimated 2D model of the “middle” of winding in a 750 kV reactor rated 110 MVAR

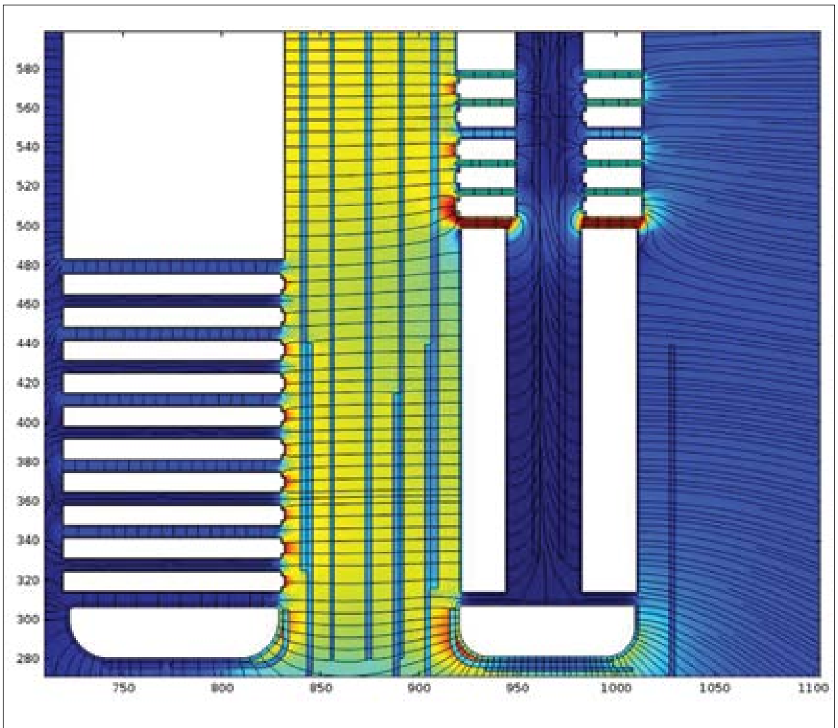


Figure 5. Calculated 2D model of the “edge”, voltage distribution and electric field lines of the windings, autotransformer 400/230 kV, rated 200 MVA

Similarly, elements and data for calculating electric field parameters in the “middle” zone of the winding were entered. Figure 4 shows AXIAL’s calculation model in the “middle” of the winding of a 750 kV reactor rated 110 MVAR. The left border of the model coincides with the surface of a rod in the magnetic system. The lower boundary of the model is the line of axial symmetry. The middle of the winding includes 6 insulated coils. Parts of vertical cylinders that insulate the inner and outer surfaces of the winding are also introduced. Dashes in Fig. 4 indicate the preprocessor-defined points segmenting contours of the calculated bodies for approximation of secondary charges. As a result of calculation from breaking points, the program produces streamlines and their parameters (length and average tension). The latter are subsequently used to evaluate the strength [4].

The proposed unified elements for complex calculation models using relative and symbolic coordinates are also used for numerical modeling of the main insulation using COMSOL software. For example, the presented preprocessor created a calculation model of the “edge” of a general winding and a two-layer regulating winding of a 400/230 kV autotransformer rated 200 MVA. The lower coils of a common winding are highlighted in Fig. 5; its other coils are represented by a block. Separate discrete elements represent coil sections in the input zone of the regulating winding. The model accounts for the main insulation structure between windings (vertical barriers and corner washers), the structure of the lower yoke insulation (horizontal barriers and support rings), and capacitive rings on winding edges. The distribution of electric fields calculated by COMSOL is shown in Fig. 5.

The electrical strength of the autotransformer insulation under study was evaluated based on the highest voltages on the power lines.

Figure 6 shows the model formed by the preprocessor and the distribution of electric fields in the lower part of the main insulation of a 500/138 kV transformer rated 300 MVA. The model contains winding fragments with linearly distributed potentials and a set of finite insulation under the windings.

Analysis of the complete model determined that the highest electric fields occurred at the edge of the inner, lower voltage winding. Figure 7 shows an edge fragment of the specified winding with streamlines along which insulation electrical strength was evaluated.

Operating experience with calculated electric fields proves the effectiveness of multivariate studies in specifying power transformers and reactor insulation [8]. An automated procedure was developed for forming complex calculation areas at the "edge" and "middle" height of windings to calculate electric fields.

3. 2D finite element models of taps

Electric fields in power transformer and reactor taps are evaluated by selecting the characteristic sections of "tap-tank wall," "tap-winding surface," "tap-winding end," and "tap-tap." The plane-parallel calculation model is demonstrated directly in COMSOL. Figure 8 shows the voltage distribution and streamlines of the tap-winding gap of a 132/13.8 kV transformer rated 60 MVA. The tap is separated by spacers of two multi-core wires with their own common insulation. The lower boundary of the model corresponds to the winding surface. There are cardboard barriers between the tap and the winding. In this case, strength assessment is based on the breakdown strength of the adjacent oil channel. Empirical dependences are normalized by the thickness of insulation on the tap, the diameter of the tap, the width of the oil gap, and the length of the tap.

The value of the most "stressed" 90% volume from the surface of the general tap insulation is also determined by standard COMSOL software tools.

4. 2D finite element models of input installations

Planar problems in the vertical section of the winding, in the horizontal plane (plane-parallel models), and directly in the bushing installation itself (axisymmetric models) are treated with regard to 3D bushing design and placement relative to windings [8].

For example, a 2D model of the high-voltage bushing installation zone

Electric fields in power transformer and reactor taps are evaluated by selecting the characteristic sections of "tap-tank wall," "tap-winding surface," "tap-winding end," and "tap-tap"

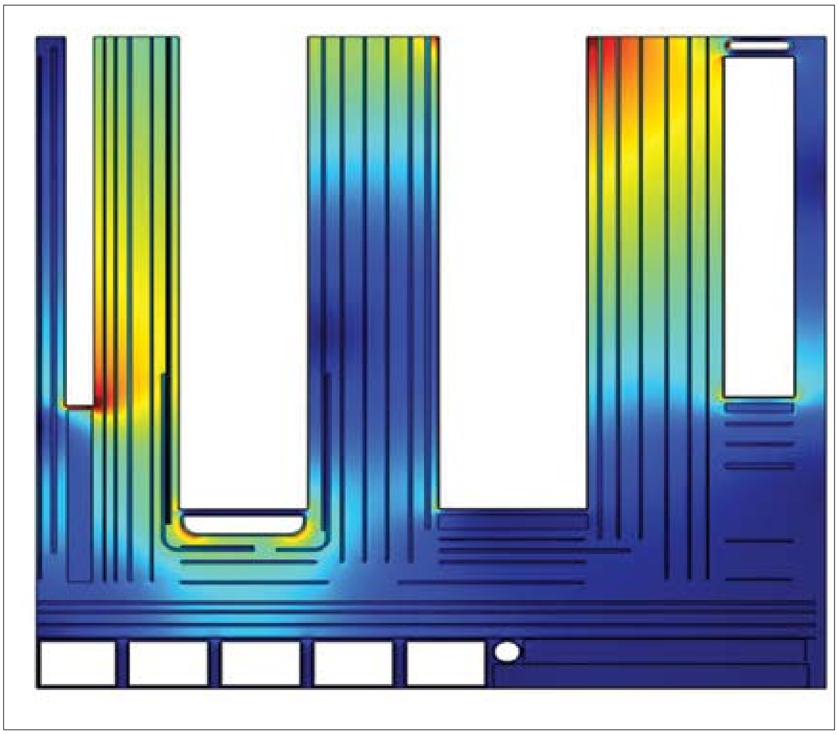


Figure 6. Calculated 2D model and distribution of electric fields in the lower part of the main insulation of a 500/138 kV transformer rated f 300 MVA

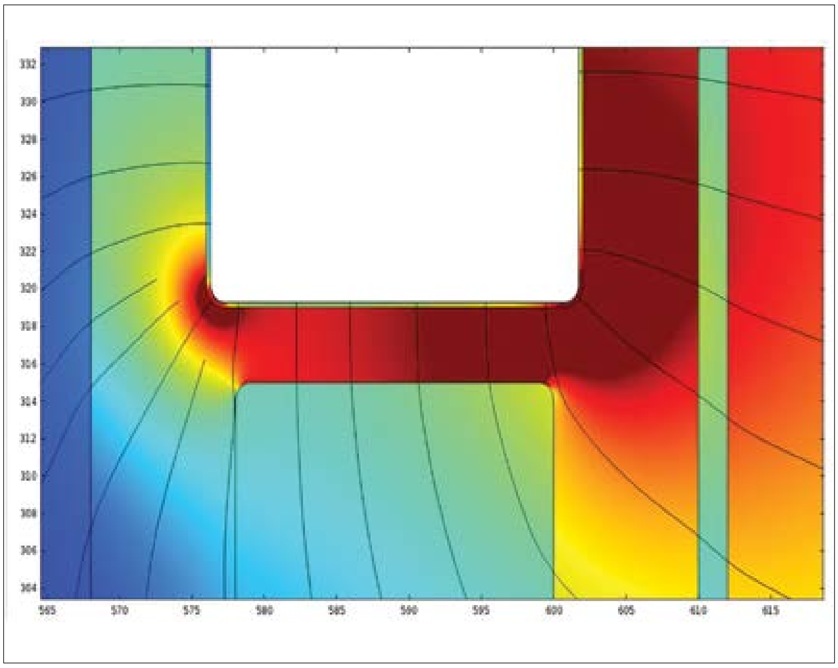


Figure 7. Distribution of potentials and electric fields in a fragment of the inner "edge" windings of a 500/138 kV transformer rated 300 MVA

A 2D model of the high-voltage bushing installation zone of a 500/220 kV autotransformer rated 500 MVA was built with the COMSOL graphic editor

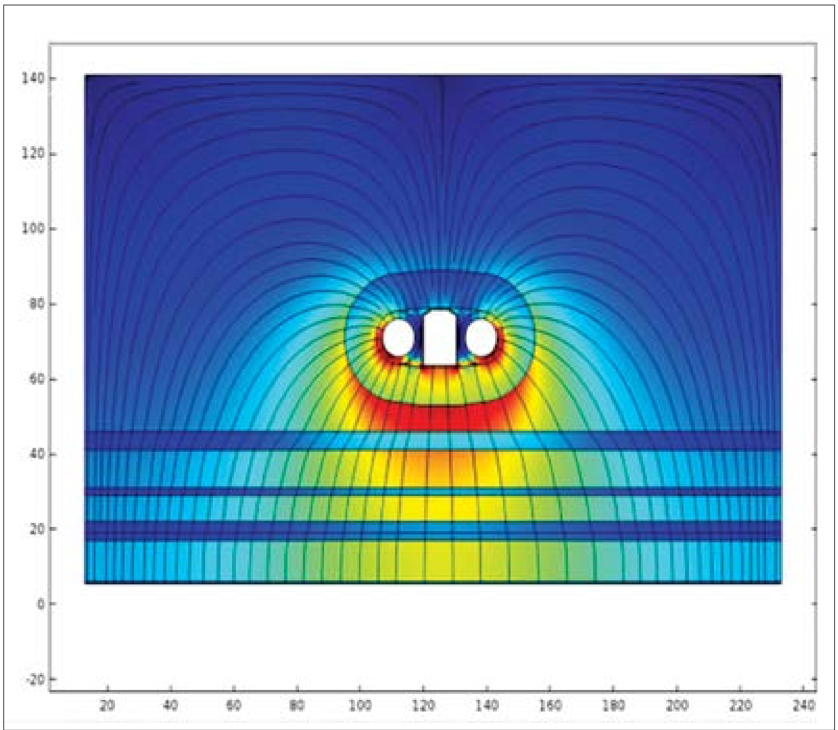


Figure 8. Estimated 2D model of the lead-winding gap of a 132/13.8 kV transformer rated 60 MVA

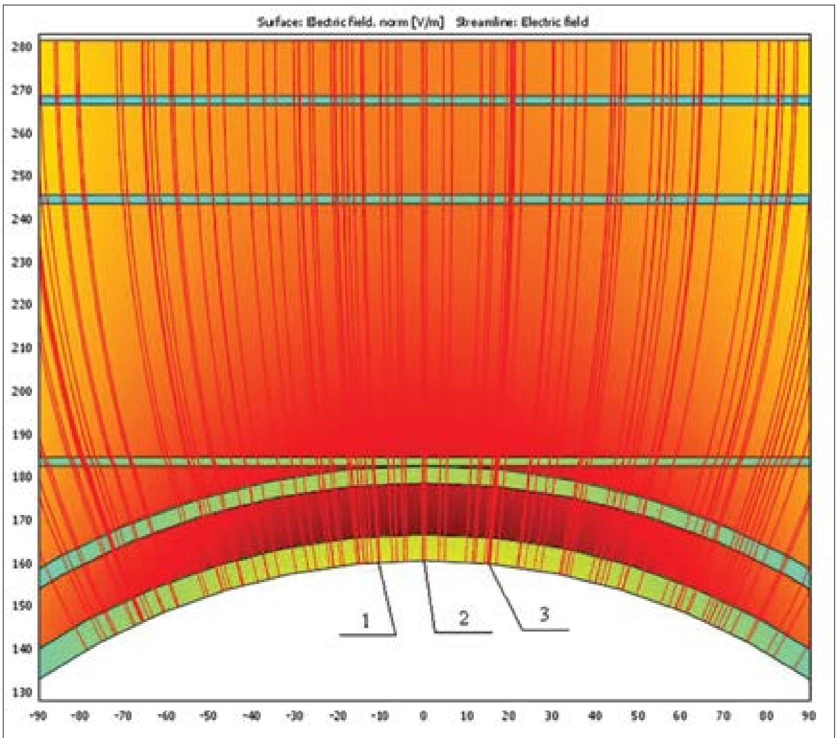


Figure 9. Distribution of tension and electric fields on the outer surface windings of a 500/22 kV autotransformer rated 500 MVA

of a 500/220 kV autotransformer rated 500 MVA was built with the COMSOL graphic editor. The model in Fig. 9 contains a flat upper boundary, winding surfaces, three winding insulation barriers, circular models of insulation, and a bushing shield in the horizontal plane. Coil potential on the winding surface is set based on the calculation of the vertical model to which streamlines extend from the most stressed point on the bushing screen. The calculation model and distribution of tension and electric fields are shown in Fig. 9.

Field values along the streamlines (marked by numbers 1-3), which come out of the bushing and are located in the first channel (from the bushing casing to the winding cylinder) and in the second channel (between the two winding cylinders), are analyzed. Electrical strength is evaluated according to the worst case.

Electric field tension and trajectory were calculated using COMSOL. Construction of the grid was carried out in automatic mode over the entire calculation area. Then, the grid was divided into finer zones of the largest field gradients with the help of the standard tool "improvement."

In a vertical section, the model (Fig. 10) contains a fragment of 33 coils in the middle of the winding. It includes input insulation, a protective casing, and three cardboard barriers located between the winding and the casing. The problem is symmetric around the axis of the winding with an expanded bushing contour. Part of the calculation model geometry (contours of coils, barriers, and oil) is built by COMSOL's graphic editor. The bushing and casing geometry, which has a complex boundary formed by combinations of arcs with different radii, is constructed in Pro/ENGINEER (Creo) and then imported into COMSOL. Flat geometry is imported by building a 3D model of the specific section and exporting a 2D drawing in DXF format. Potentials determined for a full lighting impulse are set on coil surfaces.

Bushing insulation (the lower parts) is evaluated by assessing the strength of the main insulation with corrections for smaller field utilization factors. The distribution of electric field strength and streamlines in the area between the winding coils and the bushing surface is shown in Fig. 10. The numbers 1-3 indicate the lines of force along which strength was assessed.

5. 3D numerical models of bushings and windings

Let us now consider the 3D calculation model of the bushing for a single-phase autotransformer rated 500 MVA at 765/400 kV. The calculation model was built in Pro/ENGINEER (Creo) and imported into COMSOL via the IGES format. The model includes the inner surface of the tank wall, the surface (without insulation) of the outer windings of the main and side rods of the magnetic system, cardboard barriers around the windings, cardboard barrier near the tank wall, a conductive bushing screen, paper insulation on the screen, cardboard cylinders around the input screen, porcelain input insulator, and the tap from winding with paper insulation. The model is limited by the surfaces of the winding vertical sections and the inner border of the tank wall. Transformer oil fills all volume, which is free of structural parts. Oil is limited in height by horizontal planes far enough from the bushing inlet zone to minimize the influence of boundary conditions. Symmetry conditions are set on

Bushing insulation (the lower parts) is evaluated by assessing the strength of the main insulation with corrections for smaller field utilization factors

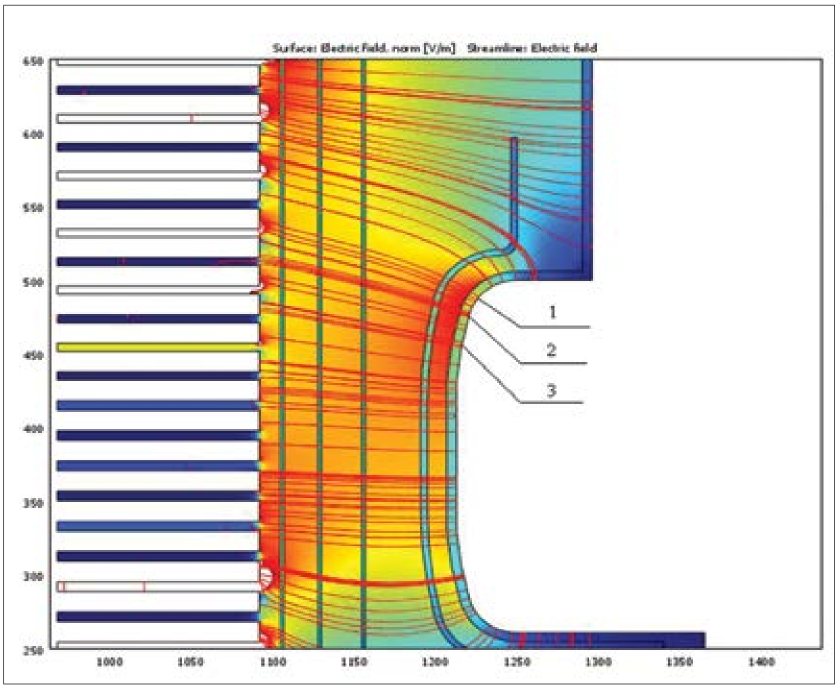


Figure 10. Distribution of the intensity and lines of force of the electric field in the input zone for a 500/220 kV autotransformer rated 500 MVA

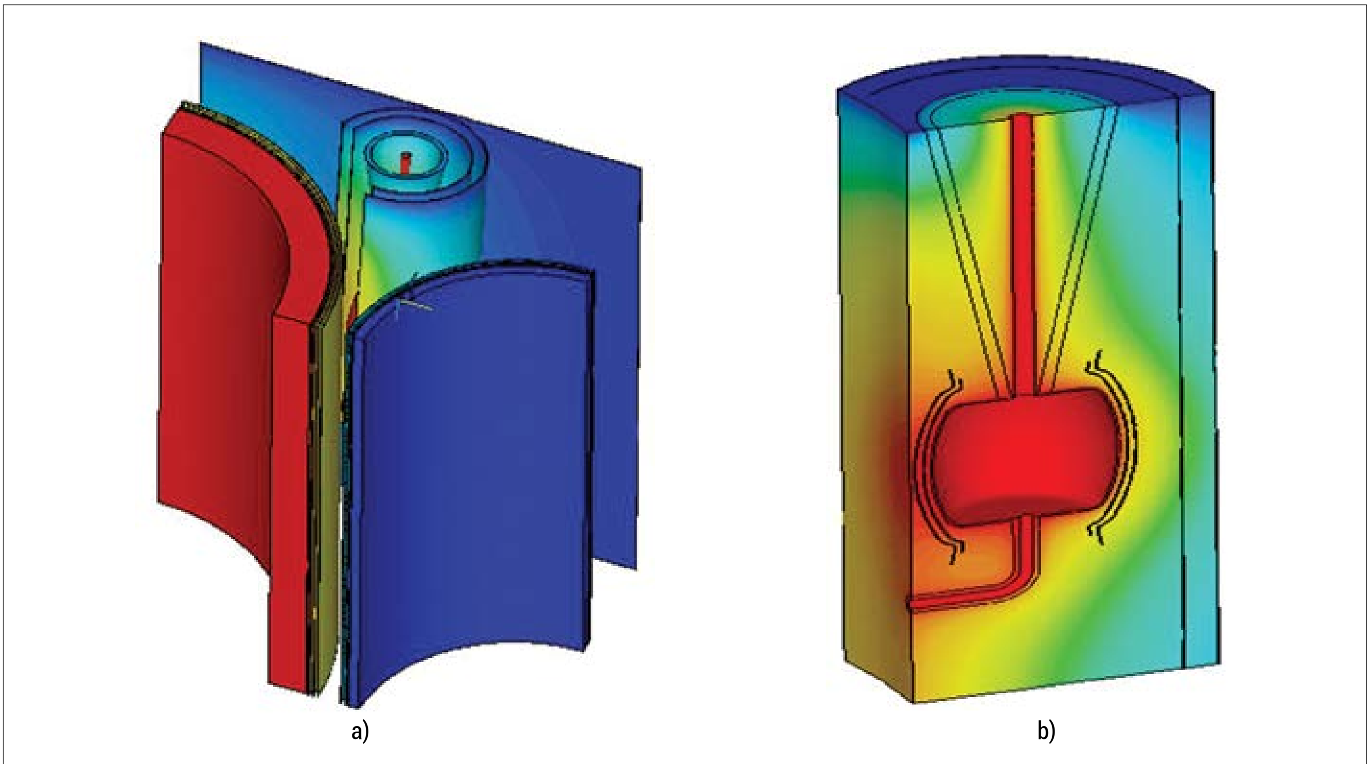


Figure 11. Potential distribution of the calculation model of a 765/400 kV autotransformer rated 500 MVA: (a) is a calculation model without oil, (b) is a cross-section of the input unit

A 100% potential is set on the surface of the screen, inlet and outlet pipes, and winding of the main rod, and ground potential on the tank surface and on the winding surface of the side rod

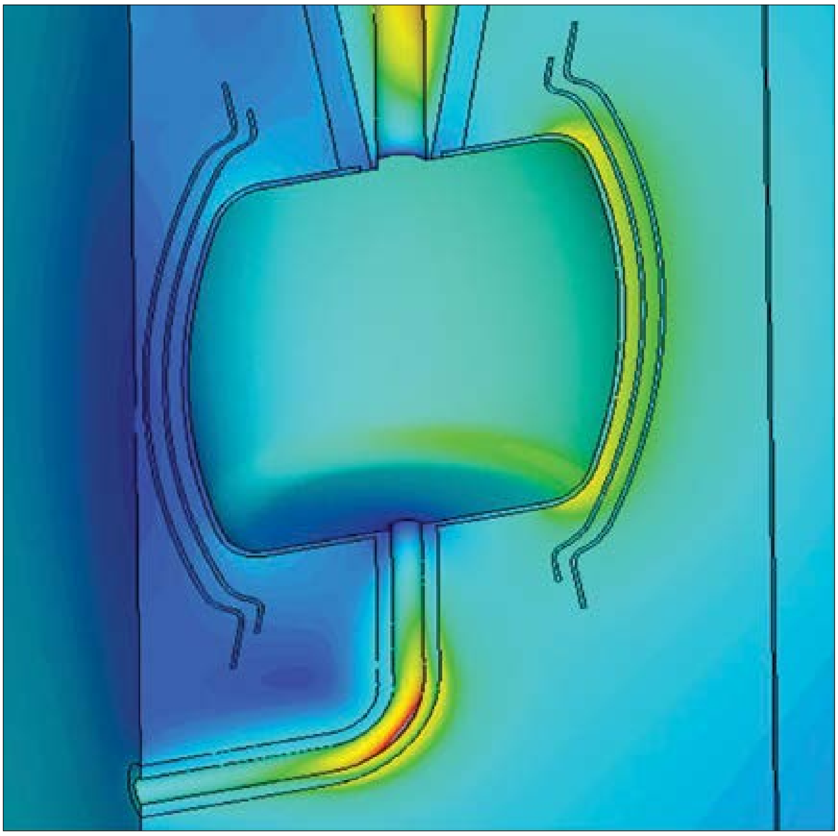


Figure 12. Voltage distribution in the input section of a 765/400 kV autotransformer rated 500MVA

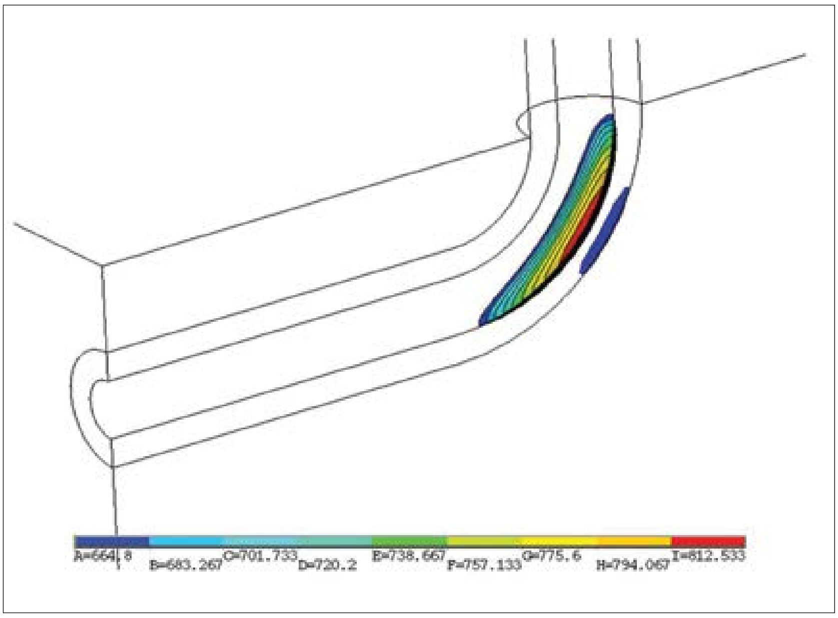


Figure 13. "Tense" volume at the bending of the lead to the winding of a 765/400 kV autotransformer rated 500 MVA

the surfaces of a model's vertical sections. Relative permeability was determined for the following materials: oil, paper insulation of the screen, porcelain insulators, and cardboard cylinders.

The distribution of potential on the general calculation model geometry without oil is shown in Fig. 11(a). Moreover, Figure 11(b) shows a cross-section of the bushing device.

A 100% potential is set on the surface of the screen, inlet and outlet pipes, and winding of the main rod, and ground potential on the tank surface and on the winding surface of the side rod. The stress distribution in the input section is shown in Fig. 12. Note that the surface of paper insulation on the tap bend and on the lower edge of the screen is the most stressed.

Volumes with 90% tension are identified with the use of specially developed calculation macros in ANSYS in order to assess insulation strength. Figure 13 shows the "stressed" volume at the tap bend of a winding.

The location of the "stressed" volume on the screen is shown in Fig. 14. Values obtained for the "stressed" volume were used to estimate the electrical strength of tap insulation.

A post-processor developed in the ANSYS software for 2D&3D problems was used to evaluate the insulation strength of the tap "along the streamline." The built-in "path" function is used for streamlining visualization carried out through selected grid nodes. The so-called initial node with the greatest intensity on the surface (3D) or line (2D) is fixed as the first node. This node is determined by traversing all nodes on the selected object. Then, mesh elements adjacent to the initial node and belonging to the medium of line propagation (oil or air) are selected. The next nodes of adjacent elements are of the next-lowest intensity, which ensures descent along the gradient of field reduction. This node is defined as the new starting node. Accordingly, trajectory coordinates are triangulated and defined as reference points of the electric field streamline. The construction of the streamline ends at the node belonging to the boundary of the two environments' distribution or on the outer surface of the calculation area. To illustrate streamlined distribution, a certain step is set according to values of initial intensity; trajectories of movement are constructed from a point with a given initial tension.

Figure 15 visualizes a streamlined trajectory from the point of isolation of the tap bend with maximum intensity in the 3D model of windings, tank, and tap according to Fig. 11.

6. Conclusion

1. Methods of forming 2D&3D numerical models by specialized preprocessors and graphic editors for calculating electric fields in the areas of windings, bushings, and taps of transformer equipment are presented.

2. To minimize labor and to automate data preparation during numerical modeling, forming 2D models of the main insulation of windings with a unified structure of elements with relative and symbolic coordinates between their surfaces is expedient.

3. The tested post-processor calculates "stressed" volumes and builds streamlined trajectories for electric fields of the greatest magnitude in 3D models of windings and bushings. This allows electrical strength reserves to be evaluated in structures characterized by significant three-dimensionality and volumetric geometry.

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A post-processor developed in the ANSYS software for 2D&3D problems was used to evaluate the insulation strength of the tap "along the streamline"

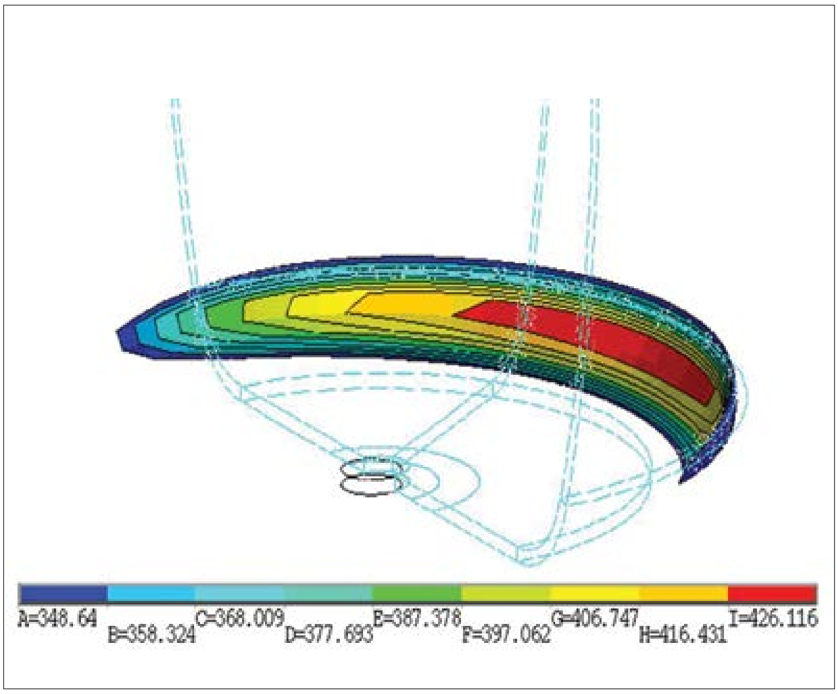


Figure 14. "Tense" volume on the screen of the winding lead of a 765/400 kV autotransformer rated 500 MVA

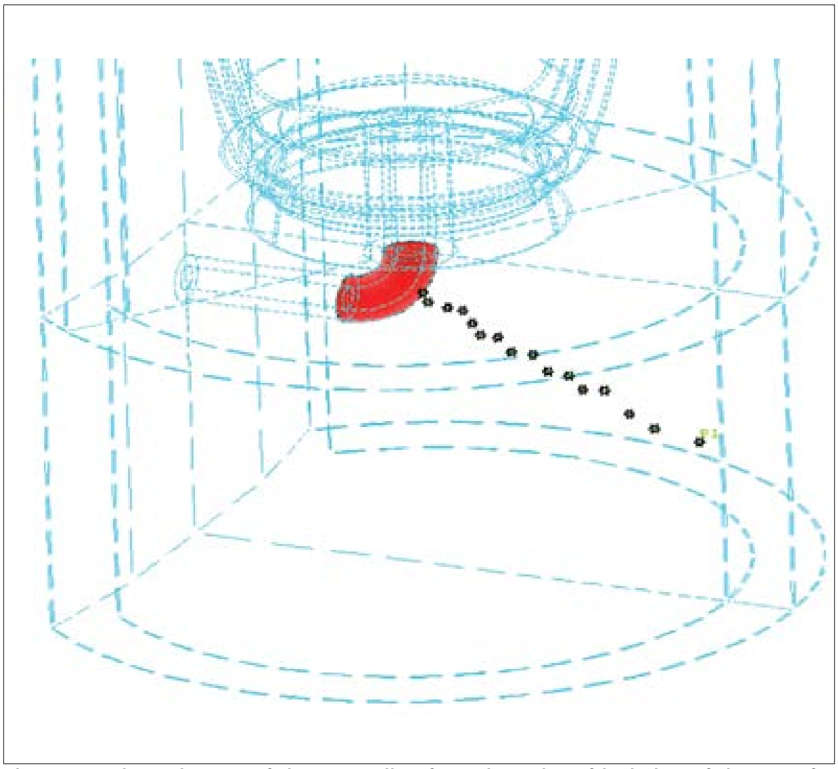
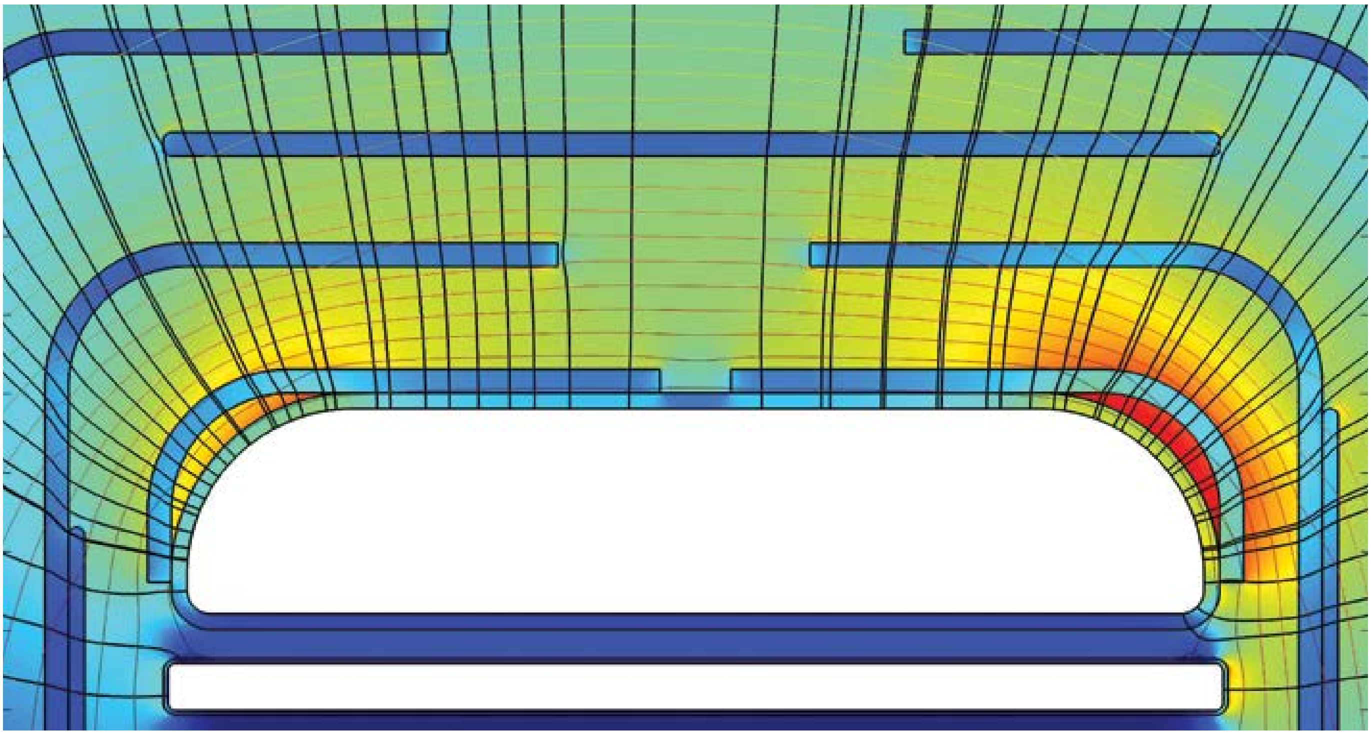


Figure 15. The trajectory of the power line from the point of isolation of the tap of a 765/400 kV autotransformer rated 500 MVA at the point of maximum intensity



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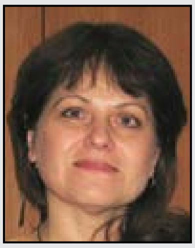

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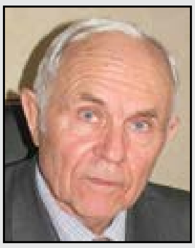

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