Optimization of Complex Electrode System for Use in Electrical Measurements

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Abstract- **In an attempt to optimize the dimensions of the electrode system for subsequent use in electrical measurements, such as electroluminescence, capacitance and conduction current, field values at key points in an axi-symmetric electrode system are simulated as a function of clearances between low voltage and guard electrodes. Since the electrode system is axi-symmetric, a two dimensional BEM solver, has been used for the field simulation. The configurations simulated, results, analyses and configurations for an optimal design are presented.**

I. INTRODUCTION

Electric field analysis plays an important role not only in the design of high voltage electrode systems for experimental investigations but also in the design and development of insulation systems. Two common approaches, namely analytical and numerical, are traditionally utilized. Analytical techniques yield accurate solutions when electric fields in electrode systems are to be determined, but are mainly restricted to simple geometries. Practical electrode systems are inherently complex, and in such cases numerical techniques provide the only alternative approach for field analysis. With the advent of fast desktop personal computers, with large memory and faster processors, relatively complex field simulations using numerical techniques can now be performed on a desktop, avoiding the need for large mainframe computers. A number of commercial field solvers have been developed for use in PC machines and relatively accurate solutions can be obtained by the use of numerical techniques in a short time. Various methods such as finite difference method (FDM), finite elements method (FEM), and boundary element method (BEM) have been developed.

FDM permits replacing differential equations describing the electric potential (essentially a boundary value problem) by finite difference equations, and involves an iterative process. The common problem when using this technique, are excessive computational time and crude modeling of geometry. FEM uses a variation of FDM technique, where the potential is approximated by a sequence of functions defined over the entire domain of the complex geometry. However, the derivative of potential could have discontinuities and it is not possible to model infinitely extended regions. An alternate approach to the solution of the boundary value problem is BEM, which is based on a formulation of the

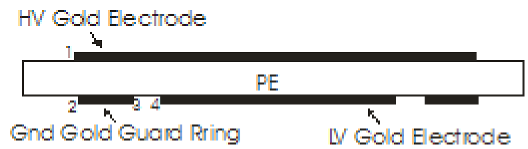

Figure 1. Simplified electrode geometry with polyethylene sandwiched between upper and lower gold electrodes.

boundary integral equation [1]. This approach involves obtaining the integral equation formulation of the problem and solving this by a discrimination procedure similar to that used in regular FEM. Since the BEM is based on the boundary integral to the governing differential they are taken as triangular elements [2]. The main advantage of this method over the direct approach is the elimination of differentiation and interpolation to calculate potential or its derivatives and it has a good means for checking the accuracy of the solution. A number of commercial software are available (Ansoft, Coulomb, Electro). In this work, we have used the most recent version (Version 6.4) of Electric Field Simulation software ELECTRO, developed by Integrated Engineering Software, Canada.

II. GEOMETRY

The main purpose of the electrode geometry studied in this work is to use this system to investigate electroluminescence phenomenon in the "polyethylene" layer under high electric stress. An idea of the electric field profiles in the region of test is therefore important to further validate the experimental results.

The electrode systems investigated for this work have one major feature, namely the overall range of the dimensions of the objects. The polyethylene insulator being studied is in ***μm*** thickness range and the dimensions of the testing electrodes and other related insulation are in the tens of ***mm*** range. This means that variation in the dimensions is several orders of magnitude.

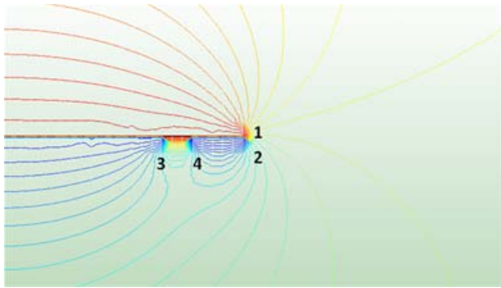

Figure 2. Electric field results produced by the BEM solver. Electrical stresses in V/m were determined at points 1, 2, 3 and 4.

Two electrode systems are analyzed. In the first, initial simulations are carried out to investigate the suitability of the software for analyzing electric field concentrations at triple junctions of gold electrode, polyethylene and air. This is our benchmark simulation. In the second set of simulations, the actual experimental electrode system that will be used in measurement of Electroluminescence in Polyethylene is modeled.

As discussed earlier, because of the large changes in the object dimensions for the geometry, BEM approach is employed to determine the profiles of electric fields.

III. Electrode Geometry

A. Simplified Geometry for Benchmark tests

Figure 1 is the simplified geometry used in first set of exploratory simulations used in evaluating the suitability of the software package. The Polyethylene (PE) film is 45mm in diameter with a thickness of 135 µm and a dielectric constant of 2.3. The high voltage (HV), Low voltage (LV) and guard electrode are made by sputtering gold, 30 nm thick. The diameter of LV is 22mm, the gap between the LV and guard ring is 2mm and the width of guard ring is 3.5mm. The HV electrode was held at 1.35kV, the LV at 100V and guard ring was grounded. Due to axi-symmetric nature of the problem 'ELECTRO' a 2-D field solver was used to determine the field values. The BEM method was used for the simulation. The model was set for "y-symmetry". The results of the field simulation are shown in Figure 2.

TABLE I
Electric field values for key points for geometry in Figure 1

Point	$\left\lVert \vec{E} \right\rVert$ V/mm
1	2.261E+04
2	2.401E+04
3	2.806E+04
4	4.386E+04

As expected we observed that there is a large stress concentration at the triple points between polyethylene, gold electrode and air at locations 1, 2, 3 and 4.

The electric stress values for the four points of interest are tabulated in table 1. These values agree well with calculated results.

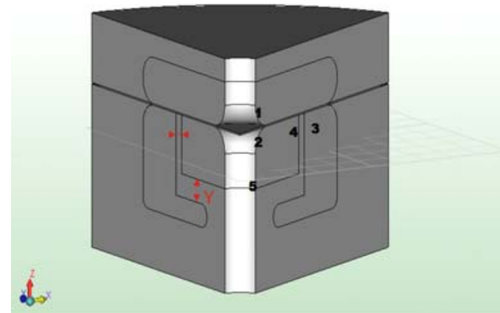

Figure 3. 3-D view of the electrode geometry used in computations. The parameters varied are 'x' & 'y' and stresses at locations 1-5 are examined.

B. Electrode Geometry for Electroluminescence measurements

Figures 3, 4 and 5 show the different views of the electrode geometry used for the electroluminescence measurement system. A 130 ***µm*** polyethylene specimen (permittivity =2.3) is sputtered with 30 nm thick gold layer to form the electrodes. The electrode configuration consists of an upper brass

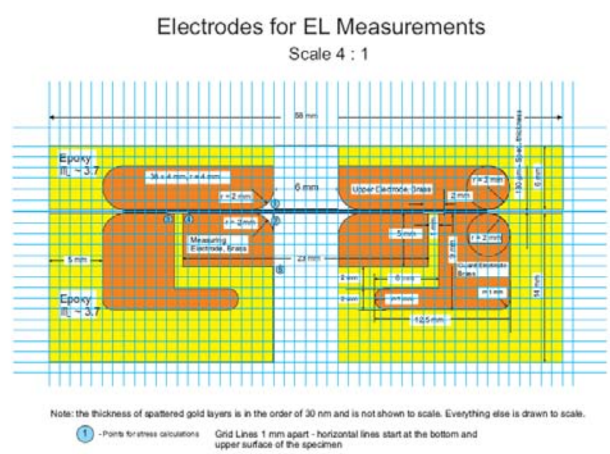

Figure 4. Electrode plane geometry with gold sputtered polyethylene sandwiched between upper and lower brass electrodes. Points 1, 2, 3, 4, and 5 were the locations used for the measurements of electrical stresses.

electrode of 38 mm diameter and 4 mm thickness. The ends have 2mm radii. The lower electrodes are measuring electrode (circular ring) and guard electrode (with an L shape in cross section). These are also are made of brass. The entire electrode system top and bottom is separately encapsulated in epoxy (permittivity = 3.7) maintaining a 6 mm diameter concentric hole. The polyethylene sample is subsequently sandwiched between these electrodes, maintaining radial symmetry as seen in the figure 3. The HV electrode was held at 1.35kV, the LV at 100V and guard ring was grounded.

As can be seen from the figures, there are five critical points of interest labeled 1,2,3,4, and 5 in the figures. The present work is intended to simulate the electric field at these points and optimize the configuration of the system such that the field values are minimum at these points.

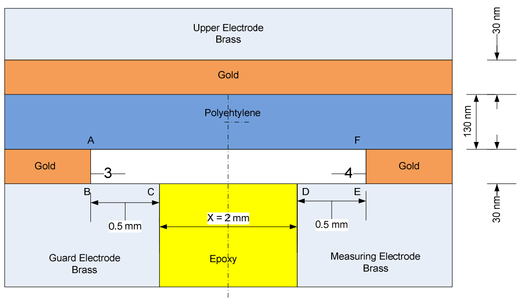

Figure 5. Expanded view (not to scale) of the electrode plane geometry showing the regions 3 and 4 and the relative dimensions of the various parts.

In particular, points 3 and 4 are shown in Figure 5 as expanded view. Due to the nature of the design of the electrode configuration, a tiny air gap ring of 30 nm thickness and 3 mm width gets embedded as shown. This does introduce triple points (air, metal and dielectric) and these regions are closely investigated in the field analysis.

From the figure 3, it can be seen that distance between the guard electrode and the measuring electrode, i.e. ***x*** and ***y***, can be altered over a range of few mm. The effect of this variation over the field at the key points is the object of the present investigation. In particular, we are looking at optimum dimensions of the geometry for electric fields to be minimum at these points (or in region surrounding them). This can ensure that the insulator under stress provides the resulting electroluminescence measured.

IV. RESULTS AND DISCUSSIONS

The field simulations have been performed using a BEM solver for a number of configurations with distances X and Y as parameters. The basis set was for a value of X= 1 mm and Y = 2 mm. For a given value of X, the simulations were performed for five sets of Y, namely 2 mm, 2.25 mm, 2.5 mm, 2.75 mm, and 3mm. Each of these five values of Y were then repeated for five values of the distance X, i.e. 1 mm, 1.25 mm, 1.5 mm, 1.75 mm, and 2 mm. Hence, there are total 25 sets of simulation performed. The results of these are plotted for the five key points (1, 2, 3, 4, and 5), as surface plots in the figures 6 through 9 respectively. The field value (uniform field region) in the center of the polyethylene sample for the all the cases was 9.62 E+03 V/mm.

The parametric electric field variation at the point 1 in the electrode system indicates that for a given value of X, the change in the E field for the range of value of Y studied was by a factor of 2. For the X variation the however, a greater effect was observed with a change by a factor of 10. The minimum value of field occurred at a value of X = 1.75 mm and Y = 3 mm. The corresponding value of field was 0.57 V/mm.

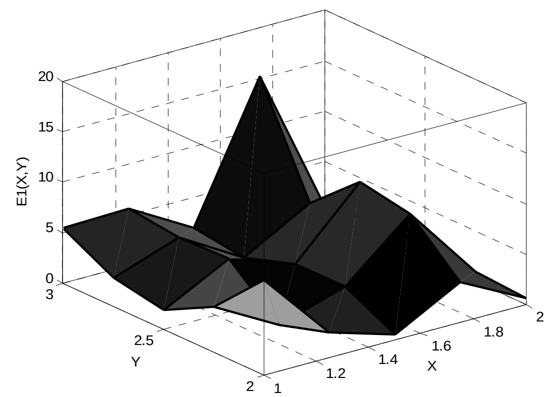

Figure 6. Electric field intensity plots (V/mm) for the point 1 for various values of the distance X and Y.

Similar observations can be made for the remaining four cases from the figures 7 through 10 respectively and are summarized below.

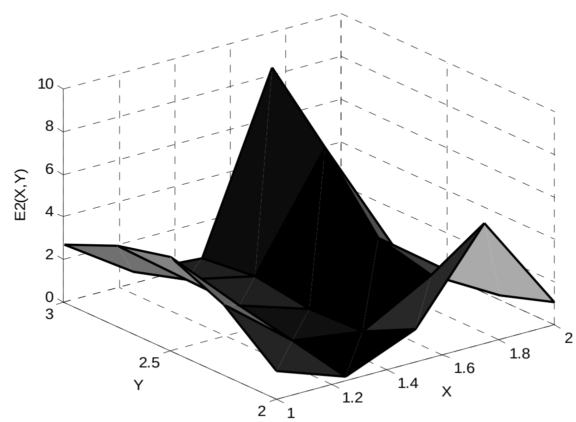

Figure 7. Electric field intensity (V/mm) plots for the point 2 for various values of the distance X and Y.

The minimum values of the field for point 2 is at (X=1.5, Y = 2), point 4 is at (X=1, Y =2) (basis set design), point 3 is at (X =1.75, Y =3), and the point 5 is at (X =1.25, Y =2). The corresponding field values are summarized in the table II. The results indicate that the overall best design for the electrode system will be for X = 1.25 mm and Y = 2mm. The corresponding values for the fields (V/mm) at the five points are:
E1 = 3.984, E2 = 5.617, E3 = 1.909 E+05, E4 = 1.365E =05 and E5 = 7.479 respectively.

TABLE II

Optimum Electric field values for key points for geometry in figure 3

Point	X,Y (mm)	$\left\|\vec{E}\right\|$ V/mm
1	1.75, 3	5.678E-01
2	1.5, 2	1.801E-01
3	1, 2	8.669E+04
4	1.75, 3	1.527E+05
5	1.25, 2	7.479E+00

Another observation indicates the field at point 5 is always large keeping X fixed.

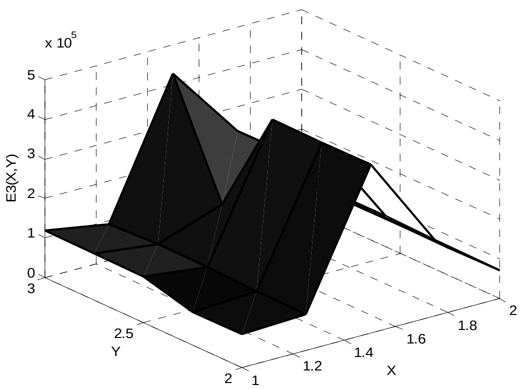

Figure 8. Electric field intensity (V/mm) plots for the point 3 for various values of the distance X and Y.

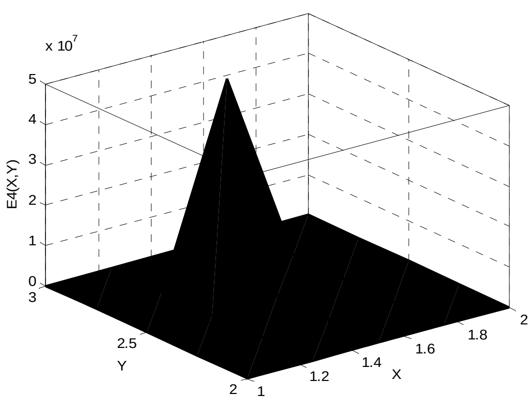

Figure 9. Electric field intensity (V/mm) plots for the point 4 for various values of the distance X and Y.

V CONCLUSIONS

Electric field profiles obtained with BEM solving software can be helpful in the design and analysis of high voltage insulation and experimental systems. An electrode system for subsequent use in electrical measurements, such as electroluminescence, capacitance and conduction current has been investigated. The results of electric field values simulated using a BEM solver at key points in the axi-symmetric electrode system as a function of clearances between low voltage and guard electrodes indicates that the optimum design will be for X= 1.25mm and Y= 2mm. Optimum field values of E field indicate that the basis set design with X = 1 and Y = 2 mm gives minimum value of E field for point 3.

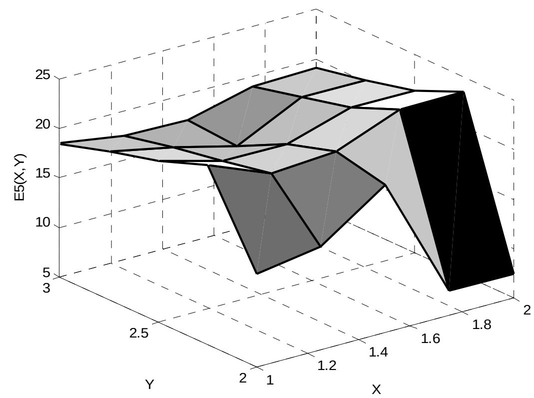

Figure 10. Electric field intensity (V/mm) plots for the point 5 for various values of the distance X and Y.

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