

Suppression of the Electrical Tree Growth in Solid Insulation Using a Transverse Layer of Dielectric Barrier

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Abstract- A solid insulation with a transverse layer of dielectric materials is described to investigate the effect on the growth of electrical trees. A needle to plane electrode is used for the simulation of the sharp protrusion in underground cable that causing tree inception field. A simulation field in polyester resin with a layer of dielectric barrier in different distance from the needle tip is presented using charge simulation method. The layer of dielectric barrier is chosen to demonstrate the suppression of the electric tree growth. The obtained results clear that the electric field simulated from charge simulation method in the presence of dielectric barrier having suddenly decreasing value in the barrier location, which reduce the probability of tree growth.

I. INTRODUCTION

A good understanding of electrical tree propagation in underground cables is a key issue for suppression of this phenomenon. The growth mechanisms of electrical tree have been modeled resorting to various approaches [1-2].

Composites materials with barriers are used to slowdown tree propagation in high voltage insulations [3-5]. The structure of barriers, their material, thickness, width and their dielectric strength are the main factors to be considered for selection of the barrier to prolong the lifetime of composite [6-7].

Electric field analysis provides important roles for the design of high voltage insulation. In some electrode geometries, the electric fields can simply be expressed analytically; in other, the electric field problem is complex because of the sophisticated boundary conditions, including media with different permittivities such as composite materials.

The calculation of electrostatic fields requires the solution of Poisson's and Laplace's equations. Several numerical techniques have been used for solving Laplace's and Poisson's equations between complex electrode arrangements [1, 8-10]. Charge simulation method (CSM) is one of the most successful numerical methods for solving electrostatic field problems [1, 11-12].

Barrier effects have been investigated by a number of authors and many papers have been published on this effect. Most of them include generally experimental studies [3-5], but there is less paper on field analysis and simulation of barrier problem.

In this study influence of dielectric barriers on electric field distribution of a needle to plane gap is examined using CSM

to calculate the electric field and potential distributions in the vertically arranged needle to plane gap inserted dielectric barrier. Knowledge of the maximum field is necessary for estimating the tree growth this value indicated by many authors to be 4 MV/cm [1, 13-16] for tree initiation. Maximum fields are examined for different barrier thickness, positions and materials of barrier.

II. PROBLEM ANALYSIS

A. Electric Field Calculation

The electric field distribution in a needle-plane gap with a dielectric barrier is numerically analyzed by using (CSM). Figure 1 shows the considered needle-plane electrode configuration.

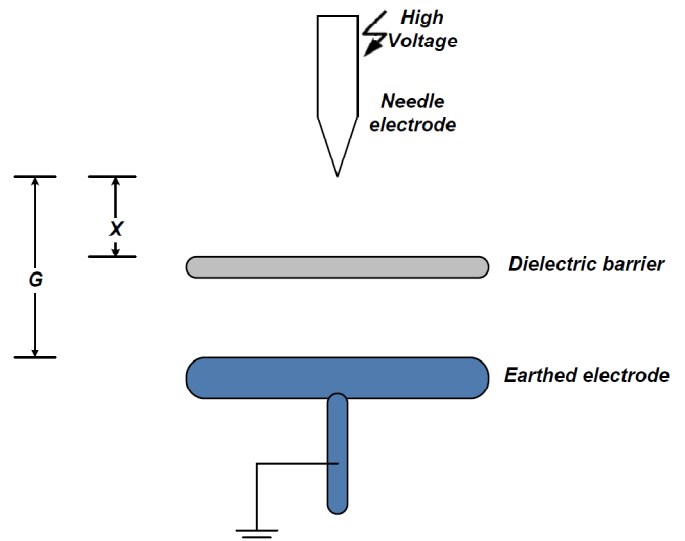


Fig. 1. Electrode configuration.

Here, a needle tip radius of $1\mu\text{m}$ was used with a hyperbolic end. The distance of 5 mm between the needle and plane was chosen to study the tree growth at vertical gap position. The applied voltage was 28 kV and the relative permittivity of the insulation medium was $\epsilon_r = 2.1$, and the barrier thickness was $25\mu\text{m}$.

The geometry of the electrode system has an axial symmetry with gap distance equal G and the barrier location away X

from needle tip, Fig.1. Therefore, problem can be solved in cylindrical coordinates. In this coordinates, it can be assumed the z-axis of coordinates coincides with the axis of symmetry.

For applications of ac having extra low frequency as 50/60 Hz or dc voltages, problems may be considered an electrostatic field problem. In electrostatics, Maxwell's equations and constitutive equation reduce to the following form

$$\nabla \times \mathbf{E} = 0.0 \quad (1)$$

$$\nabla \cdot \mathbf{D} = \rho_v \quad (2)$$

$$\mathbf{D} = \epsilon_0 \epsilon_r \mathbf{E} \quad (3)$$

where, \mathbf{E} is the electric field intensity, \mathbf{D} is the electric displacement, ρ_v is the volume charge density, ϵ_0 is the dielectric permittivity of air and ϵ_r is the relative dielectric permittivity of the material. Based on equation (1), electric field intensity is introduced by the negative gradient of the electric scalar potential V in following form

$$\mathbf{E} = -\nabla V \quad (4)$$

If the permittivity ϵ is constant such as in the isotropic dielectrics, Poisson's scalar equation is obtained as

$$\nabla^2 V = -\rho_v / (\epsilon_0 \epsilon_r) \quad (5)$$

For free volume charge ($\rho_v = 0$), field is expressed by Laplace's equation as

$$\nabla^2 V = 0.0 \quad (6)$$

In this study, solution of the problem is obtained from solution of Laplace's equation in cylindrical coordinates (ρ, ϕ, z). The three-dimensional expression of Laplace's equation is

$$\nabla^2 V = \frac{1}{\rho} \frac{\partial}{\partial \rho} \left(\rho^2 \frac{\partial V}{\partial \rho} \right) + \frac{1}{\rho^2} \frac{\partial^2 V}{\partial \phi^2} + \frac{\partial^2 V}{\partial z^2} = 0.0$$

In the case of axial symmetry, the potential distribution is independent of coordinate ϕ . Thus, in the cylindrical coordinates, two-dimensional expression of Laplace's equation is

$$\frac{1}{\rho} \frac{\partial}{\partial \rho} \left(\rho^2 \frac{\partial V}{\partial \rho} \right) + \frac{\partial^2 V}{\partial z^2} = 0.0$$

B. Physical Approach to Suppression of Electrical Tree

According to the properties and boundary condition of the dielectric materials, shown in Fig. 2, the normal component of the electric displacement \mathbf{D} is given as

$$D_{N1} - D_{N2} = \rho_s \quad (7)$$

where, D_{N1} is the normal component of the electric displacement \mathbf{D}_1 , which represents the first dielectric medium, D_{N2} is the normal component of the electric displacement \mathbf{D}_2 , which represents the second dielectric medium (barrier

medium), and ρ_s is represent the surface charge density, for free space charge $\rho_s = 0.0$, so

$$D_{N1} = D_{N2} \quad (8)$$

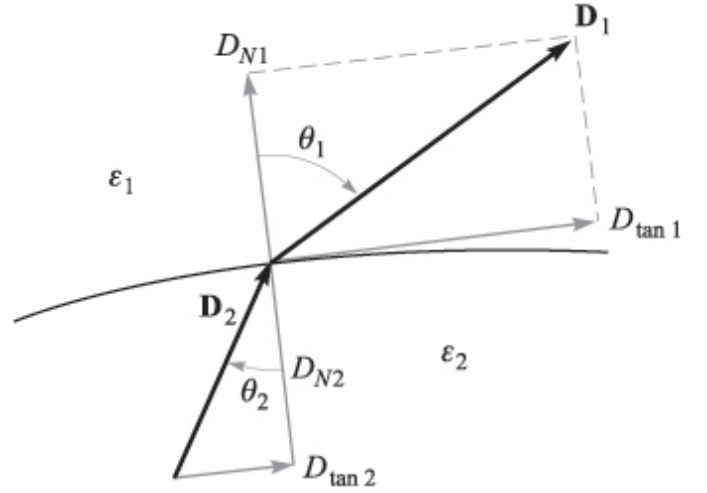


Fig. 2. The refraction of \mathbf{D} at a dielectric interface.

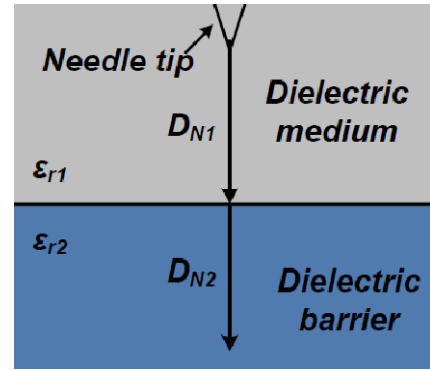


Fig. 3. The direction of D_N from needle tip towards the barrier medium.

From equation (8) the normal component is continuous in the two medium, as shown in Fig. 3. But the normal electric field intensity is discontinuous and depend on the dielectric materials,

$$\begin{aligned} \epsilon_0 \epsilon_{r1} E_{N1} &= \epsilon_0 \epsilon_{r2} E_{N2} \\ \epsilon_{r1} E_{N1} &= \epsilon_{r2} E_{N2} \end{aligned} \quad (9)$$

This equation explains that, the normal electric field intensity is inversely proportional with the relative permittivity of the medium. So if the normal electric field from the needle tip is higher than the critical field value for tree initiation (4 MV/cm), a barrier layer can reduced suddenly the normal value of the electric field intensity if its relative permittivity is higher than the dielectric medium.

For transverse layer of barrier with small relative permittivity but still higher than the dielectric medium, in order to suppress the tree growth, the thickness of the barrier layer is increased.

Although the value of the normal electric field intensity E_N is decrease, but the value of the tangential electric field intensity E_T is increase for constant electric field intensity given by equation (10).

$$\mathbf{E} = \sqrt{E_N^2 + E_T^2} \quad (10)$$

This increase allow the tree to growth horizontally inside the dielectric medium as given from experimental results given by [4] shown in Fig. 4.

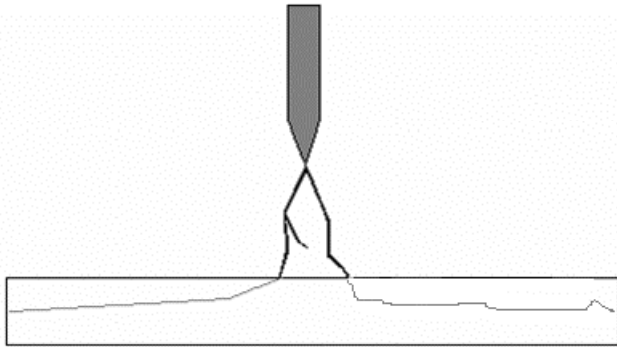


Fig. 4. Schematic diagram of side view of positive impulse tree propagation in uniaxially or biaxially oriented film [4].

III. RESULTS AND DISCUSSIONS

A. Electric Field Simulation

Figure 5, represents the CSM simulation of the normalized electric field intensity from the needle tip with no barrier layer. This field reaches 25.8993 MV/cm, which higher than the critical field required for tree initiation. The tree length produced according to the critical field value 4 MV/cm was 10 μm .

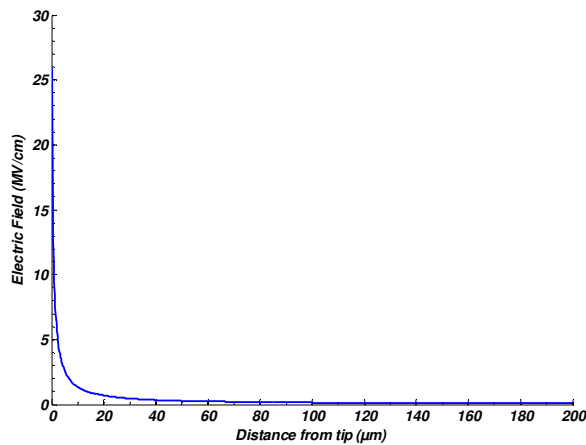


Fig. 5. The normal electric field simulation from the needle tip toward plane electrode resulting from CSM.

Figure 6, shows the suddenly decreasing of the normal electric field due to the barrier materials. In this relation the barrier thickness is fixed with all materials barrier. Also Fig. 7 shows the variation of the normal electric field intensity with the different ratio of X/G .

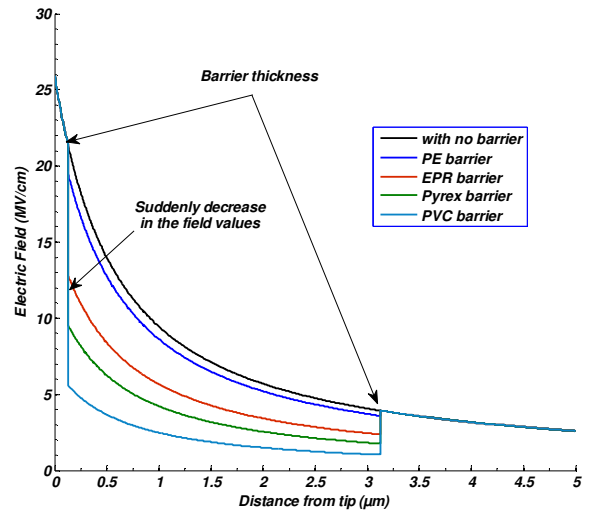


Fig. 6. The effect of barrier material on the normal value of electric field intensity.

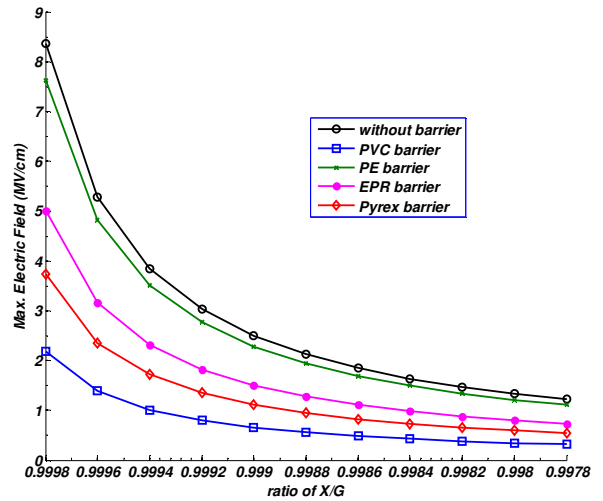


Fig. 7. The variation of normal electric field intensity with the ratio of X/G .

TABLE I
THE MAXIMUM VALUE OF NORMAL ELECTRIC FIELD AT DIFFERENT X/G RATIO WITH DIFFERENT BARRIER MATERIALS.

Ratio of X/G	Barrier materials				
	without barrier	PE $\epsilon_r = 2.3$	EPR $\epsilon_r = 3.5$	Pyrex $\epsilon_r = 4.7$	PVC $\epsilon_r = 8$
0.9998	8.3559	7.6293	5.0135	3.7335	2.1934
0.9996	5.2785	4.8195	3.1671	2.3585	1.3856
0.9994	3.8534	3.5183	2.3121	1.7217	1.0115
0.9992	3.0334	2.7696	1.8200	1.3553	0.7963
0.9990	2.5009	2.2834	1.5005	1.1174	0.6565
0.9988	2.1273	1.9424	1.2764	0.9505	0.5584
0.9986	1.8508	1.6899	1.1105	0.8270	0.4858
0.9984	1.6379	1.4955	0.9828	0.7318	0.4300
0.9982	1.4689	1.3412	0.8814	0.6563	0.3856
0.9980	1.3316	1.2158	0.7989	0.5950	0.3495
0.9978	1.2177	1.1118	0.7306	0.5441	0.3196

Max. of normal electric field intensity at the beginning of barrier surface

Table I, gives the material effect on the normal electrical stress with the variation of X/G ratio, all values obtained for constant barrier thickness $26.8 \mu\text{m}$. Four different types of insulating barriers was used which are made of polyethylene (PE) ($\epsilon_r = 2.3$), polyvinyl chloride (PVC) ($\epsilon_r = 8$), Pyrex Glass ($\epsilon_r = 4.7$) and ethylene propylene rubber (EPR) ($\epsilon_r = 3.5$). Variation of the computed E_{max} values is shown in Fig. 7.

The results show that tree propagation can be slowed down or suppressed when introducing a transverse barrier between the needle and the plane electrode and may cause significantly increased time to breakdown values. The increase depends on the barrier materials used, their thickness, the dielectric strength of the interface to the surrounding XLPE and the width of the barrier.

IV. CONCLUSIONS

In this study, variations of the electric field distribution of a needle-plane electrode system with transverse dielectric barrier are analyzed at different barrier positions, dielectric materials of barrier. If there is a dielectric barrier in the gap, maximum field intensity suddenly decreases. The maximum electric field was observed when the barriers were positioned at the nearest point to the needle electrode. CSM is highly valued to calculated electric field configurations with fairly simple programs and small computing time. This useful computer program has the ability to solve the electrostatics problems very quickly with high precision.

The effect of barriers upon tree propagation is described. Since simulations in this paper confirm that time to breakdown can significantly be enhanced by the inclusion of a barrier between two electrodes, composite materials should be used to slow down or suppress tree propagation in high voltage insulations.

When related to experimental values, the numerically calculated tree structures correlate quantitatively with the available experiments given by others. The new model therefore seems to be a powerful tool for the analysis of topological questions related to composite insulation materials.

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