SIMULATION STUDY FOR THE STREAMER DISCHARGE GROWTH WITHIN DIELECTRIC LIQUIDS AT SOLID INTERFACE

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Abstract

A computer simulation method was used to study the electrical pre-breakdown events in dielectric liquids. This study concentrated on the liquid-solid interface. The suitable model based on the cavitation theory. It was assumed that the streamer channels are weak plasmas and those channels have a high electrical resistance. The model was implemented numerically by finite element method (in two-dimensions). It was tested within a pin-plane configuration using the n-hexane and the water as dielectric liquids. Same voltage and electric field distributions were shown in the two liquids. But different distributions appeared when the solid insulator was introduced to the configuration. Also, the results show that, a strong dependence of the streamer growth path on the mismatch permittivity between the solid and the liquid. It was shown a nearest picture for the streamer behavior within the dielectric liquids. That can help the designers of the high voltage equipment.

الخلاصة

بطريقة المحاكاة الحاسوبية ، دُرس النمو الاولي للتدفق الذي يسبق حدوث الانهيار الكهربائي في السوائل العازلة. تركزت الدراسة على المنطقة الفاصلة بين عازلين احدهما سائل والاخر صلب.و يستند النموذج المُعتَمَدْ، على نظرية الفقاعة الذي يَفترض ان التدفق عبارة عن قنوات من البلازما واطئة التأين وان لهذه القنوات البلازمية مقاومة كهربائية عالية. وقد طُبق النموذج عددياً باستخدام طريقة العناصر المحددة (ببُعدين) في منطقة بين قطبين احدهما على شكل ابرة والاخر على شكل قرص مستوي. وأظهرت النتائج توزيعاً متماثلاً لكلاً من الفولتية والمجال الكهربائي في الهكسين الاعتيادي والماء ، الا ان هذه التوزيعات اختلفت عند ادخال العازل الصلب مع السائل . كما اظهرت النتائج اعتماد كبير لمسار التدفق على الفرق بين سماحيتي العازلين الصلب والسائل. ان هذه المحاكاة صورة مقربة لسلوك التدفق داخل السوائل العازلة حيث يساعد ذلك مصممي منظومات الجهد العالي التي تستخدم فيها هذه العوازل.

Introduction

Dielectric liquids have served as insulators in electrical equipment for more than 100 years [1]. They are considered to be useful as practical insulating materials for many reasons. First, since liquid and solid insulators are usually more than 10^3 times denser than gases, it follows that they should posses much higher electric strengths. Second, like a gas but unlike a solid, a liquid will fill a space to be insulated and, simultaneously by convection, will help to despite thermal energy losses for equipment cooling. Third, like a gas but unlike a solid, a liquid tends to be self-healing after electrical breakdown.

Comprehensive review of the published literature suggests that the theories that explain the mechanism of liquid breakdown fall into the following major categories: electronic theory, cavitation (bubble) theories and, suspended particle theory. The first suggests that, electrons are emitted from the cathode surface into the liquid by field emission. The applied field accelerates the electrons. Any electron gains the enough energy will cause ionization for liquid molecule by inelastic collision. The process grows by electron multiplication. The associated positive ions produced enhance the cathode field and can result in a catastrophic increase in current, causing a breakdown in the liquid. This theory dose not explains the dependent of breakdown strength on pressure, which applied externally, on liquid. The pressure dependence of breakdown has been widely observed for many liquids [2-4]. In the 1920's [5], the theory that a cavitation or bubble process may cause a breakdown in liquid dielectrics was proposed. Krasucki [6] showed, using a photographic method that in viscous liquids, electrons and ions may form local gas bubbles in which a small number of electrons avalanche is initiated resulting in ionization pulses and discharges. The avalanches develop long arbitrary channels, which may reach the cathode and initiate complete breakdown.

Kok and Corbey [7, 8] proposed a model based on the presence of polarizable spheres (suspended particles) whose dielectric constant is larger than the liquid. They suggest continues accumulation of particles due to their release from surface irregularities on the electrodes. They assumed that the particles become polarized by the electric field, and that electrostatic forces cause them to move in the direction of increasing electric stress. These particles tend to bridge the gap, which leads to breakdown. This model turns out to be unlikely in highly purified liquids.

Today with the development of new technology, it is possible to study the details behind the initiation and propagation of the events that lead to breakdown. An extensive studies were done with experimental methods [9-15] and, computer simulation methods [16-22].

This work is a computer simulation method to study the pre-breakdown events in dielectric liquids especially the case of liquid-solid interface.

Streamer Growth Model

Many facts about the pre-breakdown mechanisms for liquids insulating are still waiting for adequate theoretical explanation. The work, here, is an attempt to assemble some facts about liquid pre-breakdown and build an improved model for streamer propagation within a pin-plane configuration, figure (1). The model uses Garton and Krasuck's [23] approach of bubble discharge. This model is based on the following assumptions:

1. The region with the highest electric field is the site for streamer growth [1].
2. The streamer channels have very high resistance [23].
3. The streamer starts from the tip of the pin and extends to the region with the highest electric field.
4. The streamer branches start from the region with the highest electric field and extend to surrounding regions.
5. The streamer can propagate anywhere in the dielectric but is limited to one step in each branch.
6. A weakly ionized spherical gas bubble is suggested to form in the body of the liquid at the streamer tip [23].
7. The streamer branches do not intersect [1].
8. The growth of the streamer continues by repeating the above items with another bubble generation.
9. The current I is assumed to have an initial value I_o and increases linearly with streamer length ls [1,24](in non-dimensional equation) such as;

$$I = I_0 l_s \qquad \text{……………………………………} (1)$$

10. The voltage drop ΔV across the streamer for each iteration is equal to the current I times the streamer resistance Rs :

$$\Delta V = I R_s \qquad \text{……………………………………} (2)$$

11. The streamer growth continues until one of the stop conditions below reached:

a. The electric field value at the tip of the streamer, at any iteration, is greater than that at the tip of the pin for the first iteration [24].

b. The voltage drop across the streamer is equal to the applied voltage.

c. The streamer propagates into the bulk of the solid in the case of solid/liquid interface.

The Numerical Solution and the Simulation

The calculation of electric field in dielectric liquid in various stages of the pre-breakdown requires the solution of Laplace's equation subject to boundary and initial conditions. In many instances in physical systems, analytical solutions are difficult or impossible, and hence numerical methods are commonly used. Two-dimensional finite element method is used to solve Laplace's equation within the pin- plane configuration, shown in figure (1). The pin electrode used was 15mm long to ensure that the electric field far away from the pin tip is very small. The diameter at the top of the pin is 1mm therefore the plane angle of the head of the pin tip is about (2^o). The radius of the pin tip was assumed to be 0mm to simplify the mesh generation. The distance between the tip of the pin and the plane electrode is 3mm, which commonly used experimental gap distance.

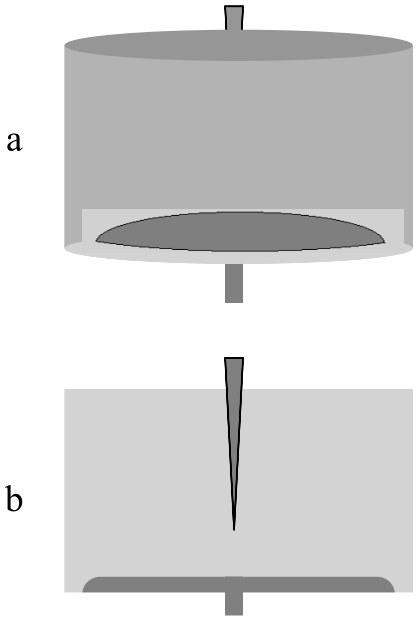

Figure (1): Pin-plane configuration, (a) the overall picture of the configuration, (b) the cross section for the configuration.

The finite element analysis of any problem involves basically four steps: discretizing the solution region into finite number of sub regions or elements, deriving governing equations for a typical element, assembling of all elements in the solution region and, solving the system turn of equations obtained.

The finite element method required a mesh to discrete the region for the solution. A linear triangular element was used for the configuration, to discrete the region between the electrodes. The region of interest is that which surrounds the pin tip. This is because a high electric field is expected in this region. Therefore, the elements in the mesh were not made with the same size. This is important in saving the time in running the program. The elements close to the pin tip were made very small and those faraway are larger. Using a large number of elements yields more accurate results but takes more time for the finite element calculation. The finite element mesh is created on the cross sections (of the configuration) on the dielectric between the two electrodes. This work was performed to investigate the solid interface effect. So that, the mesh was designed to contain many mesh areas with a special index for the elements of that area. Only one area for each configuration is needed to handle the solid thickness and spacing from the pin. In figure (2), the mesh consists of 5940 elements and 3127 nodes. The only boundary conditions for the finite element formulation are the known applied voltage values on both electrodes. These values of the voltage are assigned to the nodes on the electrodes.

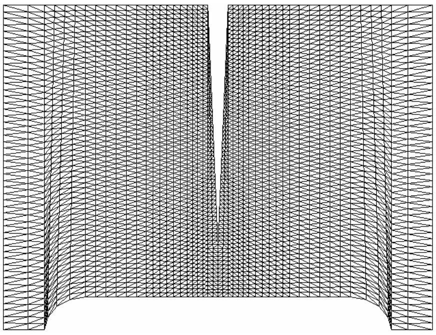

Figure (2): The mesh for the pin-plane configuration.

All calculations that required testing the present model are done by a computer program, which was built. The program is written with Fortran language. It is written to do the calculations that needed to predict the voltage and electric field distributions, and to simulate the path of the streamer within the configuration.

The Results

V and E Distributions

As mentioned earlier, it is important to identify the region where the streamer is most likely to occur. This is normally used to prevent breakdown or possibly to encourage it depending on the type of application. So that, at first, the voltage distribution must be known as well as the field distribution. Figure (3) shows the voltage distribution within the configuration and figure (4) shows the electric field distribution. The conditions of these distributions are 20kV applied voltage at the pin (needle) and 0kV at the plane. The liquid is n-hexane with relative permittivity of 1.883.

In figure (3), the contour plot shows a symmetric distribution around the pin. The region with the highest values of voltage is the nearest to the pin and that with the lowest values is the farthest. Between the two regions, the color hierarchy presents the voltage hierarchy as indicated by the color scale beside the figure.

In the same way, the contour plot in figure (4) shows, as expected, that the region with highest values, of the electric field, is at the tip of the pin and the values decreases faraway from the tip. The color scale indicates the hierarchy of the values of the electric field by colors.

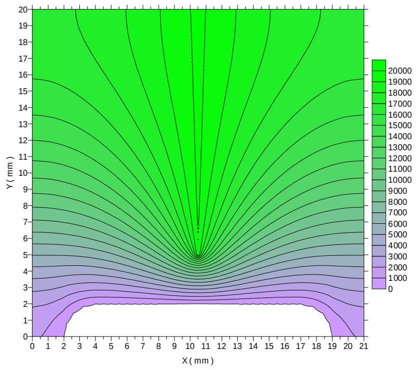

Figure (3): The voltage distribution within pin-plane configuration, in n-hexane liquid only.

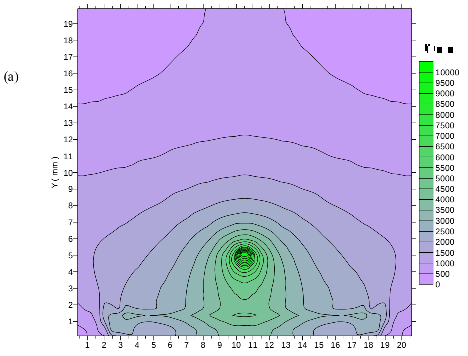

Figure (4): The electric field distribution within pin-plane configuration.

An extensive study of figure (4) shows, at the bottom of the figure, a clear disturbance in the field magnitude. That can be attributed to the edge effects of the plane electrode, in which it can be overcome experimentally by using the so-called garbing around the electrode, or using electrodes with certain profile, i.e. Rogonisky profile, at the edges, which cannot be done her because the limitation of the mesh generating procedure.

The Streamer Growth

Case I: Liquid Only

The model tested in n-hexane liquid only. As would be expected, the streamer initiates at the tip of the pin because it is the region of the highest electric field. Since our attention is concentrated on the development of the streamer growth, and due to the difficulties in obtaining details from the plots in the complete configuration, an enlargement of the regions between the electrodes is used for most of the figures in this work.

In figure (5), it was shown the development of most steps of the streamer growth. The figure shows a direct growth at the shortest distance towards the anode.

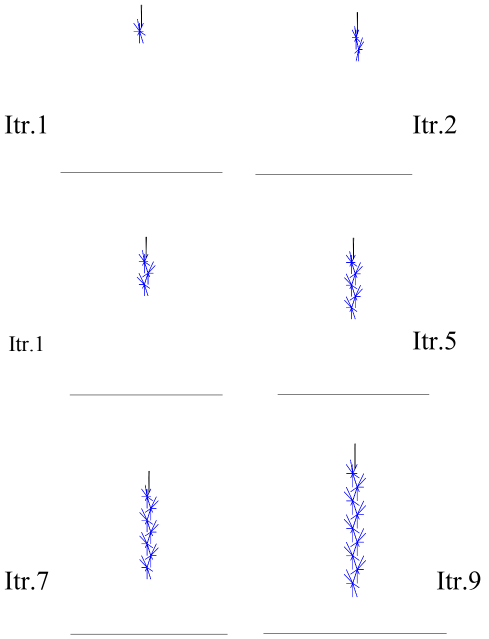

Figure (5): The streamer growth for iterations 1,2, 3, 5, 7, and 9 in n-hexane liquid only

Figures (6) and (7) show the effect of the streamer growth on the distributions of the voltage and the electric field. These figures indicate clearly the movement of the region of the highest voltages and the highest electric field according to the streamer growth. The plots for the magnitude of the electric field can identify the weak region where the breakdown may begin. For this case, the weak region was identified to be the region where the magnitude of the electric field is the highest and from this region the breakdown will initiate. The streamer moves the high region voltage from the pin tip down to the plane electrode.

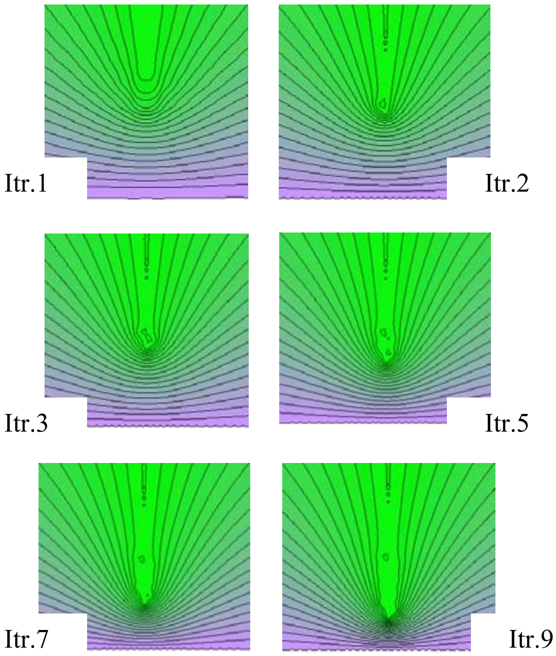

Figure (6): The effect of the streamer growth on the potential distribution for iterations 1, 2, 3, 5, 7, and 9 in n-hexane liquid only

field according to the streamer growth. The plots for the magnitude of the electric field can identify the weak region where the breakdown may begin. For this case, the weak region was identified to be the region where the magnitude of the electric field is the highest and from this region the breakdown will initiate. The streamer moves the high region voltage from the pin tip down to the plane electrode.

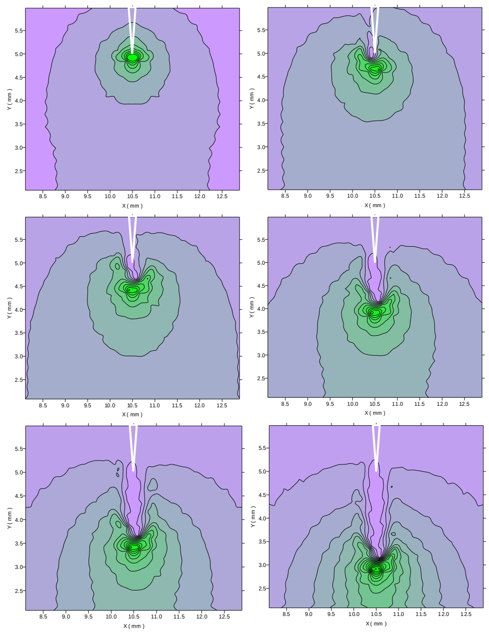

Figure (7): The movement of the region the highest value of electric field for iterations 1, 2, 3, 5, 7, and 9 in n-hexane liquid only.

Case II: Liquid with Solid Materials

A solid interface is needed in many applications. The placement of the solid interface depends on the application of the device that uses it. A simulation study was done for this case which discussed in the remaining portion of this paper

For comparison purposes, the same mesh, figure (2), is used for this case too. A solid thickness of 1mm is attached to the shank of the pin and placed perpendicular to the plane electrode as in figure (8).

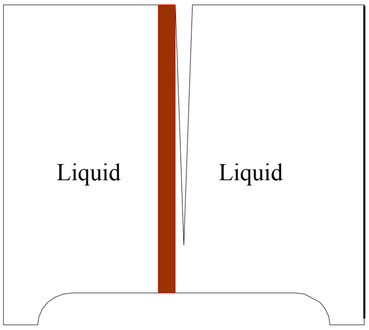

Figure (8): The solid interface within the pin-plane configuration.

A- Solid with N-hexane

N-hexane was taken as the dielectric liquid with a solid interface of relative permittivity higher than that of n-hexane. To show the effect of the solid interface on the streamer growth, the model was tested within the configuration that shown in figure (8). The same conditions in the previous section are used except the value of the relative permittivity for the solid equal 10.

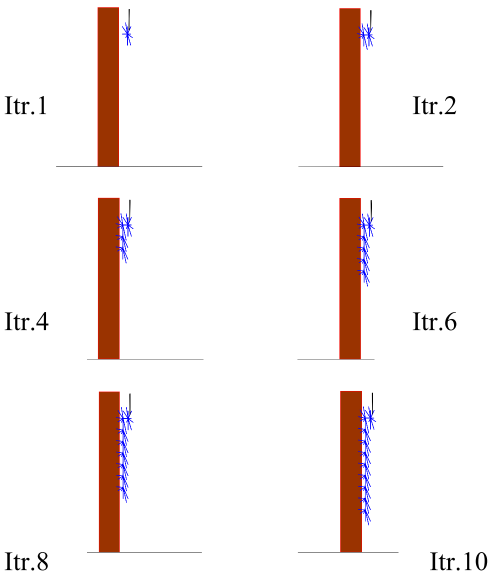

Figure (9): The streamer growth for iterations 1,2,4,6, 8, and 10 in the n-hexane liquid with solid interface.

Figure (9) shows the development of the streamer growth within the region between the electrodes. It appears clearly, when the permittivity of the solid greater than that of the liquid, the deflection of the path of the streamer growth towards and with the solid interface. That indicates the weak region within the configuration to occurring the breakdown.

Figures (10) and (11) are an enlargement of the region between the pin and the plane electrodes. The first one shows contour plots for the voltage distribution according to the streamer growth. It appears clearly the deflection and moving the region with the highest values. In the same way, the second shows the movement of the region of the highest values of the electric field for the same iterations. For this case, the weak region, that of the high value of electric field can be identified to be as the interface between the solid and liquid.

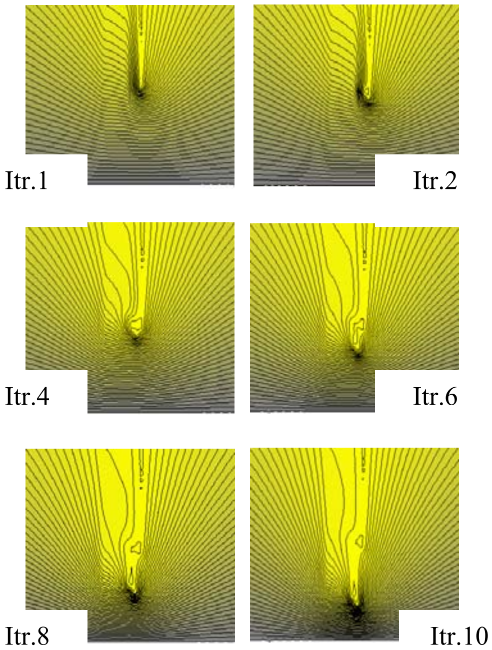

Figure (10): The effect of streamer growth on the voltage distribution for iterations 1, 2, 4, 6, 8, and 10 in n-hexane liquid with solid interface.

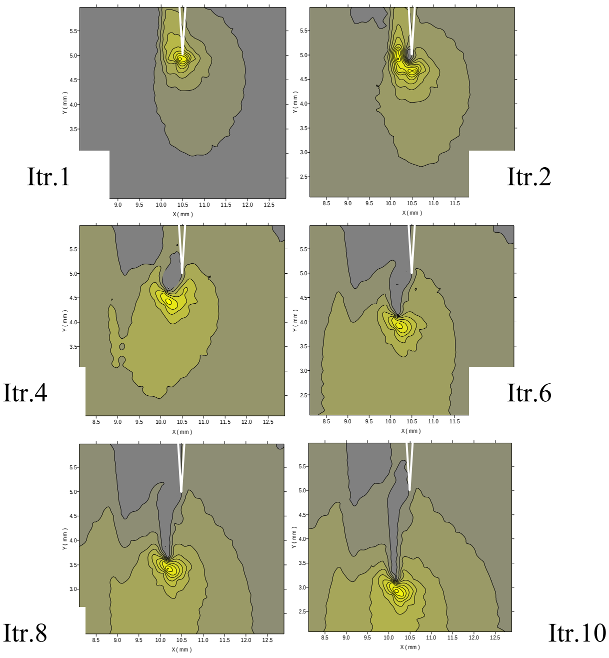

Figure (11): The movement of the highest value of electric field for iterations 1, 2, 4, 6, 8, and 10 in n-hexane liquid with solid interface

B- Solid with the Water

In this section, the water was selected as a test liquid because it's high relative permittivity. The same procedures and analysis techniques used for the n-hexane case were used for the water case. The same mesh, shown in figure (2), used for n-hexane case was used in this case. For the same purpose that discussed in the case of n-hexane, again the streamer growth was followed step by step. That was done to identify the weak region where the breakdown is initiated. When water is used as a dielectric, the weak region, with the highest electric field value, is not necessarily close to or on the solid interface**.**

Figure (12) shows an enlargement for the region between the pin and the plane electrode for most steps (iterations) of the streamer growth. The figure shows that the streamer grows far from the solid interface in the other side of the pin in the configuration. That is because the relative permittivity of the liquid (water) is greater than that of the solid.

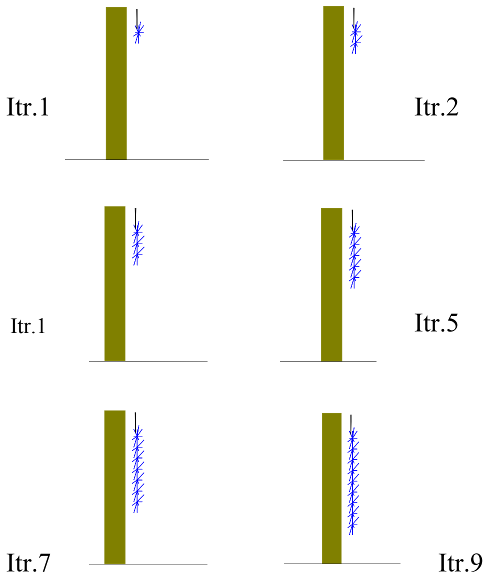

Figure (12): The streamer growth for iterations 1, 2, 3, 5, 7, and 9 in the water with solid interface.

In figures (13) and (14), a contour plots for the voltage and the electric field distributions, respectively, within the configuration for the case of the water with solid interface. The two appear that the weak region was identified to be far from the interface between the solid and the liquid**.**

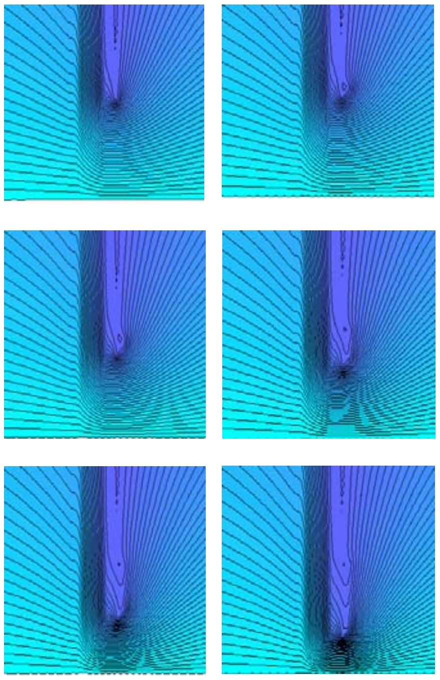

Figure (13): The effect of streamer growth on the voltage distribution for iterations 1, 2, 3, 5, 7, and 9 in the water with solid interface

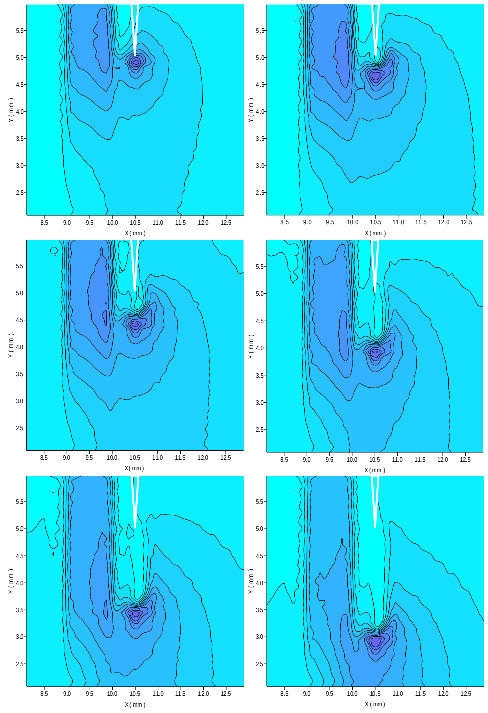

Figure (14): The effect of streamer growth on the electric field magnitude distribution for iterations 1, 2, 3, 5, 7, and 9 in the water with solid interface.

Conclusions

From an overall observation to the results of this work, one can estimate, for the pin plane configuration, which employed here, some conclusions as below:

1-For the case of only liquid, the distributions of the voltage and the electric field show symmetric distributions around the pin electrode. While, when the solid introduced to the configuration, new distributions appear. When the relative permittivity of the solid insulator greater than that of the liquid, the values of the voltage and the electric field in the region of the solid became lower and in the liquid higher than that for the only liquid case.

2-The introducing of the solid insulator, to the configuration, produces a weak region to breakdown occurring at the solid interface (with high value of electric field).

3-The breakdown can occur at or away from the solid interface depending upon the conditions. For the cases of solid of relative permittivity greater than that of the liquid, the breakdown occurs at the solid interface. While for the case of solid of relative permittivity less than that of the liquid, the breakdown occur in the liquid away from the solid interface.

4-The mismatch permittivity controls the streamer growth and the movement of regions of high values of the electric field.

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