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ELECTRIC FIELD ANALYSIS OF HVAC TESTING UNIT USING FINITE ELEMENT METHOD

Aydemir ARISOY
e-mail: a.arisoy@hho.edu.tr
Air Force Academy
Department of Electronics Engineering
34149, Yesilyurt, Istanbul, Turkey

Özcan KALENDERLI
e-mail: ozcan@elk.itu.edu.tr
Istanbul Technical University
Department of Electrical Engineering
34469, Maslak, Istanbul, Turkey

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ABSTRACT

In this study, the electric field analysis of High Voltage AC Testing Unit (HVAC TU) with Finite Element Method (FEM) is investigated by using software package (ANSYS). Aim of this analysis is to determine the dielectric field pattern in the insulation media (transformer oil) and in particular the dielectric voltage gradients along the most probable breakdown paths for designing considerations. Electric field analysis is realized using with 2-D model in ANSYS environment and drawing vertical and horizontal section views of the complete test transformer is made in exact dimensions using ANSYS command. Testing transformer's rated short duration power frequency voltage (95 kV) is considered in investigation. The possible discharge points and electric field density distribution due to the voltage gradients in HVAC TU is predicted using results of the FEM analysis.

I. INTRODUCTION

Electric field analysis of any high voltage equipment is the important investigation for designing considerations. Efficient design of high-voltage equipment requires the maximum electric stress that occurs in or around the assembly under design to be minimized. However; HV Test transformer insulation design should be made greater consideration for impulse voltage distribution and electric field analysis. Therefore, precise analysis of the electric field around the test transformer main body becomes important [1-2]. Electric stress is a critical parameter in the breakdown of insulating materials, so that the thickness of insulation, or the minimum distance required between a live conductor and ground, will depend on this maximum stress value [3]. Insulation design calculations are based on this critical parameter. So the test transformer should be discharge free that will be based on to the electric field investigations of the HV insulation.

During the design and construction processes the sharp edges, points and small radius must be avoided on conducting surfaces, as these will produce high-stress regions.

In an ideal design each part of the dielectric would be uniformly stressed at the maximum value which it will safely withstand. Such an ideal is impossible to achieve in practice, with dielectrics of different electrical strengths and permittivity and with practical limitations of construction. Also, the maximum field in a symmetrical geometry is lower than that in an asymmetrically geometry with the same distance between the electrodes. However, asymmetry is often unavoidable in practical designs.

The dielectric field analysis approach to insulation design depends on determining, by analytical or analogue methods, the dielectric field pattern in the insulation considered and in particular the dielectric voltage gradients along the most probable breakdown paths. The dimensions and quantities of insulating materials used must also be kept to a minimum if a new high-voltage design is to be cost effective.

Real design problems are too complicated for an analytical solution. Finite Element Method (FEM) is a powerful technique to these problems. Recently, commercially available software package (ANSYS) is an accurate and the popular program using FEM to solve in design and analysis of mechanic, electric, magnetic, etc. problems. Also; it is quite useful for accurately predicting the electric stress in any given geometrical arrangement of conductors and insulating materials. These techniques allow the highest stress area to be identified so that the design can be modified to reduce the stress.

II. MATHEMATICAL BASIS OF ELECTRICAL FIELD PROBLEMS

A physical basis for the electric field problems can be derived as expressing Poisson equation that defines the variation of the field as a general second-order partial differential equation with associated boundary conditions.

In the electrostatic field, the field intensity is given by

$$E = -\nabla\phi \qquad (1)$$

where ϕ is the potential and ∇ is the gradient operator. If i and j denote the unit vectors directed along the x and y axes, respectively, the gradient operator can be expressed as

$$\nabla = \frac{\partial}{\partial x} i + \frac{\partial}{\partial y} j \qquad (2)$$

The flux density in a linear medium is

$$D = \varepsilon E \qquad (3)$$

replacing Equation (1)

$$D = -\varepsilon \nabla\phi \qquad (4)$$

where $\varepsilon = \varepsilon_0 \cdot \varepsilon_r$ and ε_0, ε_r being the permittivity of the vacuum and relative permittivity of the medium, respectively.

On the other hand, according to the law of conservation of flux, flux leaving a differential volume equals the charge in the same volume i.e.

$$\nabla D = f \qquad (5)$$

Substituting equation (4) in equation (5)

$$-\nabla(\varepsilon \nabla\phi) = f \qquad (6)$$

If the medium is homogeneous

$$-\varepsilon \nabla^2\phi = f \qquad (7)$$

Equation (7) is Poisson's equation for a linear homogeneous medium.

If f = 0, i.e. there is no inner charge, then Equation (7) becomes,

$$-\varepsilon \nabla^2\phi = 0$$

which is Laplace's equation for a linear homogeneous medium.

For an anisotropic medium where ε is a function of position and direction.

$$\varepsilon = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \qquad (8)$$

those a_{11}, a_{12}, a_{21}, a_{22} are functions of position and of the angle between the reference and local principal axis. If the medium is isotropic then $a_{11} = a_{22} = \varepsilon$ and $a_{12} = a_{21} = 0$.

Substituting equation (8) into equation (6) general form of Poisson's equation is obtained

$$\frac{\partial}{\partial x}\left(a_{11}\frac{\partial\phi}{\partial x} + a_{12}\frac{\partial\phi}{\partial y}\right) - \frac{\partial}{\partial y}\left(a_{21}\frac{\partial\phi}{\partial x} + a_{22}\frac{\partial\phi}{\partial y}\right) = f$$

when f = 0, it reduces to Laplace's equation.

III. ELECTRIC FIELD ANALYSIS BY USING FINITE ELEMENT METHOD

Electric field analyses calculate the electric field in conductive or capacitive systems. Typical quantities of interest in an electric field analysis include:

- Electric field
- Current density
- Charge density
- Conduction Joule heat.

Electric field analysis plays an important role in designing many engineering applications: bus bars, fuses, transmission lines, and so forth.

ANSYS uses Poisson's equation as the basis for static electric field analysis. The primary unknowns (nodal degrees of freedom) that the finite element solution calculates are electric scalar potential (voltages). Other electric field quantities are then derived from the nodal potential.

The first derived result is the electric field. It is defined as the negative gradient of the electric scalar potential. This evaluation is performed at the integration points using the element shape functions:

$$\{E\} = -V\ \{N\}^T\ \{V_e\} \qquad (9)$$

where
{E} = electric field (output quantity EF)
V = gradient operator
{N} = shape functions
$\{V_e\}$ = nodal electric scalar potential

The electric flux density is computed from the electric field equation;

$$\{D\} = [\varepsilon]\ \{E\} \qquad (10)$$

where
{D} = electric flux density (output quantity D)
[ε] = permittivity matrix

Nodal values of field intensity and flux density are computed from the integration point values.

The electric field analysis procedure using computer software (ANSYS) consists of three main steps; firstly, using ANSYS commands that consist of exact dimensions in MKS is used to draw model and model is meshed with sufficient density.

After that, the loads to the boundary of the model are applied and obtained the solution. Finally, the results are taken as figure, graphics or tables. Analysis is fulfilled by using two-dimensional model. Since 2-D solutions are sufficiently accurate at least for practical design purposes. [9 - 11].

IV. ELECTRIC FIELD ANALYSIS AND RESULTS

Electric field investigation of the test transformer, which is the most important element of the HVAC TU, is expressed and results are discussed. Main parts of HVAC Testing Unit are shown in figure 1. Electric Field investigation of the HV test transformer consists of around the HV winding and inner connections inside the tank and field distribution in transformer oil. Transformer may be exposed to its highest (50 kV) and rated short duration power frequency voltage (95 kV). These voltages are considered in investigation.

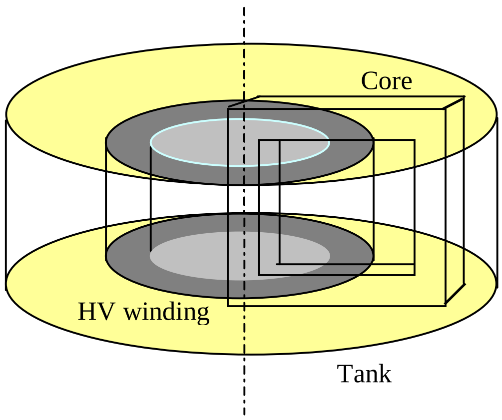

Figure 1. Main parts of the HVAC unit.

In this study insulation design working of test transformer is realized according to the dielectric field analysis approach by using ANSYS software analysis program. Aim of this analysis is to determine the dielectric field pattern in the insulation media (transformer oil) and in particular the dielectric voltage gradients along the most probable breakdown paths.

Electric field analysis is realised using with two-dimensional model in ANSYS environment. Drawing vertical and horizontal section views of the complete test transformer is made in exact dimensions using ANSYS command. Model consists of three main materials, which are iron core, high voltage and low voltage coils, and as insulation liquid, transformer oil. Material properties, permittivity, viscosity, permeability etc., of that are defined. Besides the finite element type is determined as for two-dimensional analysis. Meshing properties are chosen. Boundary conditions of the model are determined and put in exact values.

Using two-dimensional model performed analysis. Upper view and horizontal cross-section of testing transformer was used in all analysis. Figure 2 shows the element meshing in horizontal cross-section model. In this model plane 121, 8-nodes 2-D electrostatic solid model is used. Model consists of 609 elements and 1928 nodes.

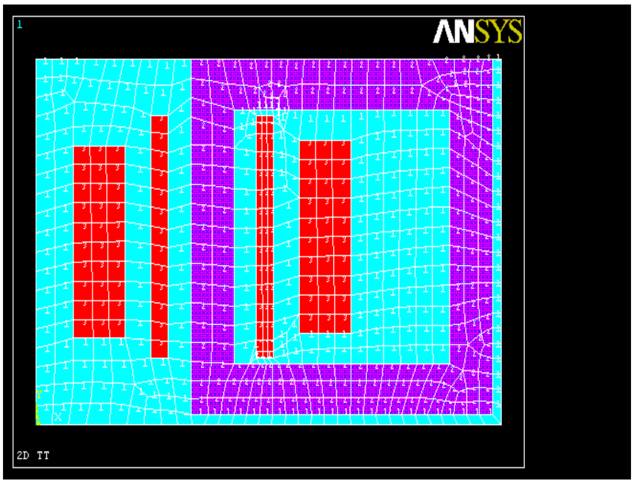

Figure 2. Finite element mesh of model.

Figure 3 also shows element meshing in upper view of test transformer model which consists of 1150 elements and 3533 nodes using with plane 121, 8-nodes 2-D electrostatic element.

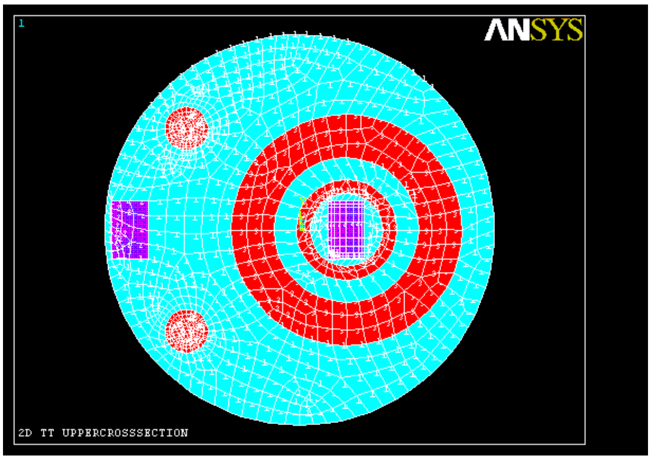

Figure 3. Element meshing in upper-view of test transformer.

Two main boundary conditions are used for analyzing. Testing transformer rated output voltage will be 50000 V. That is service voltage. In addition to that testing transformer should withstand 1 minute's power frequency test voltage that for this application is 95000 V. In this study, since the power frequency voltage is more difficult situation. Analysis was fulfilled this voltage.

In figure 4, potential distribution in vertical cross-section of the model are seen as for 95 kV. Besides that for the upper view of the model are also realised analyses of equipotential lines for each value of applied voltage. Plotting for the dielectric field pattern in horizontal section through the centre of the test transformer HV bushing and HV winding outer layer are shown in figure 5.

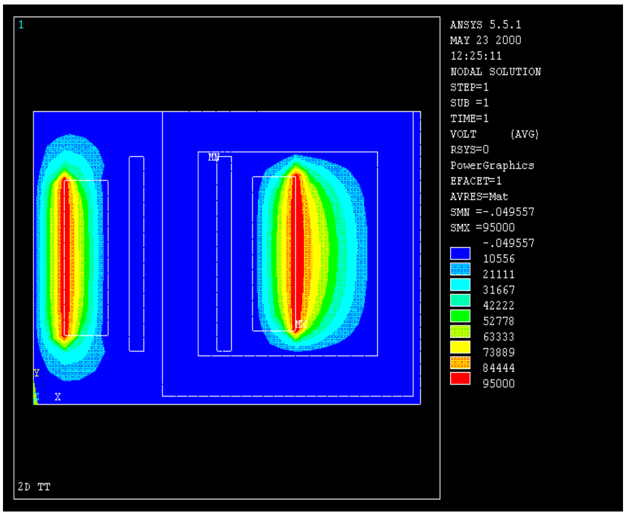

Figure 4. Test transformer equipotential lines for 95 kV.

MKS unit system has been used during the analysis. Therefore results of any analysis can be read directly on the right side of the figures.

Another crucial investigation is prediction of the possible discharge points and electric field density distribution due to the equipotential lines. However investigation of danger point aspect from field density guides the insulation design processes. According to that it is determined to increase or decrease insulation levels.

Two-dimensional solutions are given as figure 4 and 5. Equipotential lines are seen as sufficiently accurate as at least for practical design purposes in horizontal cross-sectional view and upper view of model.

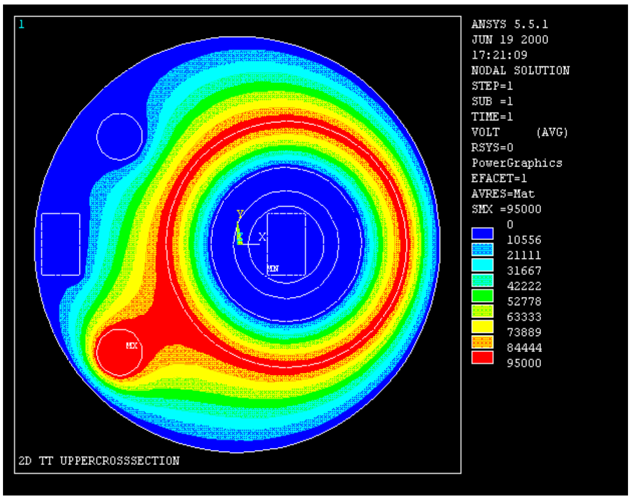

Figure 5. Dielectric field pattern in horizontal cross-section through centre of the HV bushing and HV outer layer when 95 kV is applied.

In figure 5 boundary conditions was presented in position that the outer layer of HV winding is of power frequency test voltage and the most inner layer zero potential. The core and tank wall (outer boundaries) was also considered as zero potential. Then the 100% of potential that is 95 kV is seen around the outer layer in figure 5. Upper view has both the HV bushings and the windings. Equipotential distribution in upper view was more satisfactory seen than the previous figure. Around the HV bushing and outer layer has maximum potential gradients as represented red region in figures. Yellow regions show the 60-70 kV voltage gradients. Additionally Light green regions represent about 50 kV gradients. Below the 40 kV gradients are given as blue regions. Figure 5 also shows the field surrounding one HV bushing. The maximum potential gradient, at the corner of the HV winding and HV bushing, can be determined graphically from these illustrations.

Two-dimensional approach will be enough to determine the maximum and minimum field density points. Horizontal and vertical cross-section investigations are performed. When the applied voltage is 95 kV that is exposed HV winding outer layer occurs different field density levels from center of the applied voltage to far from that. But Electric field density is more around some point. Related plotting are given as figure 6 and figure 7.

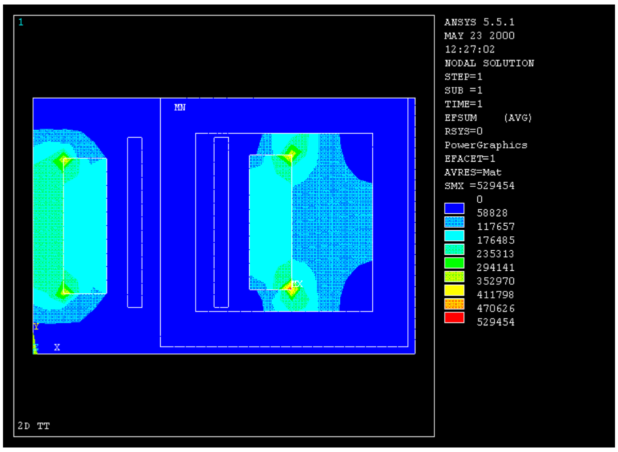

Figure 6. Electric field density when 95 kV is applied.

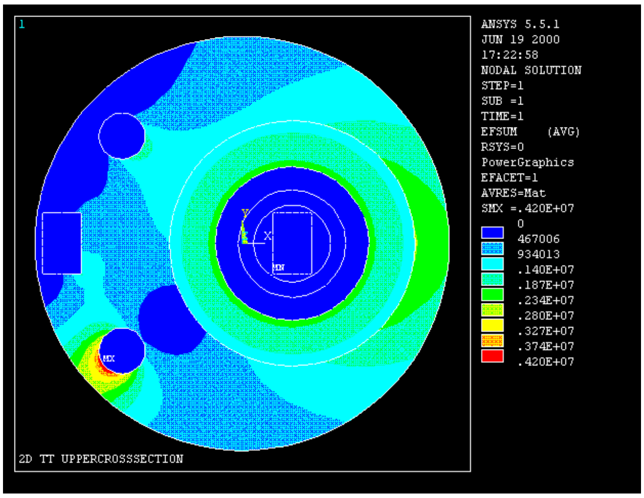

Figure 7. Upper view of electric field distribution of test transformer (for 95 kV).

Voltage gradients cause different electric field values in different regions. Figure 6 shows the electric field distribution in horizontal cross-section. In this figure is seen important region of stress concentration between around the corner of the HV bushing and core edge. Electric field strength is 52.4 kV/cm which is the maximum value from this view. The maximum point is illustrated with red region. The maximum region has been occurred to have the minimum distance with earth potential with HV outer layer. The values of the other electric field strengths are illustrated yellow region, 30-40 kV/cm and green region 20-30 kV/cm respectively.

Figure 7 shows electric field concentration distribution in upper view of the model. From this viewpoint, the maximum field strength is 42 kV/cm that can be read directly and seen as red region that is between the HV bushing and tank wall. The HV bushing and tank wall can be thought as concentric cylinders. The maximum stress was calculated analytically as cylindrical electrodes approach. Then, maximum electrical stress for rated voltage (50 000 V) was calculated as 22.6 kV/cm. For the same region, the maximum stress was calculated as 42.9 kV/cm. Meanwhile calculation and found value using ANSYS are very close each other with approximately 2% differences [5].

The distance between tank and HV bushing makes the maximum field strength region occurred. The lowest value, according to standards, of the new transformer oil dielectric strength is 200 kV/cm [4]. Another value aspect from the transformer inner connections boundary layer between paper and oil, where a power frequency voltage at the electrode surface 60-80 kV/cm, and paper/oil boundary layer field strength values of 40-50 kV/cm are permissible [6].

V. CONCLUSION

In this study, the electric field analysis of testing transformer that is the main part of the HVAC TU has been investigated by using software package (FEM/ ANSYS). The dielectric field pattern in the insulation media (transformer oil) and in particular the dielectric voltage gradients along the most probable breakdown paths for designing considerations have been determined by using 2-D model in ANSYS environment. Testing transformer's rated short duration power frequency voltage (95 000 V) was considered in investigation. The possible discharge points and electric field density distribution due to the voltage gradients in HVAC TU has been pointed using results of the FEM analysis.

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