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A Method for Power Transformer Insulation Design Improvements Through Electric Field Determination

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Knowledge of potential and field distribution in the insulation system of a transformer during transient excitation is vital to its construction [1]. This paper deals with insulation design improvements of power transformers using electric field analysis. The calculation methods for electric field analysis, inside a power transformer impressed with impulse and power frequency voltages, are presented. Initially, a lumped parameter equivalent model is constructed by dividing transformer windings into several blocks and computing the electric circuit parameters of this model. Next, the electric field is determined by employing the results of the transformer transient model circuit analysis as boundary conditions; a 2D axisymmetrical electric field finite element analysis is performed. Finally a successful application of the proposed method for analysis of a model transformer is demonstrated and the computed results verified against measured results for this model.

INTRODUCTION

Normally, transformer windings have been treated as a concentrated electric network and their transient response found by employing a lumped parameter model. By dividing each winding into a number of sections and constructing an equivalent RLC ladder, the networks are studied [2]. Grasping the transient voltage distribution at the nodes of the electric network is possible, but estimating the electric field intensities between windings and coils from the voltage difference between the nodes is very difficult. This difficulty is because the electric field intensity distribution inside a transformer is highly affected by the geometrical shapes of windings and insulators [3].

In this paper, the authors propose a new method for calculating the transient electric field intensity distribution inside a model of a power transformer impressed with impulse and power frequency voltages. It is also shown that the visualization of this distribution is very useful for insulation design problems.

The proposed method has the following features:

a) A lumped parameter equivalent ladder electric circuit is employed for the determination of transient voltage distribution inside transformer windings during impulse and power frequency voltages. The lumped parameter electric circuit is constructed of blocks, made by dividing transformer windings into an appropriate number of sections, each modeled with an RLC lumped parameter equivalent circuit [4];

b) The voltage distribution inside the transformer is calculated employing a transformer transient voltage program, which has been written in the MATLAB programming language [4];

c) The electric field intensity is computed and its distribution inside the transformer is analyzed employing a 2D axisymmetrical finite element method;

d) Considering the pattern of obtained distributions mentioned above, design improvements can be achieved easily by employing practical means to increase the insulation system efficiency, i.e. making uniform the electric field distribution in critical paths;

e) Employing finite element analysis in this work would provide high accuracy in electric field calculations.

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THE MODELING METHOD

Electric Field Calculation Methods

Two general methods for electric field calculation exist: The measurement and the numerical method.

The results of measurements indicate real values for the electric field. This is, however, too expensive, since construction of a model which simulates the real characteristics of a field is not straightforward. Recently, numerical methods have been extensively developed and have obtained efficient results.

The application of numerical methods has many advantages compared to measurement methods, such as: Comparable accuracy, simplicity, low cost etc. Therefore, the numerical methods in insulation design are rapidly employed.

There are many methods for calculation of an electric field, including Finite Difference Method (FDM), Finite Element Method (FEM), Charge Simulation Method (CSM) and Integral Equation Method (IEM), which are appropriate methods for calculating two- and three-dimensional electric fields.

FDM is based on the numerical solution of Poisson or Laplace equations i.e.:

$$\text{Div } (\varepsilon \text{ grad}\Phi) = \rho \quad \text{Poisson},$$

$$\text{Div } (\varepsilon \text{ grad}\Phi) = 0 \quad \text{Laplace}.$$

In this method, potential deviation terms, including finite differences, are replaced. The above equations are solved, considering appropriate boundary conditions [5].

For assessment of the potential distribution in all regions, it should be divided into rectangular sections with a small h dimension. For any individual node in this region, finite difference equations are derived. For example, the Poisson equation is:

$$\begin{aligned}\text{Div } (\text{grad}\varphi) \approx \{&\varphi(x+h,\ y) + \varphi(x-h, y) \\ &+ \varphi(x,\ y+h) + \varphi(x,\ y-h) \\ &- 4\varphi(x,\ y)\}/(h\hat{\ }2) = \rho/\varepsilon.\end{aligned}$$

After deriving the above equation for all nodes inside the region and considering the boundary conditions, potential distribution at all nodes can be evaluated.

FDM is used for calculating two- and three-dimensional fields with axial symmetric and, also, for calculating the field in homogenous and non-homogenous areas.

FDM calculation error can be assessed via the trial and error method and by increasing the number of elements [5].

Similarly, FEM is a method for the numerical solution of Laplace or Poisson equations. However, in FEM, this region can be divided into areas with any arbitrary shape and determining the electric field on complicated boundaries is also possible. Knowing the estimated potential distribution inside the element, determination of the electric field intensity at any point inside that element and on the boundary is possible.

In the application of FEM, the determination of boundary conditions (in comparison with FDM) is simple [5].

In the application of CSM, the determination of image charges is difficult and depends on experience. Image charges can be of a point, linear, curve or surface type. These charges can be assumed to be constant or variable in length. The determination of the number and location of these image charges is more complicated, time consuming and needs more experience.

In CSM, electric field assessment is performed by the determination of the potential on the conductor surfaces at specific points, which are not reference nodes. However, determination of electric field error by this method is more difficult.

IEM is based on the Greenberg theory by replacing the actual field with an equivalent field, which is obtained by application of charges along the conductor and dielectric boundaries.

The first stage in IEM is calculating the potential through the assessment of equivalent charges [5].

A disadvantage of IEM is an increase in the number of nodes, which leads to increasing both computer memory and running time.

By doubling the number of nodes and repeating the calculation, the accuracy of field calculation in IEM would be improved.

In IEM, applying the Minimax theory will reduce the electric field intensity calculation error on the conductor surfaces.

Therefore, the important point in IEM is the determination and selection of the number and type of charges, which simulate the electric field and their location.

With the same number of nodes, the accuracy of CSM is less than IEM.

Each numerical method has its own operational capabilities.

The other development in FEM is the capability of automatic mesh generation in advanced software. FEM has recently improved extensively for application in the electric field determination of high voltage equipment. It is, therefore, widely employed by researchers [5].

Electric Field Intensity Analysis

The construction of an equivalent circuit considering all the windings inside the transformer is an important problem for transient studies. The equivalent circuit is constructed by dividing windings into several blocks, each one made up of a number of coils, as shown in Figure 1. In Figure 1a, a general view of the winding arrangement is shown, in which the LV winding is divided into 13 blocks, the HV winding into 15 blocks and the tap winding into 13 blocks. The inter coil insulation is also shown. In Figure 1b the details of winding and insulation as angle rings, paper and oil are shown in the lower part of the set; in Figure 1c, a similar demonstration is shown for the upper section of the winding. After performing the winding divisions, the transient electric field analysis is performed as follows:

Step 1: The voltage distributions along the windings are computed employing the program written in the MATLAB domain. If required, test voltages (such as lightning impulse, power frequency, switching impulse and voltages) are applied to the related transformer windings [4];

Step 2: The voltage boundary conditions of the related block surfaces at specific time t, according to the computed voltages of the previous step, are applied [3];

Step 3: The electric field analysis is carried out employing the 2D axisymmetrical finite element method;

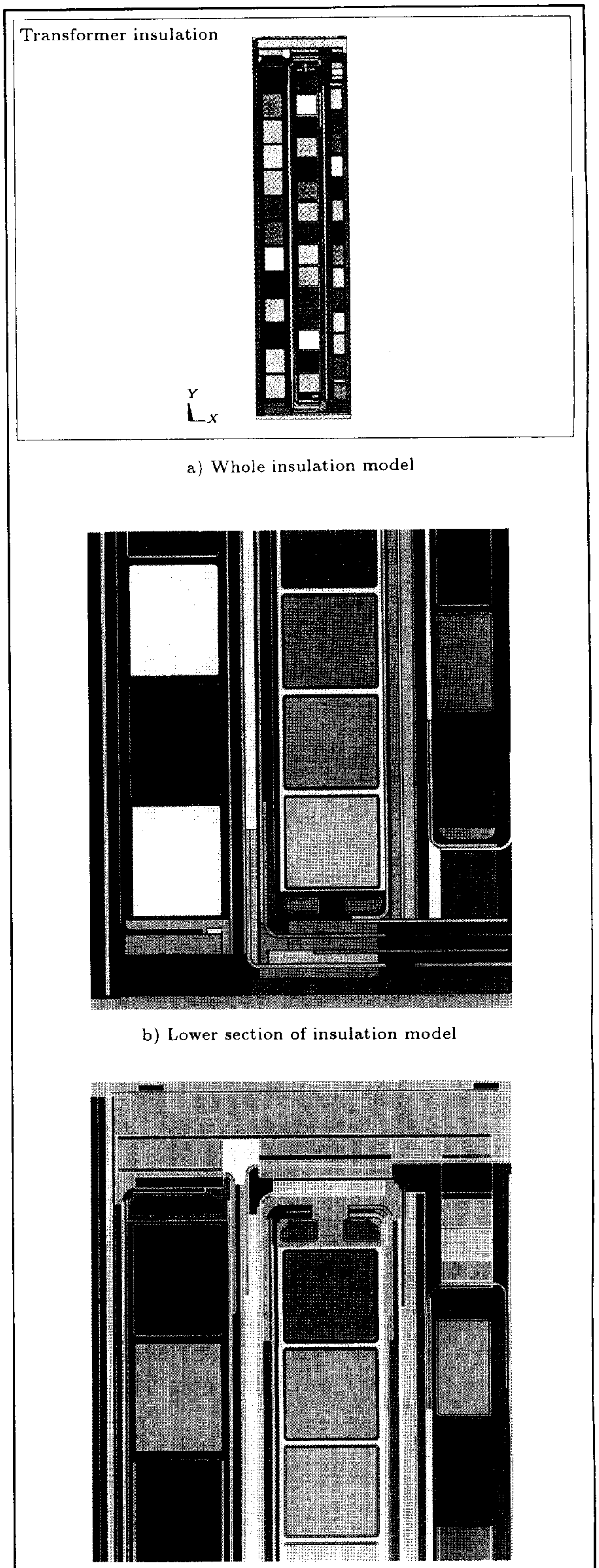
Step 4: Distribution of electric field intensity in any predefined path and in the whole transformer model between the winding and electric field vectors is demonstrated;

Step 5: The computed electric field values are compared with permissible values, considering the safety factors;

Step 6: If the calculated values for electric field intensity are lower than permissible values, the insulation system should be approved, otherwise required changes should be applied to the insulation system (as a measure for improving the insulator shape, etc.) and the process reviewed until satisfying the requirements.

Construction of the Equivalent RLC Ladder Network

The equivalent circuit for one block is constructed as a parallel connection of a self-inductance, a serial capacitance and a serial resistance. Mutual inductance is set between each set of two blocks. The parallel capacitance between any two blocks is composed of parallel capacitances between the upper and lower blocks in the same winding and the capacitance between the blocks of inner and outer windings. This parallel capacitance must be connected to the circuit



a) Whole insulation model

b) Lower section of insulation model

c) Upper section of insulation model

Figure 1. Transformer insulation model.

terminals [6]. By employing this equivalent model for all the blocks, the complete equivalent RLC ladder network will be produced.

Applying Boundary Conditions Required for the Finite Element Electric Field Analysis

From the transient analysis of the equivalent circuit constructed in the previous section, the voltage values along each winding are obtained for required test voltages, such as power frequency, lightning impulse, switching impulse etc., using programs written in this order [4].

For Electric Field Analysis, after creating the complete model of the transformer (i.e. creating the geometry and specifying the materials) and employing an appropriate meshing arrangement for the created model, the computed boundary conditions of each block for the specific test have been applied on that block.

Hereby, it should be pointed out that in this case, each set of windings was treated as a conductor. However, as each set is composed of a large number of coils, voltage distribution along the winding is not constant. Therefore, in order to calculate the electric field distribution with high accuracy, it is necessary to divide each set of windings into as many numbers of blocks as possible and, then, to set the boundary conditions on these relatively large numbers of resulted blocks. In this paper, the determined voltage distribution along the transformer windings during required tests is applied to the related block of a set of windings, assuming an equipotential level for that block and, then, the field calculation is performed.

EVALUATION METHOD

As a result of finite element analysis, physical values for voltage and electric field intensity at each node of the model are obtained as numerical information [3]. Therefore, it is very difficult to grasp the distribution and physical meaning of the obtained results directly from these data. On the other hand, observers may sometimes miss important data or may even misunderstand the obtained results. In order to solve these problems and to aid in the design process, some programs have developed a post-processor that displays electric field distribution.

To easily understand the physical phenomena, it is important to directly visualize the physical values, which are of the analyst's main interests. In the design of inner insulation, the electric field intensity distribution between insulation materials or windings is very important [3]. Therefore, visualization of the electric field intensity distribution makes the observed phenomena easier to understand. In the case of the investigation of the dielectric breakdown of power transformers during test voltage impressions, it is important that the obtained electric field intensity values of each material inside the transformer should be less than or equal to, the maximum permissible value of each material for its dielectric breakdown. It is extremely difficult to determine the exact values for the maximum permissible electric field stresses, since they depend on a large number of parameters, such as geometrical structure, type of transformer insulator, age of transformer and working conditions (such as contamination, overload and overheat history). Therefore, it is better to use the prescribed values for each dielectric material inside the transformer.

CASE STUDY ON A MODEL TRANSFORMER

In order to verify the modeling method, a 230/63 kV, 40 MVA power transformer is employed and the required test voltages (in accordance with IEC 60076-3) are applied to the related windings [7]. It means that impulse and power frequency test voltages are applied to the model transformer shown in Figure 1. The calculated values of transient voltage distribution in the windings were initially compared with measured values. Afterwards, the transient electric field intensity distributions are visualized.

Comparison of Transient Voltage Distribution

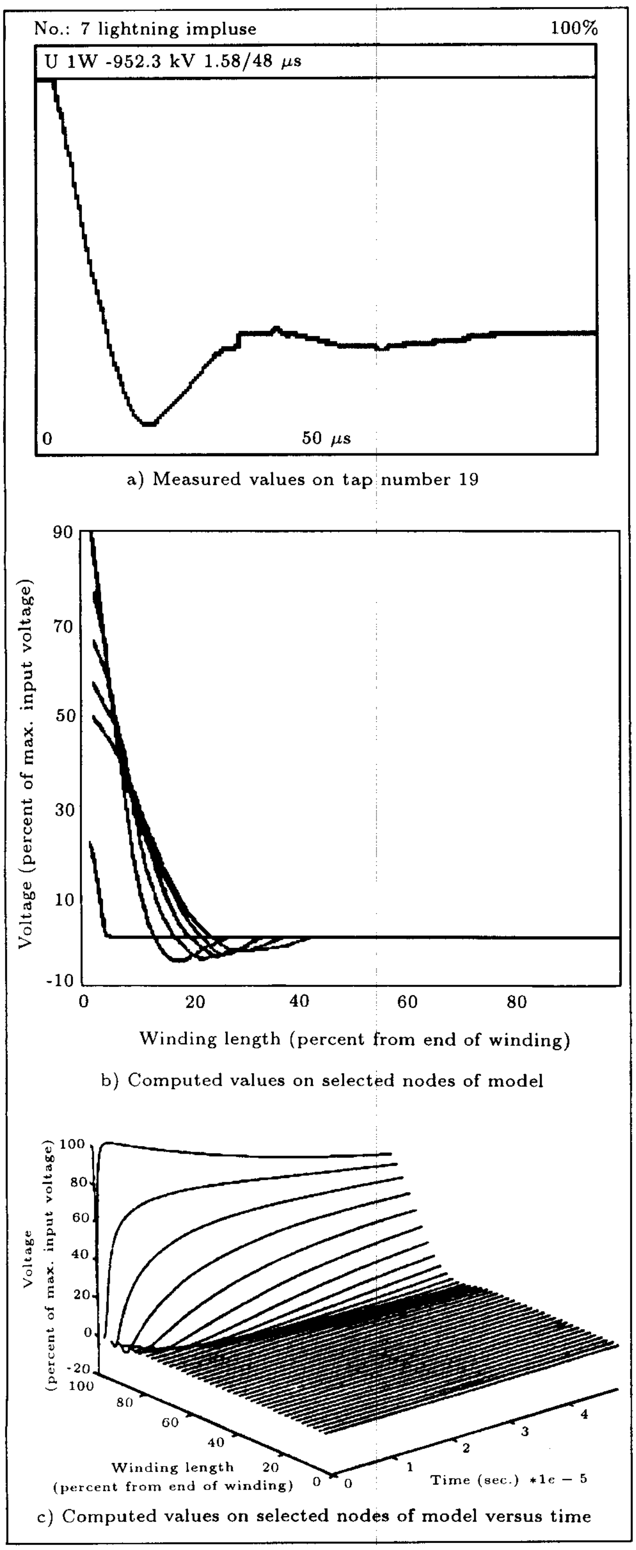
Figure 2 shows a comparison between analysis results and measured values of transient voltage when 1.2/50 μs impulse voltage is impressed to the high voltage winding.

The voltage distributions at several measuring points along high voltage and regulation windings (see Figure 2) were monitored. As evident from Figure 2, both measured and computed voltage waveforms coincide almost completely. However, in some nodes, the difference between waveforms becomes gradually larger. The reason for this discrepancy is hypothesized to be two-fold: (1) Because the distributed constant circuit was treated as a concentrated constant circuit and (2) Because the effect of circuit damping was neglected during transient electric circuit analysis.

Evaluation of Transient Electric Field Distribution

Voltage and electric field distributions are displayed. The peak value of impulse voltage is 850 kV and the peak value of power frequency test voltage is 360 kV.

The transient voltage distributions and electric field intensity distributions are recorded and animated, so that the physical phenomena inside the transformer

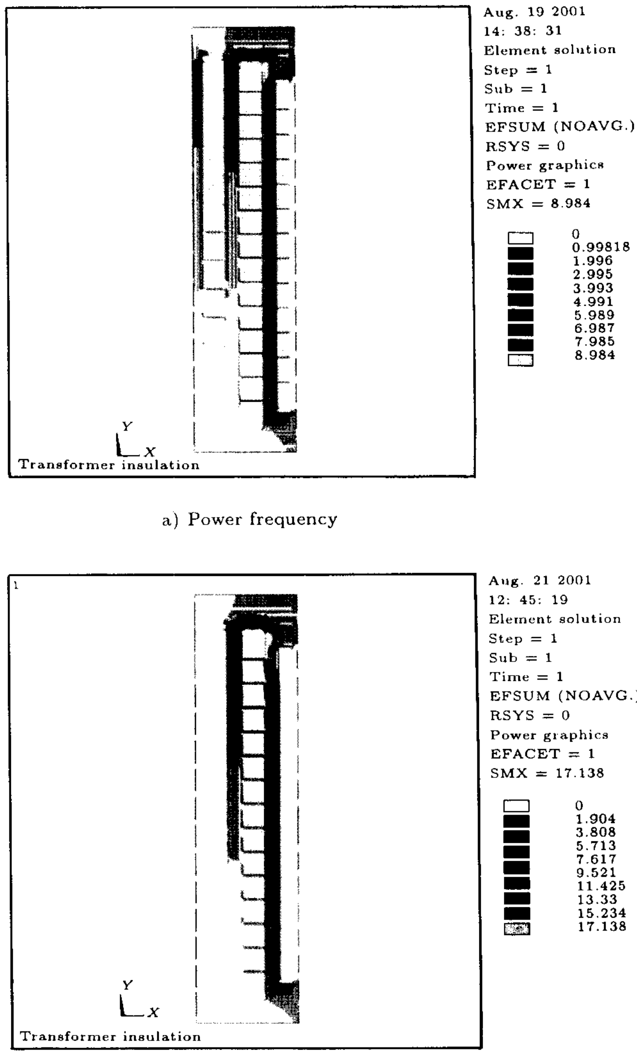


a) Measured values on tap number 19

b) Computed values on selected nodes of model

c) Computed values on selected nodes of model versus time

Figure 2. Comparison between measured and computed results for lightning impulse test voltage.



a) Power frequency

b) Lightning impulse

Figure 3. Electric field intensity distribution in insulation winding.

can be observed easily. Figures 3 and 4 show voltage and electric field intensity distributions for lightning impulse and power frequency test voltages.

It is clear that maximum electric field intensity occurs on the upper left edge of the high voltage winding. There are so many plans to reduce this electric field intensity, including the following:

a) Employing electrostatic rings,

b) Employing angle rings,

c) Employing spacer with shorter length on electrostatic rings,

d) Employing SiC semiconductor coating.

In this study, the ability to draw voltage and electric field intensities on any predefined path is available.

In order to verify this capability, two paths are defined and the variations of electric field intensity along these paths, for three models of a transformer, are compared. Path 1 is a straight line that begins from the lower left edge of the electrostatic ring (which is below the regulation winding), up to the right edge of this electrostatic ring. Path 2 is a circular shaped

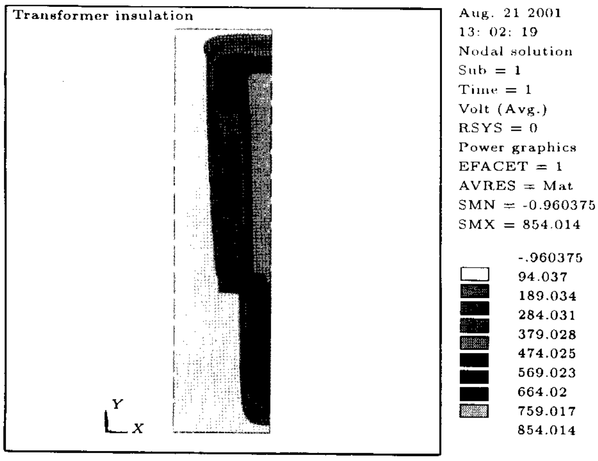


Figure 4. Voltage distribution in insulation winding for lightning impulse.

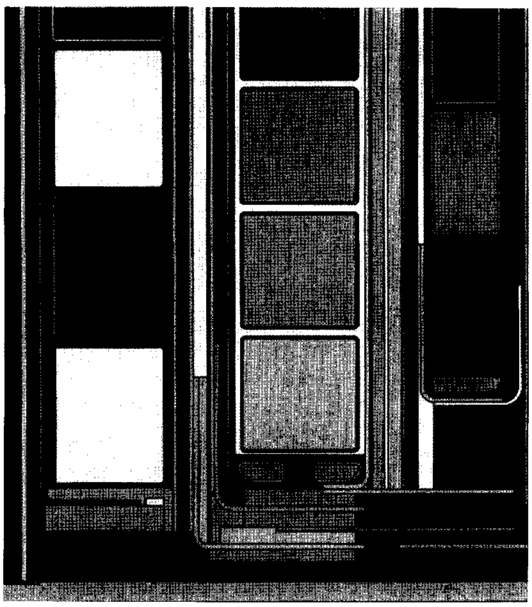


Figure 5. Transformer insulation model related to insulation model without electrostatic rings.

arc at the lower left edge of the electrostatic ring, which is under regulation winding. In other words it is along the first angle ring below the electrostatic ring.

The three models are shown, respectively, in Figures 5, 6 and 1b, which will be evaluated and compared in the following sections.

Insulation Model Without Electrostatic Rings

Electrostatic rings are rings, which are located in the upper and lower part of the windings to uniform the electric field distribution. These rings are equipotential with the closest section of related winding. This model is demonstrated in Figure 5. In this model, there are no electrostatic rings below and above the windings.

Figures 7 and 8 show the electric field intensity distribution along paths 1 and 2, respectively, when

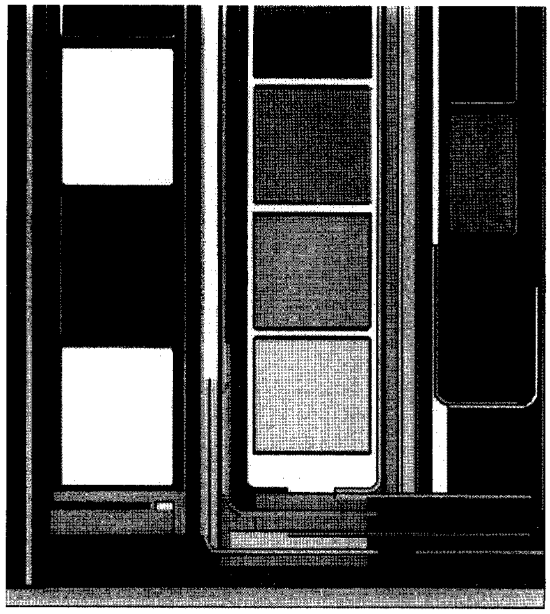


Figure 6. Transformer insulation model related to insulation model with electrostatic rings.

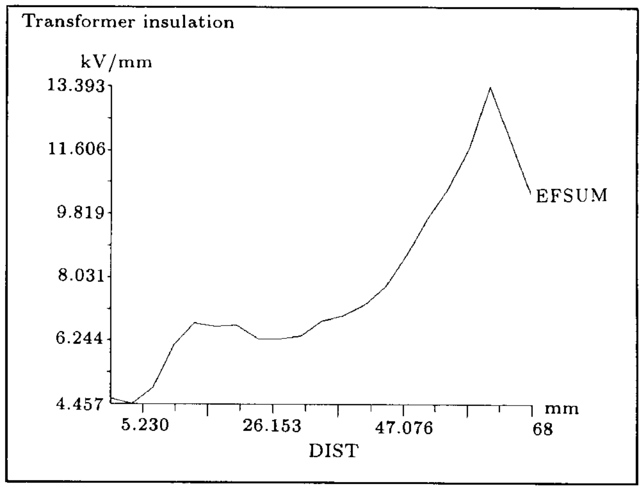


Figure 7. Electric field variation along Path 1 for Figure 5.

the transformer is impressed with a lightning impulse surge [8].

Insulation Model with Electrostatic Rings

This model is demonstrated in Figure 6. As is clear from this figure, the lower right edge of the electrostatic ring (which is located under the regulation winding) is completely circular. However, its lower left edge isn't completely circular. It is composed of two rectangular sections with a very small circular section.

Figures 9 and 10 show the electric field intensity distribution along paths 1 and 2, respectively, when the transformer is impressed with a lightning impulse surge [8].

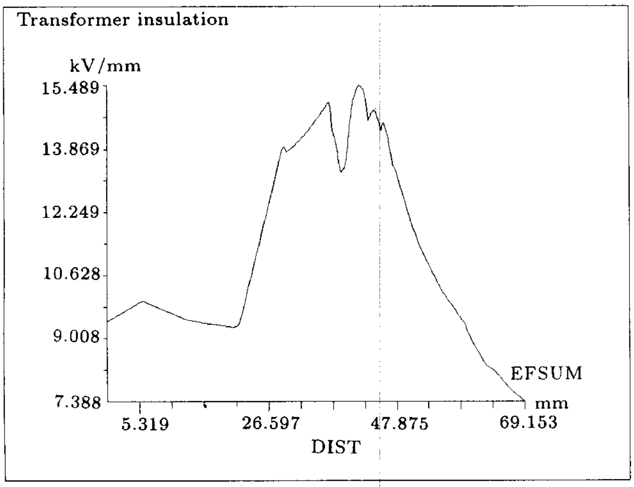


Figure 8. Electric field variation along Path 2 for Figure 5.

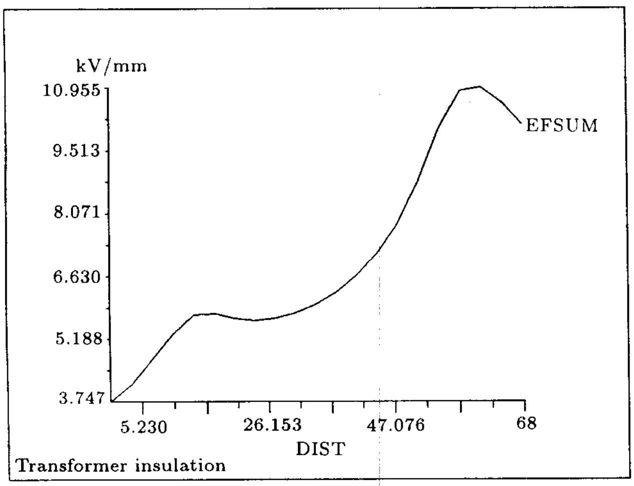


Figure 9. Electric field variation along Path 1 for Figure 6.

Final Model

This model is demonstrated in Figure 1b. In this model, both edges of the electrostatic ring (which is located under the regulation winding) are completely rectangular.

Figures 11 and 12 show the electric field intensity variations along paths 1 and 2, respectively, when the transformer is impressed with a lightning impulse surge [8].

Comparison of Electric Field Intensity Distributions

Discussion and comparison of the results for the three models in the previous section, leads to the conclusion that by employing some techniques, such as improving insulator shape, the maximum electric field will be reduced and electric field intensity distribution will be more uniform. Table 1 shows a comparison between

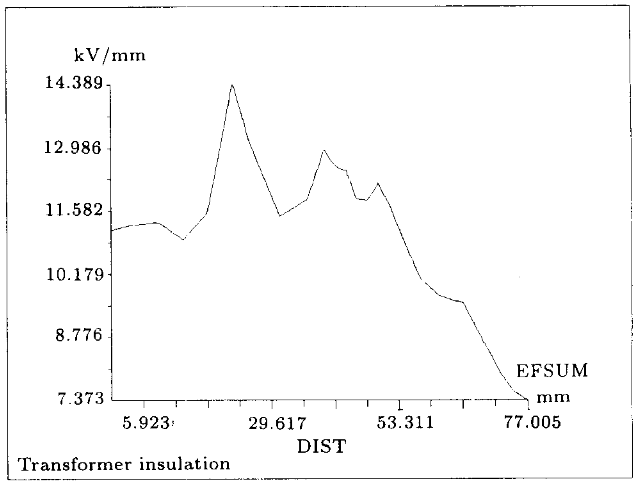


Figure 10. Electric field variation along Path 2 for Figure 6.

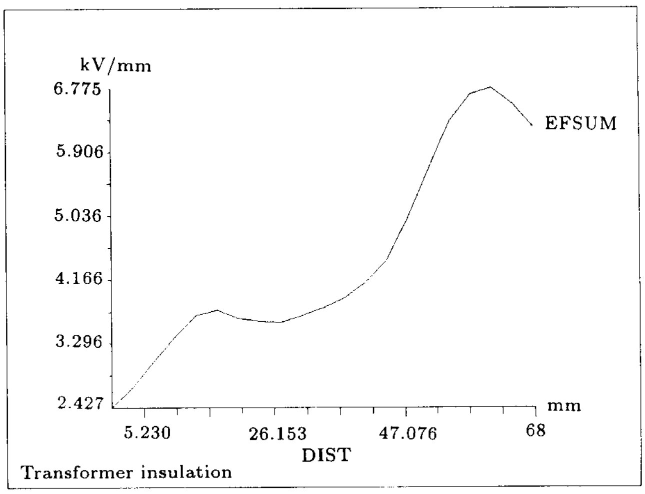


Figure 11. Electric field variation along Path 1 for Figure 1b.

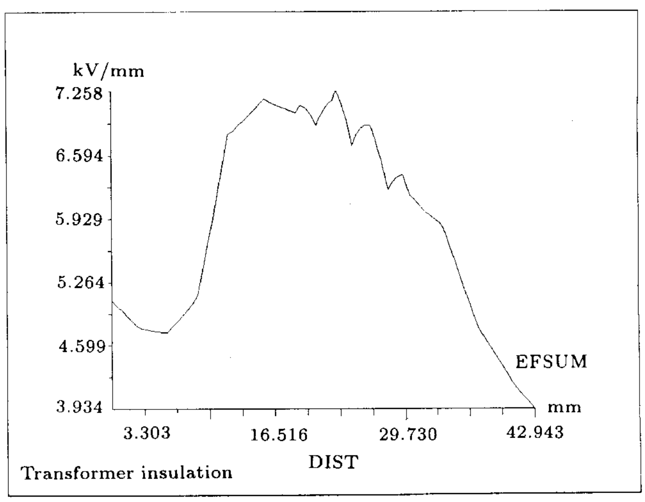


Figure 12. Electric field variation along Path 2 for Figure 1b.

Table 1. Comparison of maximum electric field intensities.

Models	Max. Elec. Field Intensity in Path 1, kV/mm	Max. Elec. Field Intensity in Path 2, kV/mm
Insulation model without electrostatic rings	13.393	15.489
Insulation model with electrostatic rings	10.955	14.389
Final model	6.775	7.258

the maximum electric field intensities in these three models [8].

SUMMARY AND CONCLUSION

In this paper, a calculation method of transient electric field intensity distribution inside a power transformer, impressed with impulse and power frequency test voltages as a contribution to the design of the internal insulation of power transformers, is proposed. The transient electric field analysis is executed using a developed model of the transformer by means of the finite element method. The obtained voltage values from circuit analysis are set as boundary conditions for a 2D axisymmetrical electric field analysis and the obtained electric field distribution inside the transformer is visualized. Although the proposed method was applied to only one type of power transformer used as a model, the method is general and applicable to any type of power transformer. The presented results show very good agreement with the measured ones. However, further investigation using different types of transformer with various insulators is advisable.

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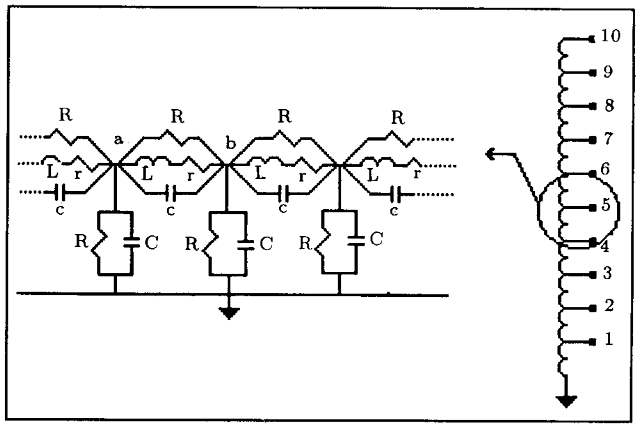

Figure A1. Equivalent lumped parameter ladder network of a simple winding.

APPENDIX 1

Power Transformer Equivalent Lumped Parameter Ladder Network Model for Transient Study

In order to construct the model, every winding should be divided into a number of small sections. This work should be performed in such a way to satisfy the quasi-static conditions.

In determination of the model parameters, three physical assumptions are employed:

a) Electromagnetic coupling exists between the windings' sections;

b) Electrostatic coupling exists between the windings' sections;

c) Insulation losses, eddy currents, skin effect, proximity effect and conductors' resistivity are considered.

As an example for a simple winding (as shown in Figure A1), the equivalent lumped parameter ladder network transient model of one section is shown in Figure A1.

APPENDIX 2

Program for Calculation of Transformer Transient Response

This program is developed in the MATLAB domain for computation of the transformer transient response. It models different types of winding, including tap winding, which is necessary for modeling transformers equipped with on-load tap changing facilities.

A lumped parameter ladder type network is employed for the transient modeling of windings and other parts of the transformer.

The transient response of the developed model is computed by solving a set of algebraic equations in the time domain.

The applied signal could be one of the following wave types: 1-Unit Step, 2-Standard Lightning Impulse, 3-Chopped Wave, 4-Switching Wave, 5-Steep Front, 6-Non-Standard Lightning Impulse, 7-Sinusoidal Wave.

The routine "Main" is the heart of the program and the other programs will be called through this program. For modeling the layer winding, the routine "Layer" and for modeling the disk winding, the routine "Disk" are employed and building the coefficient matrices is left for subroutines: "Analysis" and "Gconst".

The subroutine "Input Data" reads the data from the input file whose address and name are stored in the variable "Input File Location". According to this information, the elements of the matrices and the vectors of the main program will be specified. If there are any problems or errors in the parameters, an error message would appear and stop the program.

The input data are: Number of turns and layers, permeability constants for the insulation between the turns, thickness of insulation, distance between coils and upper and lower yoke, inner and outer diameter, number of sections on each layer and disk, direction of winding, number of strands in the wire, width of wire (in horizontal direction), wire thickness (in vertical direction) and some other parameters. Zero level flowchart for the above mentioned computer program for transient studies is shown in Figure A2.

APPENDIX 3

Laboratory Set up for Voltage Profile Measurement

The general laboratory set up for measurement of the voltage profile that is used in IRAN TRANSFO Co. under the lightning test is shown in Figure A3.

Lightning impulse test procedure is done according to IEC 60076-3 orders. In this case, a full wave lightning impulse at 100 percent is applied to a 1W winding, while the other windings are shorted to ground. The measured result is shown in Figure 2b.

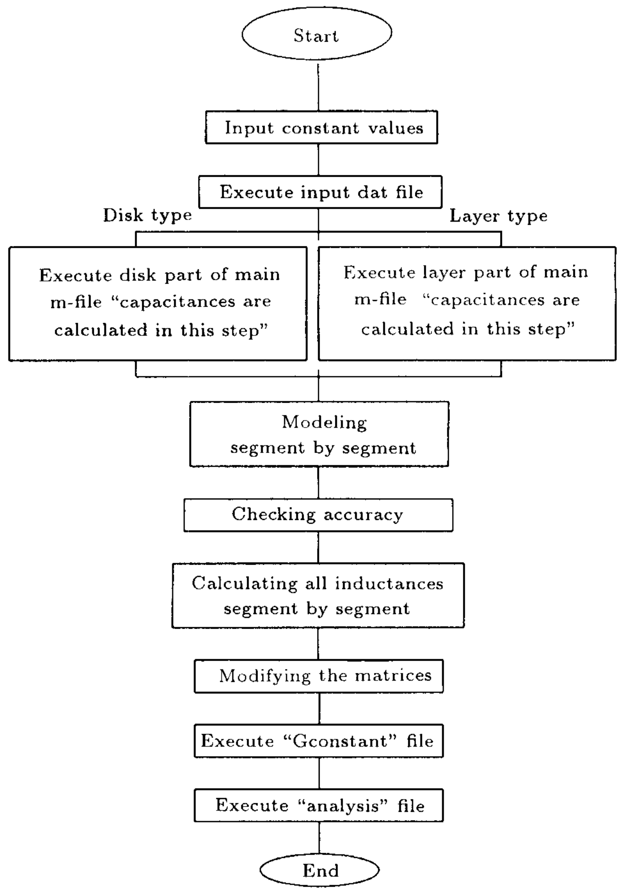

Figure A2. A zero level flowchart of the computer program for transient studies.

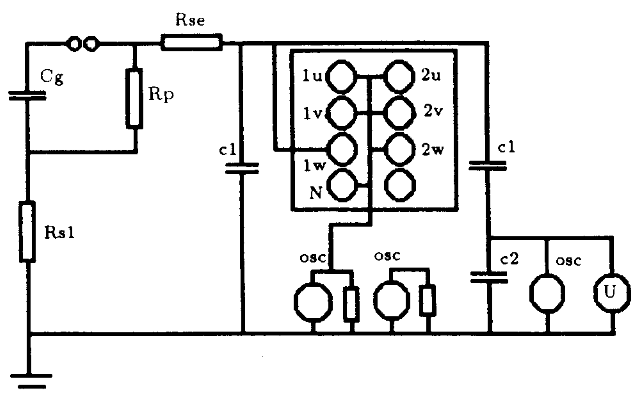

Figure A3. General laboratory set up for lightning impulse test in 1 W winding.