Numerical study of dielectric strength in point-plane air gaps with barrier and their effect on the potential and electric field under AC voltage

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Abstract

Comprehending how the electric field is distributed within and around high-voltage equipment is pivotal for designing, operating, and ensuring the efficacy of high-voltage insulators. The objective of this study is to investigate the dielectric strength of the point-barrier-plane system under alternating voltage. For this purpose, the potential and electric field distribution for both configurations (with and without barrier) are studied using a numerical method. Our study employs 2D electrostatic simulations using the finite element method (FEM) to numerically analyze the impact of a dielectric barrier on the distributions of electric field and potential in a vertically arranged point-plane gap. The obtained results are in good agreement.

Key-word: point-plane geometry, dielectric barriers, electric field analysis, finite element method.
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1. Introduction

Materials have played a predominant role in the progress achieved in the development of electrical equipment. In the field of electrical engineering, dielectric materials are used to ensure optimal functionality of equipment while guaranteeing the safety of both property and individuals. Air, as a dielectric, is commonly encountered as the sole insulation between electrodes in high voltage techniques.[1-16]

The presence of a dielectric barrier within the air gap is a highly important factor upon which the characteristics of electrical discharge and its cleanliness depend. Its impact is mainly associated with the buildup of charges on its surface adjacent to the active electrode. Consequently, the barrier serves as a hindrance to the progression of discharge.[8-16]

The application field of insulating barriers is extensive and encompasses various industrial sectors. The small air gaps between the active and metallic parts of this equipment are electrically equivalent to configurations with non-uniform electric fields, namely, point-point and point-plane configurations.[8, 12, 15]

Numerous studies have been dedicated to electrical discharge in air for various geometries and configurations, both experimental and numerical, and several mathematical models have been proposed to study electrical discharges. Among the various electrode system configurations studied, the most common are point-plane systems.[3-14]

The study of electrical insulation strengths in air gaps is of great interest from an industrial standpoint, aiming to address issues related to insulation and protection of energy transmission and distribution networks (such as high voltage transmission lines, transformers, circuit breakers, etc.).[16]

Several studies have examined the impact of barriers in point-plane air gaps, revealing that their influence is predominantly tied to the accumulation of charges on their surface adjacent to the active electrode. Functioning as both a mechanical and electrostatic impediment, the barrier obstructs the progression of electrical discharge. [16]

Our simulation work aims to verify the effect of a rectangular-shaped insulating barrier on the dielectric strength and electric field within a point-plane air gap at an industrial frequency of 50 Hz.

In the present study, we utilized the Comsol multiphysics computational code, based on the finite element method, to compute and visualize the distribution of potential and electric field within the point-barrier-plane configuration under alternating voltage.

2. Simulation model

The main factor behind dielectric breakdown is the electrical stress resulting from high voltage application. Our study focused on conducting a numerical analysis of electric field and potential distributions between point and plane electrodes in the presence of insulating barriers, utilizing the finite element method (FEM). All simulation studies and numerical computations were carried out using the Comsol Multiphysics modeling software, which is based on FEM [1].

For the point-barrier-plane arrangement, we used a copper point measuring 30 cm in length, 2.8 cm in diameter, and tapered to a 30° angle and a 5 cm wide square glass barrier presented in figure 1.

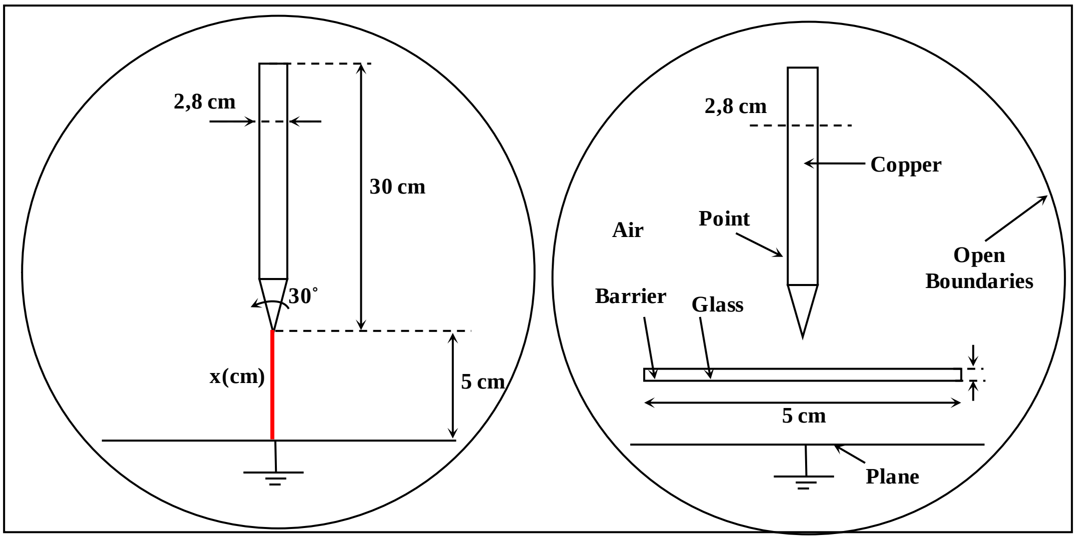

Figure 1. Point-plane arrangement with and without barrier.

3. Calculation method

In Comsol Multiphysics, the resolution step involves solving the system of equations obtained from the finite element discretization of the governing physical equations. This process includes setting up the problem geometry, selecting the physics involved, defining material properties and boundary conditions, meshing the geometry, and finally solving the system of equations using appropriate numerical methods. Comsol Multiphysics utilizes advanced solvers and algorithms to efficiently solve these equations, providing accurate results for various engineering and scientific problems.

For applications involving alternating current (AC) with frequencies as low as 50/60 Hz or direct current (DC) voltages, challenges can be treated as electrostatic field problems. Consequently, the electric and magnetic field components can be analyzed independently, and calculations can be based on static field principles. In scenarios involving electrostatic (and quasi-static) fields, Maxwell's equations serve as the governing equations due to the absence of other electromagnetic field effects [17-18]. In the realm of electrostatics, Maxwell's equations and constitutive equations can be simplified to the following expressions:

$$\vec{E} = -gra\vec{V} \tag{1}$$

$$\nabla.D = \rho \tag{2}$$

Defining D as:

$$D = \varepsilon\, E \tag{3}$$

and the gradient relation, (equation 1) or:

$$E = \nabla V \tag{4}$$

upon substituting equations 2, 3, and 4, we obtain:

$$\nabla.\, D = \rho = \nabla.(\varepsilon\, E) = -\nabla.(\varepsilon \nabla V) = \rho \tag{5}$$

or:

$$\varepsilon\nabla.(\nabla V) = -\rho \tag{6}$$

In the absence of charge $\rho = 0$,

Poisson’s equation reduces to Laplace’s equation:

$$\varepsilon\nabla.(\nabla V) = 0 \tag{7}$$

Ultimately:

$$\nabla^2 V = 0 \tag{8}$$

Determine the solution to the equation for the potential V within a specifically tailored field, while establishing both source and boundary conditions. In this context, we utilize the model under investigation, employing the configuration known as point-barrier-plane, which consists of three segments characterized by unique properties:

- The insulating barrier possesses a relative permittivity of ε_r=6 and a conductivity of $\sigma=10^{-14}$.
- The conductive core comprises copper electrodes with a relative permittivity of $\varepsilon_r=10^6$ and conductivity of $\sigma=10^6$.
- The surrounding air in the insulator model has a permittivity of ε_r=1.0005 and a conductivity of $\sigma=10^{-14}$.

Based on this, the boundary conditions are set as V = 10000 Volts on the point, V = 0 Volts (ground) on the plane, and ∂V/∂n = 0 on all remaining outer boundaries. The subsequent section elaborates on the results derived from solving the problem using the Finite Element Method (FEM) under the specified conditions.

4. Simulation results

The simulation of our configuration was carried out using two-dimensional software ”Comsol Multiphysics” using the FEM. Figure 2 present the configuration of our model gives an easy representation.

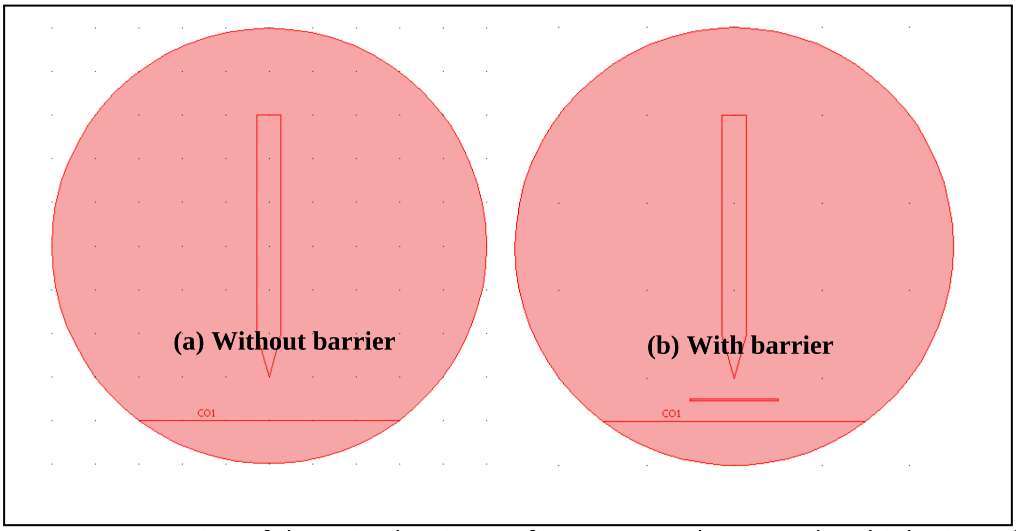

Figure 2. Representation of the point-barrier configuration on the Comsol multiphysics software

Concerning the mesh, the density of the finite elements is important for the critical regions (close to the barrier). Indeed, we considered 588 elements, and after refinement 2352 elements. For the point-plane configuration, and 1315 elements, and after refinement 5260 elements. For the point-plane with barrier configuration. The quality of the mesh is crucial for the quality of the results. The choice of mesh in order to obtain a reduced simulation time with a satisfactory result. The mesh is illustrated in Figure 3

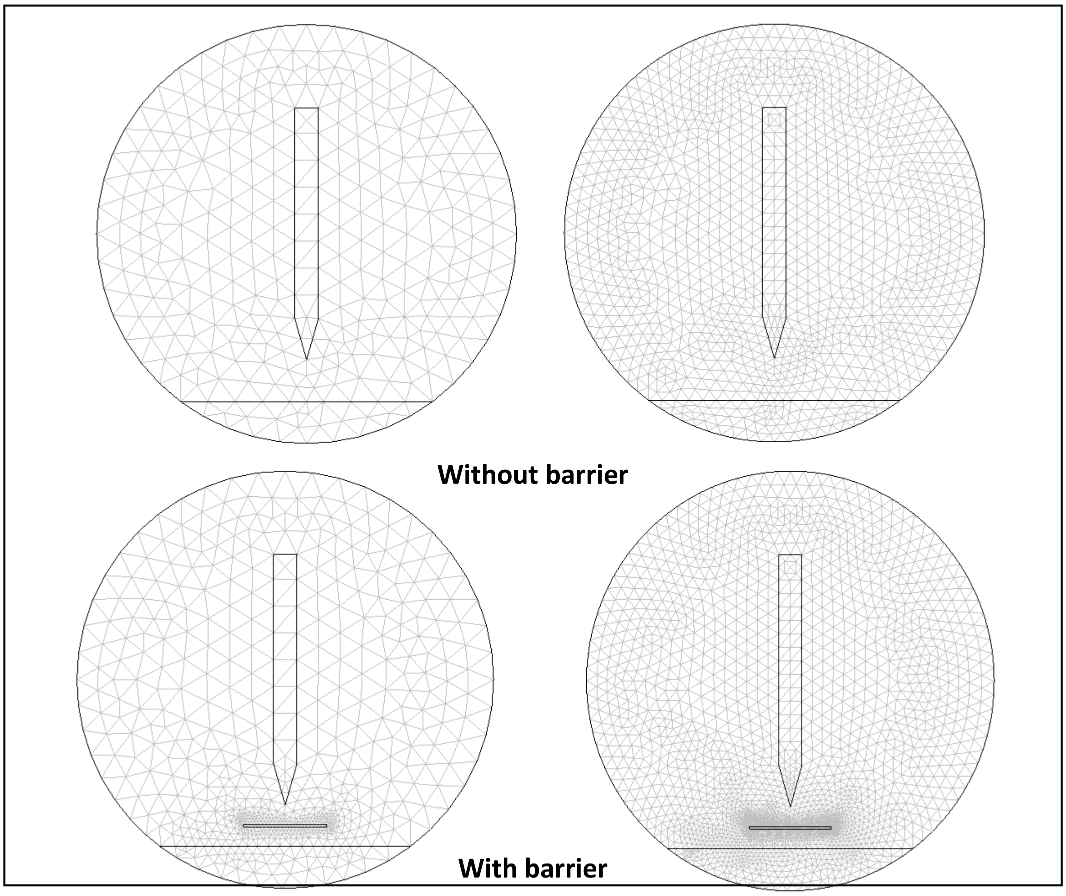

Figure 3. Discretization by finite elements Mesh of arrangement point-plan with and without barrier.

4.1. Potential of the Point-Plane Gap with and without a Dielectric Barrier

At the outset, the electric field of the point-plane gap (as depicted in Figure 2), with and without a dielectric barrier, is computed using the finite element method (FEM), taking into account both initial and boundary conditions. The initial condition is relevant when there is no charge present in the gap before voltage application. We assume the application of a voltage of 10000 Volts across a gap distance of x=5cm in air at atmospheric pressure. This setup allows for simulating the behavior akin to a needle-plane configuration. Figure 4 depicts the distribution of electric potential for both configurations, with and without a barrier, while Figure 5 illustrates the variation of potential with gap spacing obtained in the point-plane gap without a barrier.

We notice that the variation in configuration (with and without a barrier) has a slight effect on the distribution of inter-electrode voltage. This is due to the presence of the barrier creating a zone between the barrier and the plane where the field is uniform. Thus, the needle-plane system in the presence of the barrier consists of two subsystems: one needle-barrier and the other barrier-plane. The latter is considered as a plane-plane system, which is the most rigid system. Our results coincide with those obtained by other researchers [16-19].

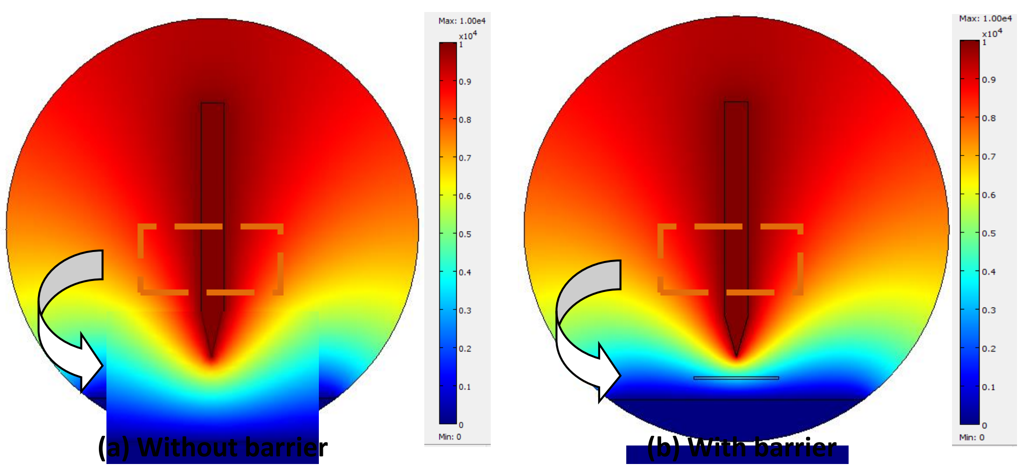

Figure 4. Electric potential distribution with and without barrier.

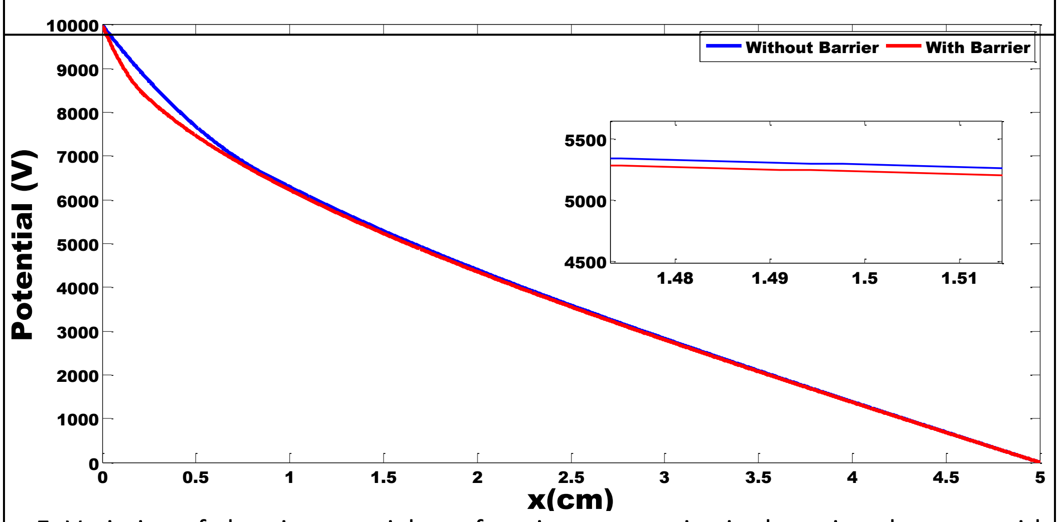

Figure 5. Variation of electric potential as a function gap spacing in the point-plane gap with and without the barrier.

4.2. Field of the Point-Plane Gap with and without a Dielectric Barrier

For a applied voltage of 10 kV, figures 6 and 7 respectively show the distribution of the electric field intensity, as well as the electric field lines for both cases with and without a barrier.

Figure 6 (b) and 7 (b) depict the presentation of the problem's geometry and mesh, along with the resulting electric field distribution and equipotential lines within the gap containing the dielectric barrier.

The primary factor affecting the occurrence and features of electrical discharges across a gap is the distribution of the electric field within that gap. Evaluating discharge behavior necessitates understanding the electric field's variation around an electrode, particularly focusing on the maximum electric field present on the electrode.

- The electric field is intense near the active electrode (the point). It decreases gradually as one moves towards the ground electrode (the plane) perpendicular to the straight line; moreover, the field lines diverge (emanating from the high-voltage electrode) as one moves away from the active zone, for both cases studied.

The following remarks can be drawn from these characteristics:

- The electric field is intense at the end of the high-voltage electrode.
- The electric field is practically zero inside both electrodes because both electrodes are conductors. • The electric field is significant in the area near the active electrode.
- Since the electric field lines are perpendicular to equipotential surfaces, they emanate from the high-voltage electrode and reach the ground electrode.
- The vectors depicted in figure 7 are tangential to the electric field lines, and we notice that the electric field is stronger on the side closer to the pointed electrodes.

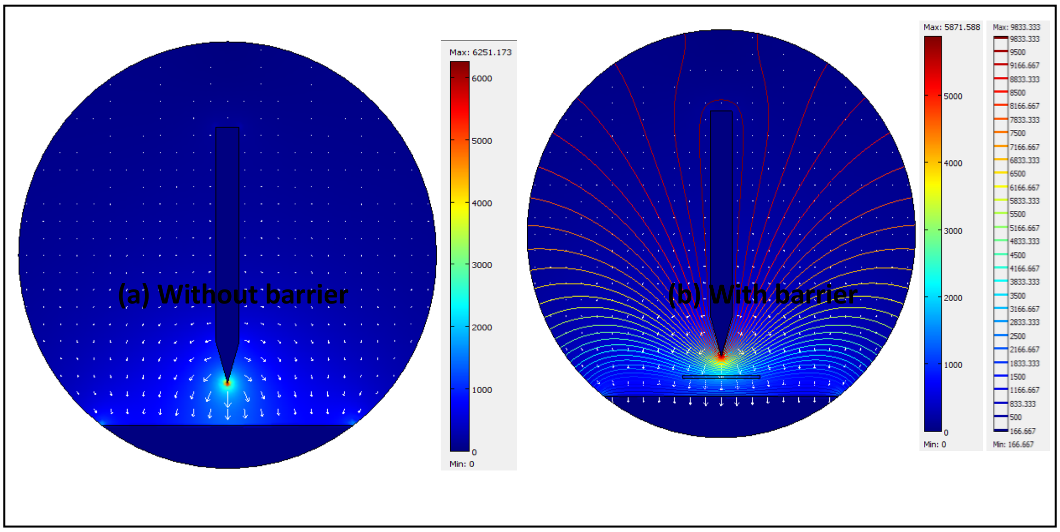

Figure 6. Electric field distribution with and without barrier.

To illustrate the impact of the barrier on the electric field, a comparison is conducted between the point-plane gap configurations with and without the dielectric barrier, each having a width of 5 cm. For this analysis, the barrier was positioned centrally.

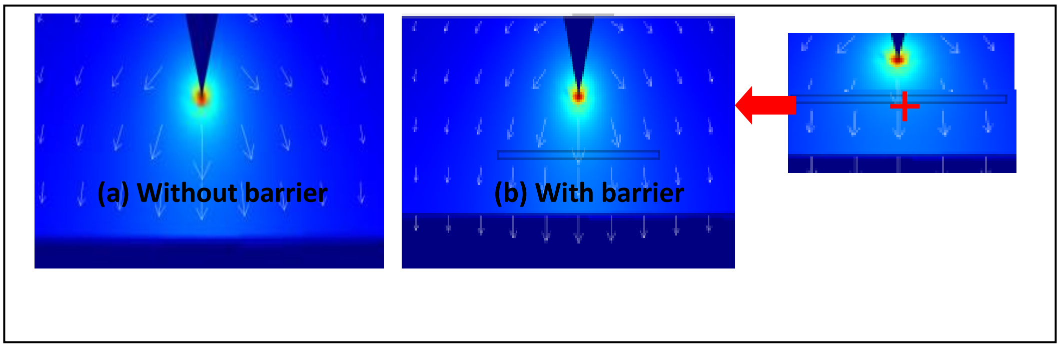

Figure 7. Electric field line distribution with and without barrier.

Figure 8 illustrates the change in the maximum electric field concerning the gap spacing in the point-plane configuration, both with and without a barrier. The E_{max} values are correlated with a 10000 Volt applied voltage (unit potential). Consequently, the maximum electric field at the pointed end diminishes rapidly as the gap distance increases, as depicted in Fig. 8. Smaller gap distances are crucial for achieving higher maximum field values.

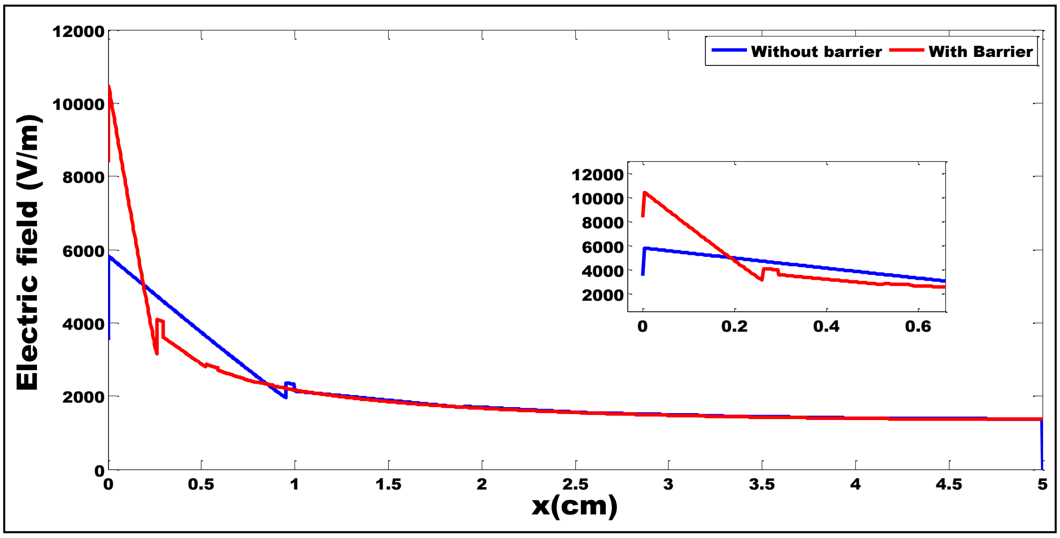

Figure 8. Variation of electric field as a function gap spacing in the point-plane gap with and without the barrier.

5. Conclusion

In this work, we present the results of various simulations conducted on both the point-plane and point-barrier-plane configurations under 50Hz alternating voltage.

This study enabled us to analyze the distribution of potential and electric field using the Comsol Multiphysics software, based on the finite element method, to assess dielectric strength.

The main conclusions we have reached are as follows:

- The insertion of an insulating barrier in a non-uniform field system acts as an electrical obstacle, thereby lengthening the disruptive discharge and consequently enhancing the electrical withstand and rigidity of the system.
- The insertion of an insulating barrier in a non-uniform field system acts as an electrical obstacle, thereby lengthening the disruptive discharge and consequently enhancing the electrical withstand and rigidity of the system.
- The insertion of the insulating barrier in the point-plane system creates a zone between the barrier and the plane where the field is uniform. Therefore, the point-plane

system in the presence of the barrier consists of two subsystems: one being point-barrier (plane) and the other being plane-plane. The latter is considered a plane-plane system, which is the most rigid system.

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