

A Prediction Methodology of Electrical Tree Propagation in Solid Dielectrics

A. El-Zein, M. M. El Bahy and M. Talaat

Abstract-- In predicting electrical tree growth behavior of practical insulation materials under operating voltages, one must consider the effects of mechanical tensile residual stresses, electrical field stresses and the voids distribution to the electrical tree growth. In this study a general model of electrical tree propagation is firstly proposed depend on voids location in the polymer, combines both the mechanical tensile residual stresses and the electrical field distribution in the medium using charge simulation method in combined with genetic algorithms to describe the local damage features around the tree tip, and enables this effect of compressive to predict the electrical tree dynamic growth. The obtained results have been assessed through comparison with available experimental data.

Index Terms-- Electrical Tree, Tree Progress, Types of Electrical Trees, Charge Simulation Method,

I. INTRODUCTION

ELECTRICAL treeing is a factor which seriously affects the practical lifetime of various power apparatus. The tree channel starts from field enhancement points which cause divergent fields, or from gaseous cavities leading to partial discharge (PD) activity. In practical extruded and cast insulation, imperfections such as contaminant particles, delaminating at the electrode/polymer interface, bad adhesion at fiber/polymer interface in the case of fiber-reinforced insulation, protrusion of a semiconducting layer in the case of extruded cables, and gaseous voids in the bulk of insulation, produce potential starting points for trees [1-4].

To simulate defects leading to local field enhancement, treeing has been studied using polymer blocks into which a metallic or semi-conducting needle electrode was inserted. This kind of samples is called a treeing test sample. Alternatively, artificial gaseous cavities of different shape and size were used to simulate voids which sustain PD [1, 3-5].

Tree initiation from gas discharge in a void is different from that in a void-free condition [2]. In tree initiation from voids, gaseous discharge is the first phenomenon and occurs at relatively low voltage. Investigation of tree initiation in

laboratory models has shown that tree growth from cavity depends on its shape and size [6]. Rapid tree growth is observed for needle shaped voids. In the case of cylindrical, spherical or ellipsoidal cavities of $\sim 30\mu\text{m}$ size, the tree is initiated after erosion of the cavity walls by PD which can take a much longer time [5].

II. ELECTRICAL TREE FROM A CAVITY

The presence of gas-filled cavities in the insulating material is one of the causes of breakdown through treeing [7, 8]. In certain cases, the conditions of extrusion or the operational stresses experienced by the finished product can lead to the formation of bubbles inside the material or to a separation at the interface between materials e.g. semiconductor shield insulation interface, joint and cable. Such defects are sites of origin for PD. Real progress has been made in the production of cables and more especially in the production of XLPE insulated cables, since the paper published by McKean [9], the author counted up to 10^5 voids $/\text{mm}^3$, which were due to the cable insulation manufacturing process. The dimension of the voids, i.e. between 1 and $5\mu\text{m}$ was important as well as the number.

The study of the potential distribution in such a system below the inception voltage shows that the maximum field stress occurs along the cavity axis and the minimum field stress across the cavity walls. Therefore discharges have a tendency to initiate along the cavity axis. At voltages above the inception voltage, the PD leaves, on the cavity surface, a charge which reduces the stress originally acting in the cavity. Therefore, not only the field stress amplitude but also the field distribution itself becomes time-dependent [10].

The transition to treeing is determined entirely by the value of the electric field at the cavity edge or around the defects created at the surface of the insulating material by discharge impact. This transition is therefore dependent on the geometry of the cavity and the variation of the conductivity of the walls. The different regimes of discharges give rise to different pulse shapes which can be generated simultaneously from the same cavity. This is presented by Kreuger as a cause of error in the location of PD in HV cables [11]. The same author and his team had previously reported on the effect of different discharge mechanisms on the detection of PD.

Deterioration was more rapid if the void was adjacent to the metal electrode than with the void enclosed in the dielectric because the initial discharge intensity is greater [5, 10]. Final breakdown is related to the development of tree

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channels from deep pits created by localized discharges both with cylindrical and hemispherical voids. But the local field is not always homogeneous, and in order to simulate the breakdown process in that situation, a needle-shaped cavity adjacent to a needle electrode may be studied. Breakdown results from tree generation and growth from the sharp end of the void, but the process depends on numerous parameters such as void depth, nature of the gas, and electric stress. The trees are much easier to initiate than in a void-free sample, but their shape is different and they exhibit a linear increasing propagation versus voltage. The radius of curvature of the void tip has a marked influence on the tree inception voltage together with the radius of the needle tip. It is likely that the use of a needle electrode introduces highly localized streamer-like discharges along the axis of the cavity [4, 5, 10].

These discharges impinge the cone-shaped end of the cavity and lead to charge transfer in the volume of the dielectric around the cavity tip. Self-extinction of internal discharge in the cavity has not been reported before treeing since the discharges are created along the axis of the system. The tip of the void acts as 'pits' seen with a cylindrical or spherical cavity. The high field concentration at the tip controls the subsequent generation and growth.

The real voids which are present in insulated systems differ mainly by their shape and size. In the case of XLPE insulated power cables, the cavities appear to be spherical but their size and density depends on the curing process [12]. The possible occurrence of discharges in such a small volume (1 to 10 μm) is controversial since the Paschen law is established for plane and parallel metal electrodes and the minimum inception distance is $\sim 6 \mu\text{m}$ for air at atmospheric pressure [13].

III. PRESSURE ANALYSIS INSIDE MICRO VOID DEFECT

At protrusion tip site the electric field intensity is very high and equal to (E).

$$E = \frac{2V}{r \ln(1 + 4d/r)} \quad (1)$$

where r : protrusion tip radius inside cable of applied voltage (V) and insulating thickness (d),

Also the breakdown voltage (V_b) is given by:

$$V_b = \frac{BPd}{\ln(APd/\ln(1 + \frac{1}{\gamma}))} \quad (2)$$

where, P is the pressure at breakdown, γ secondary ionization coefficient, A and B are gas constants.

The electric field intensity inside the reside air void must be higher than that of dielectric medium of relative permittivity ϵ_r , by a factor, $m = \frac{3\epsilon_r}{(2\epsilon_r+1)}$, with void of diameter (t) and protrusion radius (r_o).

From equations (1), (2), and the factor m we can conclude that, at pressure P_m according to [14];

$$E = \frac{(B/m)p_m}{(\ln p_m + G)} \quad (3)$$

where $G = \ln \left[\frac{At}{\ln(1 + \frac{1}{\gamma})} \right]$, p_m is the pressure inside air void, which must reach the mechanical tensile strength for crack starting, with void of diameter (t).

Figure 1 show that the relationship between the mechanical tensile strength and the corresponding intrinsic breakdown stress according to equation (3). The values of A , B and γ for air are taken to be 12, 365 and 0.02 as given by [15].

The $Ei-p_m$ relation shown in figure 1 described that the critical electric field that is intersect with E_i axis for $p_m = 4450$ torr ($4450 \text{ torr} = 0.593 \text{ N/mm}^2$) given by [14], is around 4MV/cm for different types of dielectric mediums this value can be called the critical electric field for tree initiation, ($E_c = 4\text{MV/cm}$) which agree with many paper [7, 16-21].

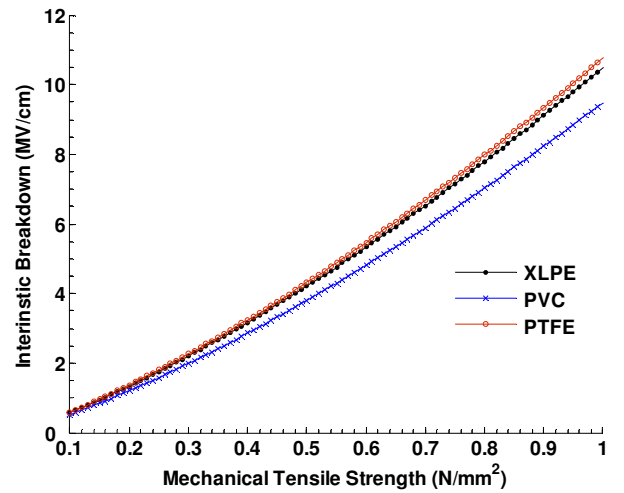


Fig. 1. The effect of the mechanical tensile strength of solid dielectric cables on the intrinsic breakdown stress value under specified micro void diameter.

IV. TREE PROPAGATION ACCORDING TO VOIDS DISTRIBUTION

During the tree propagation process, the damage process zone is visualized to evolve in a self-similar fashion and evolves through the transformation of polymer from some initial morphology figure 2.

In this way the nature of damage is intrinsically related to the microstructure of the polymer. The damage in the damage process zone may manifest itself as an ensemble of micro-defects in the form of voids, cracks, or other features.

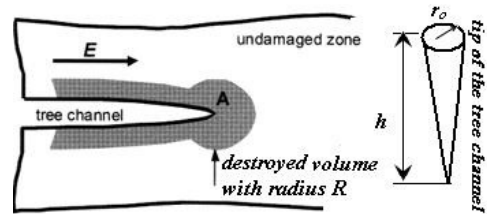


Fig. 2. Microstructure of the local field around the tree tip: damage zone with radius R and a tree channel with radius r_o and height h considered as cone shape [19].

Figure 3 illustrates the microphysical characteristics of tree propagation. Damage in the damage process zone ahead of a tree gives rise to micro-voids, which eventually coalesce, as

an extension or branch. The characteristic micro-void density and its distribution in the damage process zone depend upon material, specimen geometry, and loading conditions. The angle between the planes in which the tree channel lies is a random value, also the direction of the tree extension is random. The interval between two consecutive increments of tree propagation depends also on the random distribution of micro-voids in the damage process zone. The consequence of this approach is therefore that tree propagation is essentially considered here to be a random process.

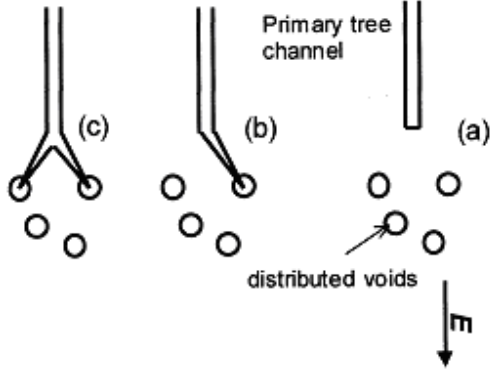


Fig. 3. A propagation tree and its branching process; (a) Micro-voids initiate in the damage process zone at the tree tip when the intensity of the local field ultimately builds up to some critical level; (b) The primary tree channel departs from its original straight trajectory to connect to a neighboring cavity being absorbed; (c) Another neighbor cavity is absorbed by the main tree channel to form branching tree channels [22].

V. THE PROPOSED MODEL

The dielectric material is divided into several layers, each layer contains a random number of voids with random location in two dimension specimen depend on the value of voids given by [9].

For 1mm^2 of dielectric the specimen is divided into group of layers (100 layers), each layer equal to $10\mu\text{m}$ in thickness, see figure 4.

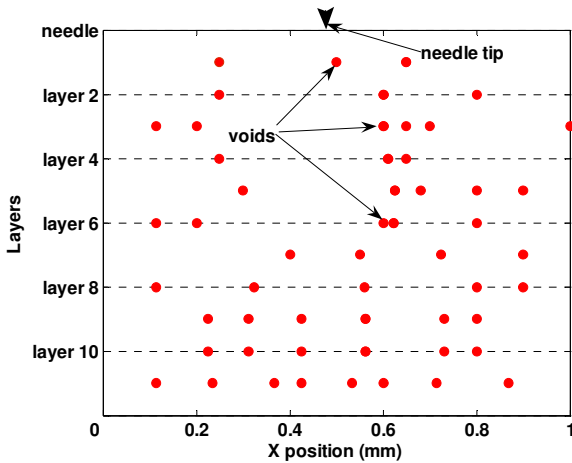


Fig. 4. A model for voids distribution in solid dielectric.

The simulated needle is chosen to be in hyperbolic shaped with radius $5\mu\text{m}$ and 1mm separation gap from the plane earthed electrode and have an applied voltage of 10kV . For electric field distribution in the dielectric medium during each

tree branch formed, a charge simulation method (CSM) in combined with genetic algorithms (GAs) for optimum charge location given by [20, 21] is used, assuming each tree branch as an extension for the needle surface i.e. conducting tree channel.

A. Physical approach for the electrical tree growth

For the tree to start at certain site large electric field intensity at this site must exist. This field value has been given to be 4MV/cm [4, 16-21].

In the present paper we visualize that the high electric field starts a protrusion conducting tip inside dielectric medium such as semi-conducting tape or copper tape in solid dielectric power cables. These dielectric solid medium contains some defects during manufacturing, especially micro air voids in solid dielectric insulation of power cables.

When such micro-voids reside on the protrusion tip or very near to it the high field in this medium will be manifested by a factor m mentioned before.

When the field inside the medium reaches 4MV/cm , the electric stress is sufficient to overcome the mechanical stress and crack starts from this void site. But according to previous finding in [14] all dielectric materials gives a constant surface tension pressure for these micro air voids at ambient temperature, irrespective that these materials has different surface tension at its liquefied phase temperature, and when its surface tension pressure referred to ambient temperature gives a constant value of 4450 mmHg [14].

Also the breakdown of air inside micro-void starts at 1.31MV/cm , i.e. this value equal $1.31/m = 1.063\text{MV/cm}$, for $\epsilon_r = 2.3$.

In this new paper, we consider the path of tree will select the path of minimum energy required. This path will be between the position of 4MV/cm and that site at which inception field inside air void starts (1.31MV/cm in void and 1.063MV/cm in solid medium). According to Fig. 5 the distance will be nearly $10\mu\text{m}$, which is in accordance with the finding given after many references.

B. Method of tree progress

We can put the following items for tree progress:

- At the needle tip the electric field must reach a value of 4MV/cm [7, 16-21], which called the critical field value E_c .
- There is one branch crack of ($1\mu\text{m}$) in radius and ($10\mu\text{m}$) in length [19-25] under 4MV/cm .
- This initiated crack will be increased in size due to ionization at its surface, so its surface is assumed to be a conducting medium [23-26].
- The minimum inception electric field inside air void in the solid is $E_i = 1.31\text{MV/cm}$ [14]. This field in the solid insulation reaches a value of 1.063MV/cm , and is considered the required value for discharge inception.

- The inception value for discharge gives the minimum mechanical tensile strength to reach the energy required inside the adjacent void to the needle.
- The distance between the stressed electrode tip and the position at which the electric field reaches E_i will be considered the crack branch step length.
- The tree starts from the protrusion or needle tip toward the nearest void according to the previous postulation. When the first crack or path starts a discharge occurs inside it which converts it to a conducting path. From this initial stem its tip considered as the new starting position. So another path is added from the new position.
- For each branch added to the tree shaped, the electric field distribution in the dielectric medium and voids is pre-request from the simulation model given by [20, 21] using (CSM) coupled with (GAs).
- At each tip the ratio of E/E_c is calculated to determine the number of branches which should be added at each layer [19].
- The electric field at each branch tip is calculated and the priority for path advance will be for the branch of highest electric field value. The other branch is considered dead, i.e. without electric charges during computation of electric field till the next advanced positions.
- The simulation takes the above points into consideration by calculating the electric field at each intended position in the medium due to all charges present at the surface of the needle, the main tree stem up to this position.

C. The simulation model

For our proposed model to get a value higher than $E_c = 4\text{MV/cm}$ in the 1mm of XLPE, ($\epsilon_r=2.3$), dielectric specimen, we use a needle of $5\mu\text{m}$ in radius in the middle of the upper surface of the specimen, see figure 4, and 10kV is applied for this needle.

1. The shape of the needle may be described by the hyperbolic function
2. The distributed charge on the needle surface is simulated by a set of n ring charges arranged along the needle axis. The vector of unknown charges, Q is computed as:

$$[P] \times [Q] = [V] \quad (4)$$

3. For a given charge distribution, the potential Φ at an arbitrary point is a summation of the potentials resulting from the individual charges,

$$\phi_i = \sum_{j=1}^n P_{ij} Q_j, \quad i = 1, 2, \dots, M \quad (5)$$

where, M and P_{ij} are the number of contour points, ($M = n$) and potential coefficients, respectively.

4. The GAs using the objective function to obtain the arrangement and the minimum number of ring charges along the needle axis, the used objective function is simply the accumulated squared error which has the form

$$U = \sum_{i=1}^m [V - \phi_i]^2 \quad (6)$$

5. After the first branch is formed the simulation called again for electric field calculation, but here the simulation take in consideration the total shaped contained the needle and the added branch assuming it as conducting medium [23-26], here the tip considered is the branch tree tip which chosen to be in range ($1\mu\text{m}$) [23-25].
6. The field at the tip of the branch tree becomes higher than E_c . Hence, the tree tip will grow with time and form other number of tree branches. Each branch is assumed to have a cylindrical shape terminated by a hyperbolic.
7. Each added branch with its terminated tip is simulated by k of series finite or inclined line charges arranged along the z-axis of the tree shape. Then the potential at an arbitrary point is expressed by:
$$\phi_i = \sum_{j=1}^n P_{ij} Q_j + \sum_{j=n+1}^{n+k} P_{ij} Q_j, \quad i = 1, 2, \dots, M \quad (7)$$
 where, M equals $(n + k)$.
8. Then the computer repeated the above steps to predict the new branch formed till the value of E/E_c indicate that the tree is converted into bush-type tree.

VI. RESULT AND DISCUSSION

A. The electric field simulation

In order to demonstrate the proposed approach, the needle simulated with (131 ring charges), and the number of generations used in the GAs is 100, the population size is 10 and the mutation rate is 0.01. Then each branch added is simulated by adding a number of vertical and inclined finite line charges connected in series and adjoin to the needle surface [20, 21].

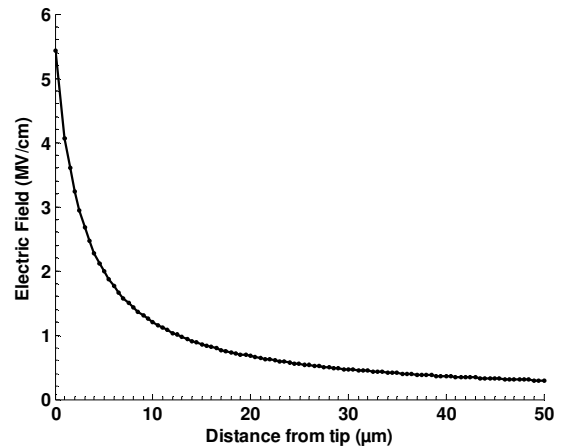


Fig. 5. Electric field distributions from the needle along the gap axis using CSM.

Figure 5, shows that E at the needle tip exceeds E_c , which give the advantage for branch formation.

TABLE I
THE SIMULATION RESULTS OF THE NEEDLE

Position	% max. absolute potential errors	max. field deviation angle (degree)
Along needle surface	0.0774	0.8204
Along needle tip	0.7596	2.5623

When the gap distance reaches 340 μ m to the plane electrode, the electric field reach a value higher than the critical and E/E_c indicated that many number of branched are required so the branch-type tree converted to bush-type tree and the dielectric goes to breakdown. This distance means that the branch length through the gap reaches a value of (0.6) of the total gap length which leads to the breakdown [27].

B. The predicted tree

Figures from 6 to11 show that our simulation program and our predict computer program give varies types of predicted tree for different type of random void distribution before it converted to bush-type tree.

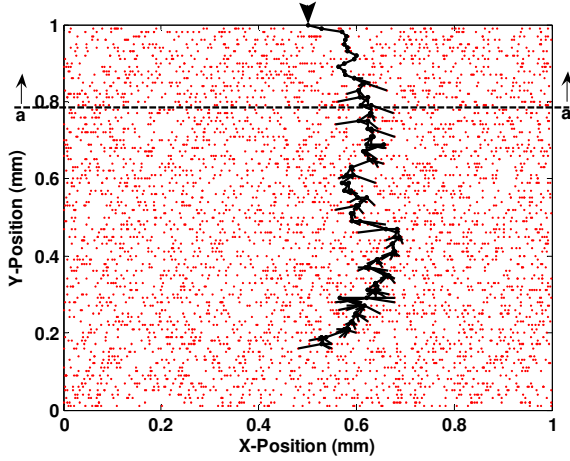


Fig. 6. The predicted shape (model 1) of branch-type tree depended on voids distribution and the critical value of electric field distribution given from a simulation programmed.

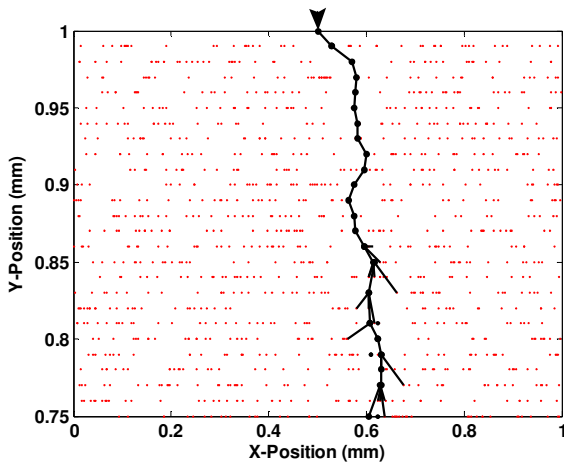


Fig. 7. The magnification of section (a-a) shown in figure 6, to describe the branch direction added in each layer.

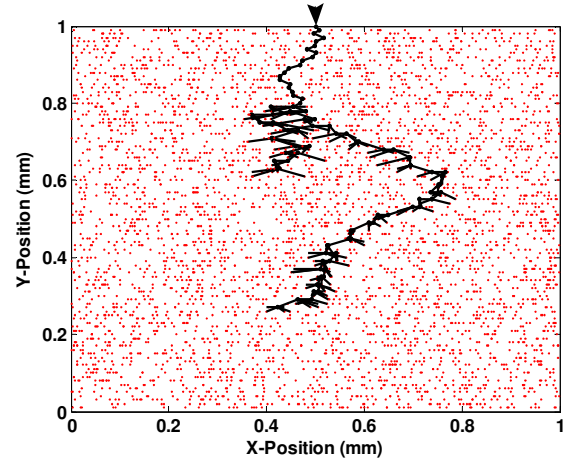


Fig. 8. The predicted shape (model 2) of branch-type tree depended on voids distribution and the critical value of electric field distribution given from a simulation programmed.

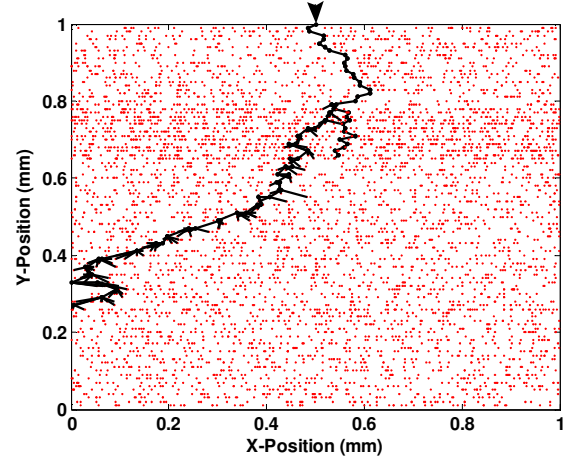


Fig. 9. The predicted shape (model 3) of branch-type tree depended on voids distribution and the critical value of electric field distribution given from a simulation programmed.

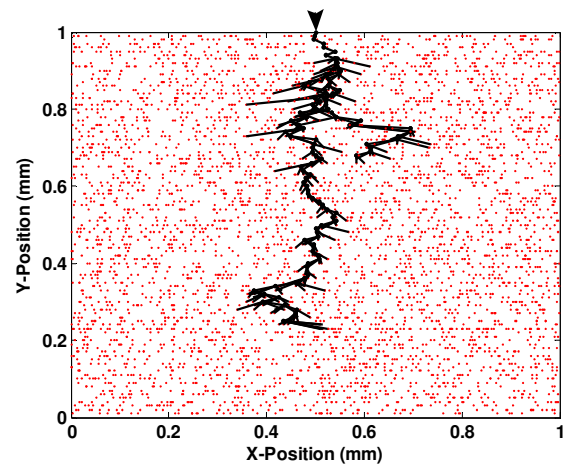


Fig. 10. The predicted shape (model 4) of branch-type tree depended on voids distribution and the critical value of electric field distribution given from a simulation programmed.

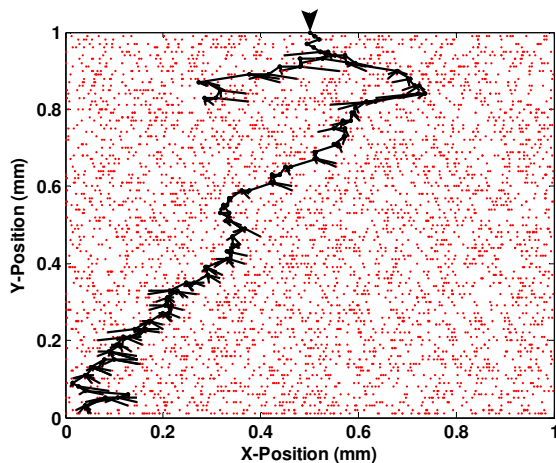


Fig. 11. The predicted shape (model 5) of branch-type tree depended on voids distribution and the critical value of electric field distribution given from a simulation programmed.

C. Comparison with Experimental Results

Figure 12 shows different types of branched tree using the same data in our simulation, where the needle tip radius using in each one is $5\mu\text{m}$ and the applied voltage using in each one is 10kV but with different gaps length.

From this figure there is a great acceptance of our prediction model which in accordance with these experimental results.

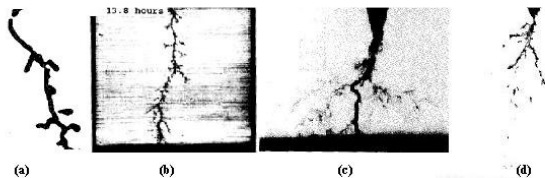


Fig. 12. Comparison with experimental results; (a) given by [28] with gap equal 2mm, (b) given by [29] with gap equal 10mm, (c) given by [30] with gap equal 3mm, and (d) given by [31] with gap equal 10mm.

VII. CONCLUSIONS

The present study investigates the growth of electrical trees in solid polymeric insulation subjected to electrical stress as well as a combined electrical and mechanical tensile strength in the polymer and voids included to predict the tree propagation.

From the results obtained in the present study the following conclusion are drawn:

1. This model has the ability to predict the electric tree from the protrusion defect site or the needle tip when the electric field reaches value of 4 MV/cm.
2. The advance of this tree choose the path of minimum energy level which is the distance between the needle or main tree stem tip and the position of air void at which electric field reach the inception value of 1.31 MV/cm, this distance equal to $10\mu\text{m}$.
3. At tip with an electric field equal E_c a one crack of nearly $10\mu\text{m}$ distance and $1\mu\text{m}$ radius occurs.

4. At high electric field, the ratio of E/E_c decide the type of tree; if its branch or bush tree types, when E/E_c is sufficient to initiate two or more branches respectively.
5. The present model has the ability to predict different types of tree patterns which have been assessed through comparison with available experimental data.

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liquid and solid).



studies, breakdown of dielectric materials, digital calculation of electric fields, investigations of high voltage phenomena.



(gasses, liquid and solid), also the interest of digital calculation of electric fields by using (CSM, FEM)..

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