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Electrostatic field calculation in air gaps with a transverse layer of dielectric barrier

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A B S T R A C T

In this paper the influence of transverse layer of dielectric barrier to the electrostatic field strength of air gaps using a hyperbolic needle-to-plane configuration is investigated. A three dimensional field problem is presented for simulating the electrostatic field in the air gap. This is achieved by using the charge simulation method. Group of ring charges are used to simulate the needle surface. A genetic algorithm is used for optimum number, location, dimension and value of simulating ring charges. The used needle tip radius was 8 μm while the gap spacing varied from 0.3 cm to 50 cm. The optimum barrier position minimizes the maximum electrostatic field and the electric energy density at the needle tip and consequently maximizes the required breakdown value. The simulation result has been compared with available experimental observations. A good agreement is found between the numerical and experimental data.

1. Introduction

The electric field analysis is very important due to its role in the dielectrics and conducting medium; streamer and fluid flow in electrolytic solutions [1], breakdown and induced electric field in gases [2,3], treeing in solids [4,5], and the design of high voltage insulation [6]. In some electrode geometries, the electric fields can simply be expressed analytically [1]; in other, the electric field problem is complex because of the sophisticated boundary conditions [3], including media with different permittivities such as composite materials [7,8].

The barrier effect to the dielectric behavior of air gaps under high stress has been investigated [8–12]. Also, all the experimental setups differ not only in the dimensions, material of the barrier but also in the gap geometry.

Barriers materials are used in high voltage insulations to slowdown the electric field strength [10,11]. Barriers material, their dimensions and dielectric strength are the main factors used for selection of the best barrier to prolong the breakdown voltage lifetime.

The barrier optimum location is near the needle tip. This optimum location makes the voltage required for the breakdown is doubled [10].

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 [1–4]. The simulation of non-uniform electric field is a pre-requisite for understanding of electrical phenomena, especially in the composite dielectrics and conducting medium. Numerical methods, such as finite element method (FEM) [1,6,7], charge simulation method (CSM) [2–4], and integral equation methods have been used to simulate the non-uniform electric fields. Charge simulation method (CSM) is one of the most successful numerical methods for solving electrostatic field problems [2–4,13,14].

This paper presented a new simulation model for the electrostatic field strength in air gaps with a transverse layer of dielectric barrier by using a hyperbolic needle-to-plane gap. The analysis of electrostatic field is a pre-requisite for determining the field distribution along the air gap and the effect of the transverse barrier. This is achieved by using charge simulation method (CSM). Ring charges are used to simulate the needle electrode. The optimum locations, values and numbers of these ring charges are achieved by using optimization technique "genetic algorithms (GAs)" [3,15,16].

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The needle tip radius has been chosen to be 8 μm with gap spacing varied from 0.3 cm to 50 cm which is appropriate for the available experimental data.

2. Method of analysis

2.1. Electrostatic field calculation

The published results concern the electric field distribution as well as the shape of the insulating sheet. Barriers insulating materials were used like Bakelite, Pyrex Glass, Kraft paper and hard paperboard. The hyperbolic needle-to-plane arrangement is the more common gap used for high field investigation (Fig. 1). Most of researchers performed experiments on small or medium gaps up to 50 cm.

The interface between two dielectric materials is determined by a charge density ρ_S that is given by the formula [17]:

$$\rho_S = \varepsilon_o\left(\varepsilon_{r2} - \varepsilon_{r1}\frac{\sigma_2}{\sigma_1}\right)E_2 = \varepsilon_o\left(-\varepsilon_{r1} + \varepsilon_{r2}\frac{\sigma_1}{\sigma_2}\right)E_1 \tag{1}$$

where ε_o is the permittivity of free space, E_1, E_2 are the electrostatic field inside the two materials forming the interface, ε_{r1}, ε_{r2} are the relative permittivities of the same materials and σ_1 and σ_2 are the conductivities of them.

The local electric field, E_l, as a function of the applied electric field, E_a, and the internal field, E_{in}, due to space charge accumulation in the first interface between the two dielectrics:

$$E_l = E_a - E_{in}(t)$$

$$E_l = \frac{V}{x} - E_{in}(t) \tag{2}$$

where V is the applied voltage, x is the electrode spacing. The internal field E_{in} due to the accumulated charge trapped with a sufficient time in the upper interface between air and barrier dielectric materials can be calculated by assuming that the charge is a disk with charge density ρ_S and radius R_{disk} given by [18]:

$$E_{disk} = \frac{\rho_S}{2\varepsilon_o\varepsilon_{r1}}\left(1 - \frac{z}{\sqrt{\left(R_{disk}^2 + z^2\right)}}\right) \tag{3}$$

This equation gives the value of the normal electrostatic field of the charged disk in the z-axis. So the internal field in the needle tip is equal to:

$$E_{in} = \frac{\rho_S}{2\varepsilon_o\varepsilon_{r1}}\left(1 - \frac{y}{\sqrt{\left(R_{disk}^2 + y^2\right)}}\right)(1-\xi) \tag{4}$$

where y is the vertical distance between the needle tip and the upper barrier surface and $\xi = y/x$ is the interface location in the specimen, see Fig. 1. The electrostatic field at the needle tip, E_{tip}, in the absence of space charge, which satisfy Laplace's equation, is obtained from the simulation program using CSM at the tip of the needle (maximum value of electrostatic field).

So, the local electrostatic field is given by:

$$E_l = E_{tip} - E_{in}$$

or:

$$E_l = E_{tip} - \frac{\rho_S}{2\varepsilon_o\varepsilon_{r1}}\left(1 - \frac{y}{\sqrt{\left(R_{disk}^2 + y^2\right)}}\right)(1-\xi) \tag{5}$$

Assume that $R_{disk}^2 \gg y^2$, then:

$$E_l = E_{tip} - \frac{\rho_S}{2\varepsilon_o\varepsilon_{r1}}(1-\xi) \tag{6}$$

Substituting Eq. (1) into Eq. (6) becomes:

$$E_l = E_{tip} - \left(\varepsilon_{r2}\frac{\sigma_1}{\sigma_2} - \varepsilon_{r1}\right)E_1\frac{(1-\xi)}{2\varepsilon_{r1}} \tag{7}$$

The value of E_l is obtained also from the simulation program using CSM but at different values of y measured from the tip of the needle to the barrier upper surface.

The ratio of E_l/E_1 is given by:

$$\frac{E_l}{E_1} = \frac{E_{tip}}{E_1} - \left(\frac{\varepsilon_{r2}}{\varepsilon_{r1}}\frac{\sigma_1}{\sigma_2} - 1\right)\frac{(1-\xi)}{2} \tag{8}$$

Considering the fact that the value of electrical breakdown field at the needle tip strongly depends of the energy density W_S of the local electrostatic field and since the former quantity is proportional to the square of the local electric field

$$W_S = \frac{1}{2}\varepsilon E_l^2$$

So a quadratic relation between W_S and ξ is expected.

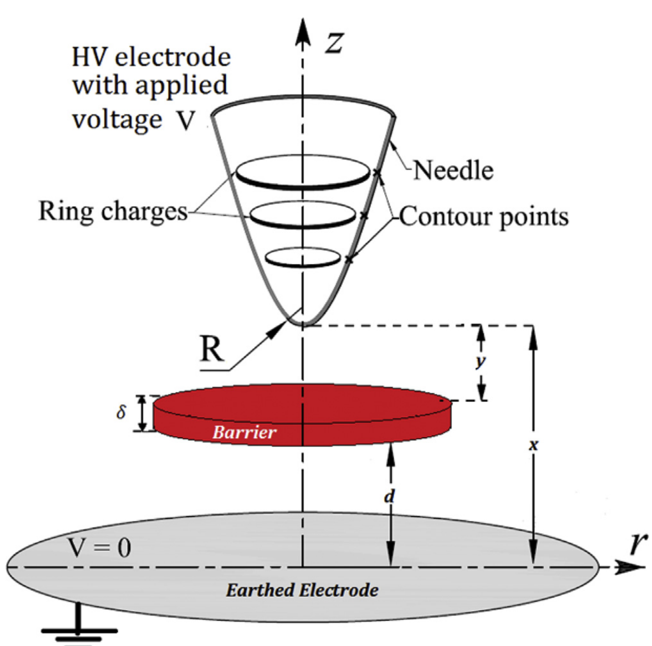

Fig. 1. Schematic diagram of the hyperbolic needle-to-plane air gap with a transverse barrier specimen. The barrier location is defined by the parameter $\xi = y/x$.

2.2. Needle simulation

The estimation of E_{tip} and E_1 calls at first for accurate computation of the electric field in the air gap. This is achieved using CSM which satisfy Laplace's [2–4]. Group of ring charges are used to