

A New Model of Investigating the Electric Field in Dielectric Liquid for Streamer Initiation

A. El-Zein and M. Talaat

Electrical Power & Machines Department, Faculty of Engineering, Zagazig University, Egypt.

Abstract-- The initial filamentary streamers in liquid dielectrics drastically changes by the tip curvature of the electrode and the applied voltage. In this paper to get the non uniform field a sphere-to-plane electrodes configuration is used. Also, an immersed air bubble adjacent to the sphere electrode is presented, to obtain the sharp tip, after the air bubble compressed against the sphere electrode i.e., sharp conducting protrusion tip, which considered as a source of high non-uniform field and streamer initiation. A simulation model for field distribution in the dielectric medium is presented by using Finite Element Method. An experimental technique was used to investigate the accuracy of the field simulation. Also an analytical equation for field calculation was used to investigate the percentage field error.

Index Terms-- Electrical Field Simulation, Streamer Formation, Composited Dielectric, Finite Element Method, Sphere-to-Plane Configuration, Bubble Streamer Initiation.

I. INTRODUCTION

ELECTRIC field plays an important role in the streamer morphology propagation. Field ionization of the liquid has been assumed to be the charge creation mechanism at the streamer tip [1-3].

The pre-breakdown phenomena occurred in the needle-to-plane electrode gap, which are well known as the development of long-gap discharges in gases, tree formation in solids [4, 5], and streamers in liquid. The observed disturbance is called positive or negative streamers. Here, the positive streamers correspond to the disturbance growing from the anode needle to the cathode plane, while the negative streamers are described as the disturbance from the cathode needle to the anode plane [6]. It has been thought that it is of great importance in the field of high voltage-electrical insulation engineering to make a breakdown mechanism clear in dielectric liquids under non-uniform field conditions, and most researches have been reported [7-10].

So far it has been found out that point-to-plane breakdown in dielectric liquids is preceded by the development of disturbances with altered refractive index, and that breakdown occurs very quickly once these disturbances cross the gap [7].

In this paper a simulation model for electric field calculation using Finite Element Method (FEM) is presented to simulate and calculate the electric field in the region of filamentary streamer formation in the dielectric liquid.

To investigate the accuracy of the simulation results, an analytical equation for axial field calculation and experimental technique are used to indicate the field error of the simulation results.

II. BUBBLE DEFORMATION

In order to increase the non-uniformity of the electric field and to get a sharp tip curvature, an immersed air bubble is used [8, 9]. After [8, 9] the injected air bubble assumes as a prolate spheroid shape under no applied voltage and then starts to elongate with the applied voltage assuming a spherical and then elliptical shape. The elongation ratio of major to minor semi-axis increase as the applied voltage increases, and it is found to be extended in the direction parallel to the applied electric field. The air bubble is first ionized by increasing the high voltage, and then the spherical shape of the air bubble is deformed due to the high electric field, and compressed against the sphere electrode. This compression causes the formation of sharp conducting protrusion tip. The more the bubble is compressed, the smaller is the radius of tip curvature [10].

III. EXPERIMENTAL TECHNIQUE

Figure 1, shows the technique used for experimental recording [8-10]. The test cell consists of a transparent glass container of $5 \times 5 \times 20$ cm. The upper Perspex cover of the cell supports the inlet copper pipe of 6 mm with inner diameter of 3 mm; this pipe has screwed externally to 5 mm from one side. The cover also supports an inlet, for dielectric liquid input. The pipe carries a high voltage sphere termination which is open till the sphere tip and screwed internally to 5 mm to be erected in the mentioned copper pipe. The other side of the pipe is connected to the injection air bubble system. Also the bottom of the test cell is made of Perspex and supports the earthed plane, 3 cm in diameter. The earthed plane position can be changed to adjust the tested gap against high voltage sphere electrode. In the present experiment one sphere termination of 11.28 mm diameter has been used.

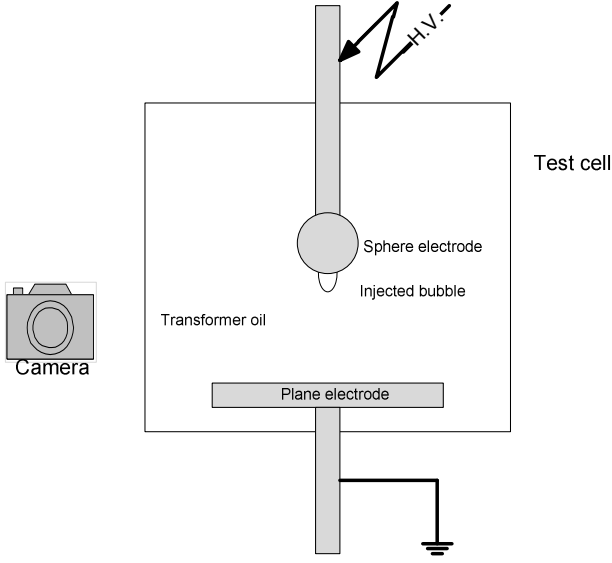


Figure 1: Scheme of a bubble injected in a liquid dielectric under a sphere-to-plane configuration.

The tests were carried out using 0~60kV D.C. supply with negative polarity. The high voltage D.C. supply was connected to the sphere electrode, using 0.5 MΩ series resistor.

IV. STREAMER INITIATION

After the bubble compressed against the sphere electrode the local electric field enhanced and the filamentary began to appear from the plane electrode toward the compressed air bubble.

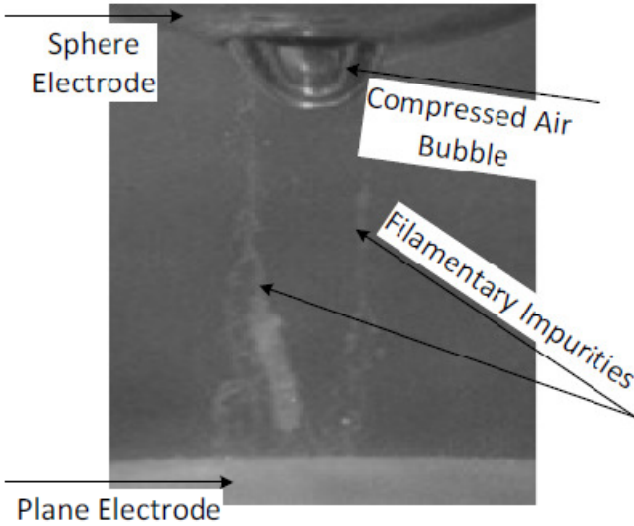


Figure 2: Photographic recording of a compressed bubble injected in a liquid dielectric under a divergent electric field (sphere-to-plane).

Figure 2 described the experimental recording of the compressed air bubble i.e., conducting protrusion tip, and a filamentary impurities taken the shape which can be contributed to the field lines, so from the electric field

simulation the shape of the filamentary streamers can be predicted.

V. THE SIMULATION MODEL

A new model for investigating the electrical field in dielectric liquid is presented. This is achieved by using a sphere-to-plane gap; in combined with an immersed air bubble. The divergent field and the ionization inside the air bubble cause the filamentary streamer formation [10-11].

Hence, accurate computation of electric field is a pre-requisite for determining the mode and calculating the growth of streamer formation. A simulation model for electric field calculation using FEM is presented to simulate and calculate the electric field in the region of filamentary streamer formation in the dielectric liquid. The chosen sphere diameter was 11.28 mm and the gap spacing varied from 6 mm to 14 mm. The results have been assessed through comparison with available analytical and experimental data.

The progress of streamer in an insulating system calls at first for accurate computation of the electrostatic field. This is obtained from Laplace's equation using FEM. After the bubble deformation its shape changes to hyperbolic shape with radius getting from the photographic recording. In order to assess the computation accuracy, the computed electric field, along the gap axis $E(z)$, is compared with the following analytical formula [12]:

$$E(z) = \frac{-2V}{a[1 - (z/a)^2] \ln[(1+w)/(1-w)]} \quad (1)$$

with $a = d\sqrt{1 + (r/d)^2}$, and $w = d/a$ where, d equals to the gap distance from the compressed air bubble tip to the plane electrode and r equals to the compressed air bubble tip radius.

Figure 3 shows a sphere-to-plane electrode system stressed by a voltage V and immersed in dielectric liquid.

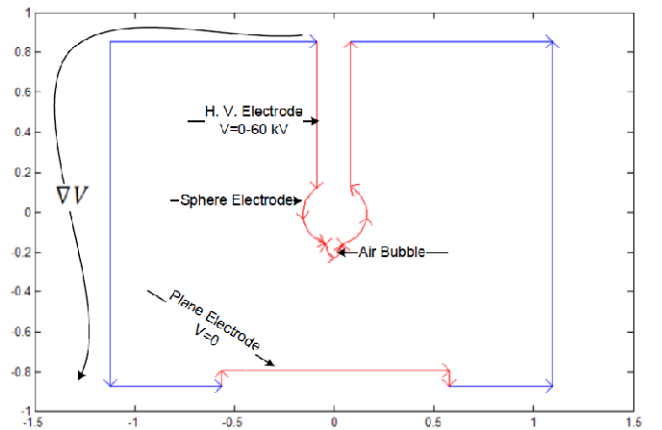


Figure 3: A sphere-to-plane gap configuration with air bubble immersed and simulation technique.

From previous analysis, the proposed field simulation can be given by the following steps:

Experimental Technique:

1. The gap spacing adjusted between the sphere-to-plane electrodes.
2. The sphere electrode is maintained at zero voltage till the air bubble appears.
3. The applied voltage increasing till the bubble compressed and streamer started.
4. The compressed air bubble considered as conducting medium after the internal discharges ceases [9], then it considered as a protrusion tip of sphere electrode.
5. After the streamer initiated the new gap spacing from the compressed air bubble tip to the plane electrode and the radius of curvature of the compressed air bubble are determined from the photographic recording.

Simulation Technique:

6. The simulation program calls the FEM to investigate the field simulation, taken into account the Laplace equation for field calculation with the Neumann and Dirichlet boundary conditions.
7. The boundary condition considered the sphere electrode and the compressed air bubble at the high voltage value, also the plane electrode at zero potential, and the container surface voltage gradient from the high voltage to zero voltage as shown in Figure 3.

Figure 4 describes the auto mesh scheme, which generates non-uniform triangular elements in accordance to the objective geometries; the obtained results give accurate potential and field distributions.

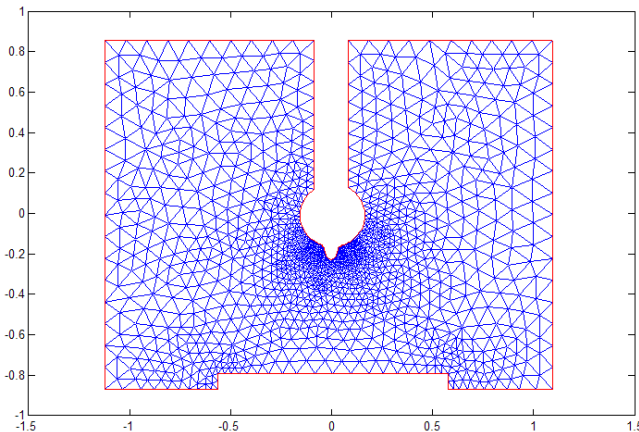


Figure 4: A sphere-to-plane geometry and its FEM model.

A simulation model used to display the interested region of high electric field by using FEM simulation techniques. Figure 5 shows the flow chart algorithms which describe the technique of the simulation program till the electric field calculation has been achieved and also the determination of maximum field direction which takes in consideration the streamer advance.

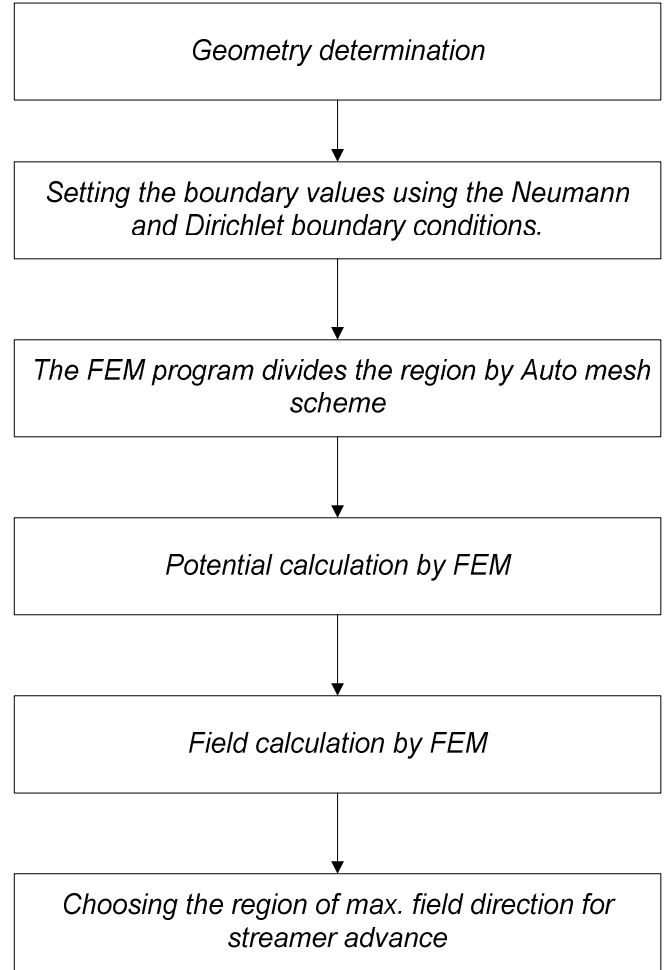


Figure 5: Flow chart of simulation algorithm.

The electric field E can be obtained from [13]:

$$E = -\nabla V \quad \text{V/m} \quad (2)$$

The divergent of the electric flux density D is given by [13]:

$$\nabla \cdot D = \rho_v \quad \text{C/m}^3 \quad (3)$$

where, ρ_v is the volume charge density.

From the relation between D and E

$$D = \epsilon_0 \epsilon_r E \quad \text{C/m}^2 \quad (4)$$

where, ϵ_r is the relative permittivity of the dielectric medium.

Then,

$$-\nabla \cdot (\epsilon_0 \epsilon_r \nabla V) = \rho_v \quad \text{C/m}^3 \quad (5)$$

Equation (5) used when the charge density is known “the Neumann boundary conditions” or the voltage gradient “charge distributed” across the boundary surfaces. If the

voltage at the surface is known the Dirichlet conditions are used.

Apply Laplace equation for the bulk of the liquid $\nabla^2 V = 0.0$

$$-\nabla \cdot (\epsilon_0 \epsilon_r \nabla V) = 0.0 \quad (6)$$

Using these results from Neumann and Dirichlet for setting the boundary values and deduces the potential and field values at any position.

VI. RESULT AND DISCUSSION

A. The Electric Field Simulation

The electric field simulation from the FEM program gives accurate values compared with the analytical equation, and also gives the prediction region for streamer advance which have maximum field direction value. This model results agrees well with the obtained experimental one.

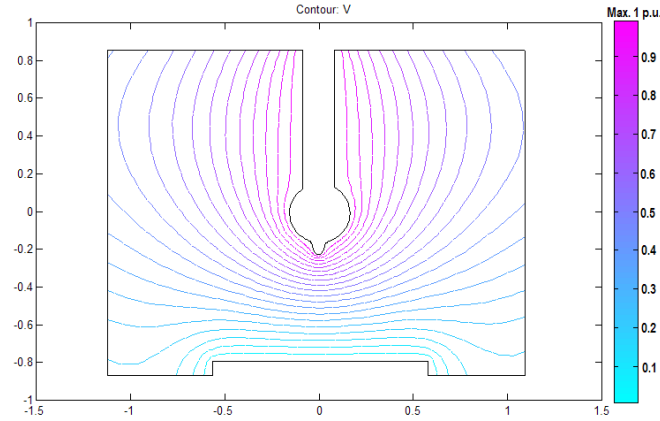


Figure 6: Simulated equipotential lines from FEM model.

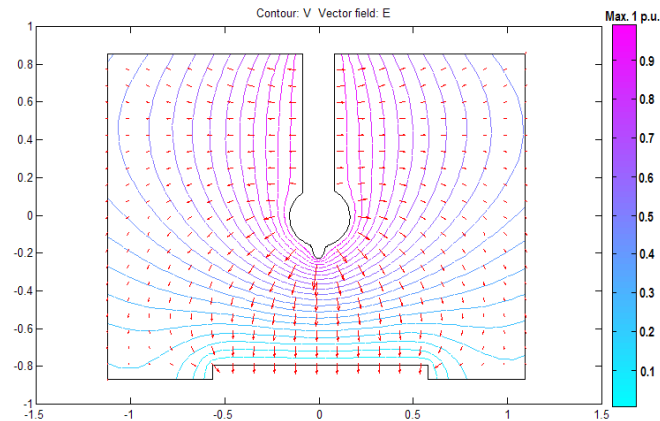


Figure 7: Simulated equipotential lines and vector field direction from FEM model.

The obtained potential and electric field from FEM program has been achieved. The equipotential lines are shown in Figure 6 and it can be easily observed that the potential lines are concentrated near the air bubble deformed tip. Also the vector field directions are shown in Figure 7 which describes the interested region for streamer formation, as shown in Figure 8.

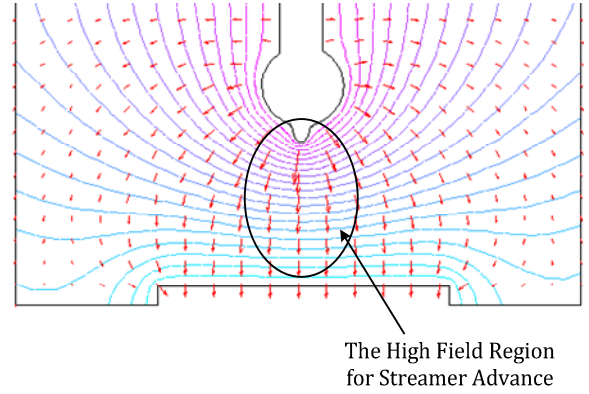


Figure 8: The interested region of high field direction which causes the streamer formation.

Figure 9, shows the simulation results for electric field computations by using FEM with various gap spacing from 6 to 14 mm from the sphere electrode with hyperbolic bubble tip towards the plane electrode.

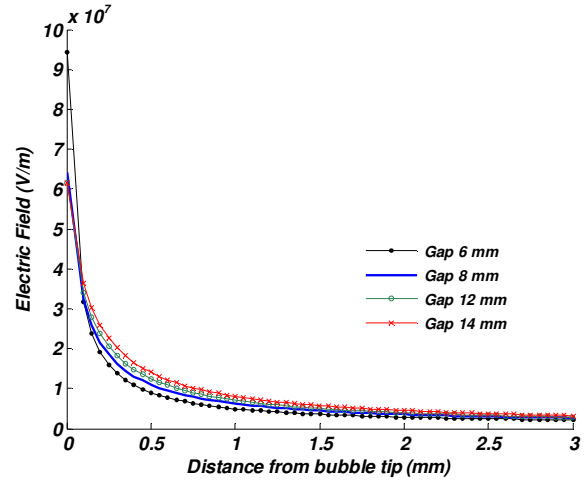


Figure 9: Electric field distributions along the gap axis using FEM.

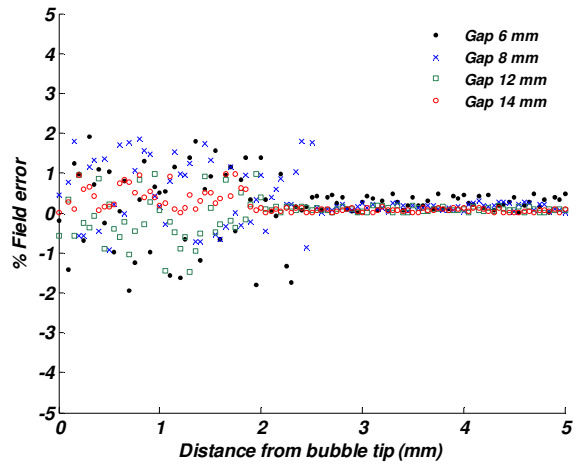


Figure 10: Per cent field error along the gap axis from analytical values.

From Figure 9 the value of the electric field near the protrusion hyperbolic bubble tip is higher than 600 kV/cm for

different using gapes. While the previous reported values of the required electric field for streamer initiation are 400-500 kV/cm for hydrocarbon liquids [14], 570 kV/cm for transformer oil [15] and 300-400 kV/cm for liquid Argon and Xenon [16]. Also, the computed electric field error on the axis of the compressed air bubble which is considered as hyperbolic protrusion tip-to-plane gap deviates from the results of equation (1) by less than 2 %, Figure 10.

B. The Experimental Results

Figure 11, shows the photographic recording of different gaps and different voltages for streamers formation.

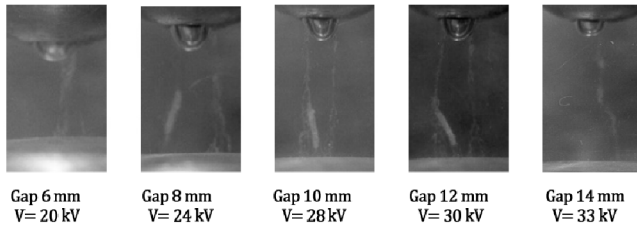


Figure 11: Photographic recording of different gaps and different voltages.

From this Figure it is clear that the streamer region is the region for maximum field direction which obtained by the simulation program using FEM. And this achieved for different gap spacing.

VII. CONCLUSIONS

A new model for investigating the electrical field in dielectric liquid using a sphere-to-plane gap is presented combined with immersed air bubble adjacent to sphere electrode. This accurate computation of the electric field is a pre-requisite to determine the streamer region formation. The electric field distribution is obtained using Laplace's equation by treating the immersed deformed air bubble as an extension of the high voltage electrode i.e., conducting medium. This is achieved by using the Finite Element Method. The deformed air bubble was treated as hyperbolic shape with tip radius curvature getting from photographic recording while the gap spacing varied from 6 to 14 mm. The results have been assessed through comparison with available analytical and experimental data. The computed electric field error on the axis of the needle-to-plane gap deviates from the analytical solution by less than 2 per cent. The accuracy of simulation results can predict the streamer region which has been confirmed by comparison with many experimental results.

VIII. REFERENCES

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A. El-Zein (Professor) was born in El-Dakhia, Egypt in 1948. He received the B.Sc. and M.Sc. degrees from the Faculty of Engineering, Cairo University, Egypt in 1971, and 1977 respectively, and the Ph.D. degree from Ain-Shams University in 1985. Now he is Professor at Zagazig University, Egypt. The research interest covers different types of high voltage insulation, breakdown of dielectric materials (gasses, liquids and solids).



M. Talaat (Lecturer, **M. IEEE**) was born in El-Sharkia, Egypt in 1979. He received the B.Sc., M.Sc. and Ph.D. degrees from the Faculty of Engineering, Zagazig University, Egypt in 2000, 2005 and 2009 respectively, and now he is Lecturer at Zagazig University, Egypt. He has many published papers in IEEE Transaction, IEEE conferences (CEIDP, MEPCON), ISH 2009. Also he is a reviewer at Journal of JEE, and a reviewer at Journal of Electric power components and systems. The research interest covers different types of high voltage insulation, Computer programs using simulation models.