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Electrostatic Analysis of DC Discharge Phenomena in Air with Dielectric Barriers

A. Kara, Ö. Kalenderli and K. Mardikyan

***Abstract*—**Dielectric barrier discharge (DBD) is the electrical discharge between the electrodes in the presence of an insulating barrier. In this study, double-layered solid dielectric barriers and plane-plane electrode system are used to examine the DC discharge characteristics of air under atmospheric pressure. Experiments have been carried out with positive and negative DC voltage; the breakdown voltage of air is measured in both cases. Charge accumulation in a dielectrically covered insulation system seems to increase the insulation level when the results compared with those given by classical systems. A comparison of voltage variation with the air gap and the material of insulating barrier are also presented. The results presented show that the presence of the second insulating barrier and the polarity of the direct voltage, as well as the air gap between the electrodes influence the breakdown voltage and discharge characteristics. The main role of the second insulating barrier is to improve the dielectric strength of the system by altering the space charge and electric field distribution. In addition, computer program that is based on finite element method carried out the electrostatic field and voltage computations.

***Keywords*—**High direct voltage, dielectric barrier, electrostatic field analysis, breakdown voltage.

I. Introduction

INSULATING barriers used as shields in HV equipment are known to affect the electric strength of their adjacent spark gaps. The effect is not only due to the modification of the electric field based on permittivity but also to the electric charge accumulated on the barriers. The influence of the accumulated charge on the breakdown probability of the spark gap is not fully investigated [1-4].

The present work is aimed at the experimental study of the interaction between the plane-to-plane spark gap and dielectric barriers. Barrier effects have been investigated by a number of authors and many papers have been published on barrier discharge [5-7].

In this study, double-layered insulating barrier is used to examine the dielectric behavior of small plane-plane air gap under positive and negative DC voltages (Fig. 1). The barriers are made of PVC (polyvinyl chloride) have disc geometry and clean and dry surfaces as the electrodes. In each case, the barriers are located horizontally between the electrodes.

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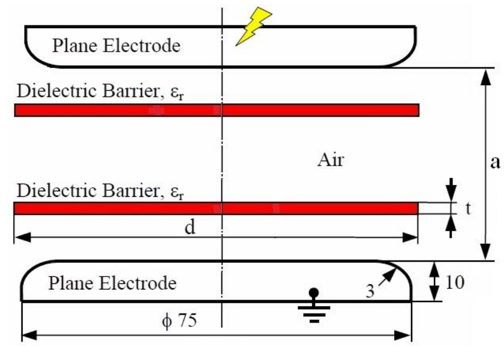


Fig. 1. Electrode configuration (dimensions in mm)

Figure 1 shows the considered plane-plane electrode configuration with its dimensions. Here, the brass made plane disc is of 75 mm diameter and with a thickness of 10 mm. As the electrodes, the diameter of each insulating barrier is 75 mm and the thickness of the barriers, t is 3 mm. The gap is at the vertical position and the geometry of the electrode system has an axial symmetry. The relative dielectric constant, ε_r of PVC made insulating barriers assumed to be 4 for the tests and computer analysis.

II. Experimental Study

A. Test Setup

The experimental arrangement is utilized to study DBD, formed by a pair of planar electrodes. Figure 2 shows test setup that generates the discharges between two polymer covered plane electrodes. A high voltage test transformer that has capacities of 100 kV, 5 kVA and 50 Hz was used in the experiments. For the generation of DC voltages from the AC supply voltage, it was used single stage - half wave type rectifier with semiconductor diode of 140 kV, 5 mA. Positive and negative high DC voltages are applied to the top electrode and the bottom electrode is grounded.

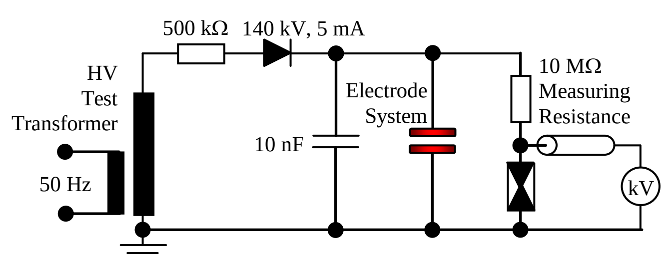


Fig. 2. Test setup

B. Measuring Procedure

First, the breakdown voltage of each gap without the insulating barrier is determined, after the insertion of barriers the measurements are repeated. Applied voltages are measured by high ohmic series resistance having 10 MΩ resistance value with milliammeter method. Here, the milliammeter acts as high-voltage measuring device according to Ohm's law. Accuracy of the voltage measurements is about ± %1. The air conditions of the laboratory during the test set to be constant between acceptable intervals. DC voltage is raised at a 2 kV/s speed manually until the breakdown occurs. The time interval between two measurement points is 2 minutes. The position of the barriers remained unchanged; only the gap length is varied between 10 mm and 50 mm in steps of 10 mm as reference [8]. Thicknesses of the barriers and electrode gap are measured with a micrometer of ± 0,001 mm resolution.

The insulating barriers are checked to be completely clean and smooth just before the tests. As all of the tests are non-destructive, the same barriers are used during the tests.

III. Test Results

A. Positive DC Voltage Test Results

It is begun the tests applying positive DC voltage. The tests are performed for cases of no-barrier, single barrier and double barrier between the electrodes. The results of performed positive DC voltage test are shown in Figure 3 for the breakdown voltages of five gaps with length a = 10 mm, 20 mm, 30 mm, 40 mm and 50 mm, respectively.

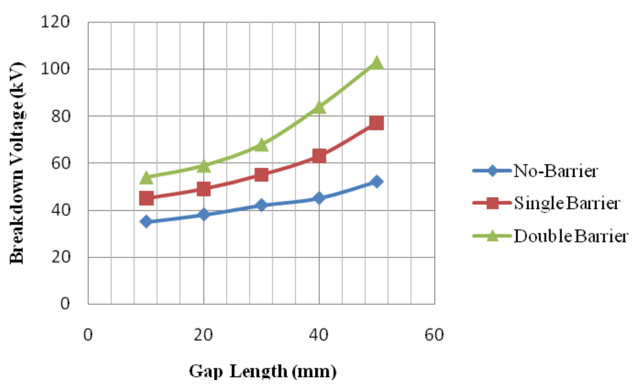


Fig. 3. Breakdown voltage of air under positive DC voltage

First of all, the breakdown voltage of air with plane electrode configuration is noticed for both measurement points for comparison with each case. During the examination of the discharge phenomena in non-uniform fields, it has been seen that the theoretical calculation or estimation of the breakdown voltage is very difficult because of the existence of many parameters affecting discharge phenomena.

When the barriers are located between the electrodes, we first observe a discharge growing directly from the energized electrode towards the center of the nearest electrode, then the appearance of sliding discharges on the barrier surface, and finally the breakdown of the air gap.

It is clearly observed that the effect of insulating barriers on the breakdown voltage, either with one or two insulating barriers, increases uniformly with the increase of the electrode gap. The breakdown voltage becomes nearly double in the largest point of the gap (a = 50 mm) when the tests are conducted with double-layered barriers. The effect of single dielectric barrier is nearly half of double barrier effect for the same distance.

B. Negative DC Voltage Test Results

Figure 4 shows the variation of breakdown voltage of air under negative DC voltage without any barrier and in the presence of single and double barrier respectively.

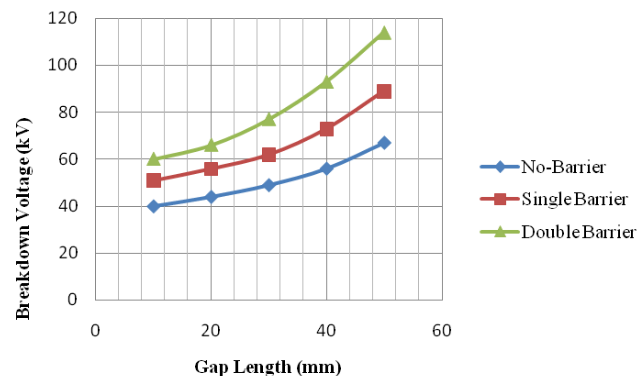


Fig. 4. Breakdown voltage of air under negative DC voltage

An insulating barrier leads a considerable increase in the breakdown voltage of plane-plane air gaps, when the gap becomes larger than the half of the total range. The improvement of the dielectric strength is mainly due to the fact that the barriers act as a geometrical obstacle to direct discharges.

It is clearly seen in Figures 3 and 4 that the breakdown voltage of large gaps (a = 40 mm, 50 mm) increases remarkably with the insertion of insulating barriers under both negative and positive DC voltages. Solid barriers strongly enhance the insulation ability of air gaps and behave like diaphragms.

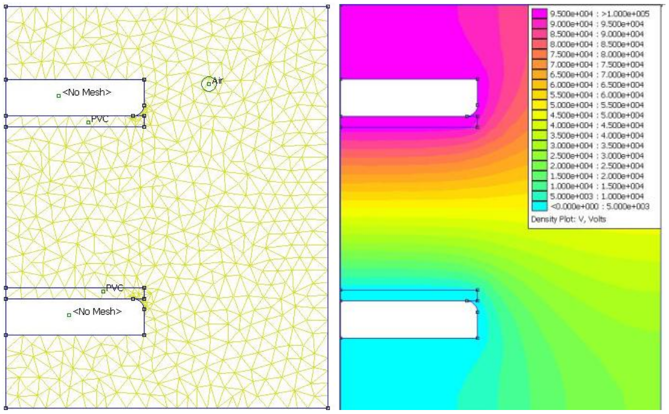
The breakdown voltage with double barrier configuration is nearly %50 more than the barrier-free situation at the closest electrode gap, while it is %100 more in the maximum point.

According to streamer theory, when an insulating barrier is placed between the electrodes, the barrier is charged with the same polarity as the high voltage electrode. The main role of the second barrier is to act as a supporting plane to reduce the effect of the charged barrier.

When studying the barrier effect in divergent field, it has been demonstrated that this effect is observed under DC voltage and depends on the energized electrode polarity. Breakdown voltages under negative DC voltage are higher than breakdown voltages under positive DC voltage for all measurement points along the air gap, confirms the theoretical facts, when the comparison is made in terms of polarity effect.

IV. Computer Analysis

In addition to the experimental study, the electrostatic field and potential distribution in a plane-plane air gap with double dielectric barrier is numerically analyzed by finite element method (FEM) using open source - FEMM 4.2 (Finite Element Method Magnetics) computer program.



(a) (b)

Fig. 5. (a) Geometry and finite element mesh, and (b) Potential distribution of the problem (insulating barriers on the electrodes)

Figure 5 shows the considered plane-plane electrode configuration, its finite triangle elements mesh and potential distribution. During the finite element solution, solution region is closed an artificial boundary. The geometry of the electrode system has an axial symmetry. Therefore, the electrostatic analysis is carried out in cylindrical coordinates. According to cylindrical coordinates, it can be assumed that the z-axis of coordinates coincides with the axis of symmetry. The potential and electric field intensity value range are shown with tables in the upper right corner of related figures.

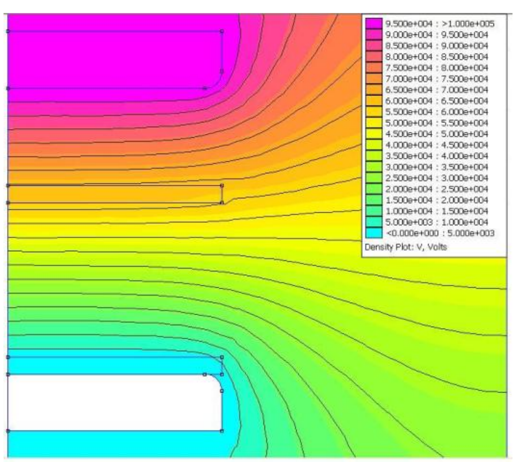


Fig. 6. Potential distribution (one of the barriers located between the electrodes)

An exemplary figure for a potential distribution where is the barrier between the electrodes is shown in Figure 6. The results obtained from FEM analysis show that the equipotential lines are condensed around the electrodes and electrostatic field distribution in the gap is non-uniform.

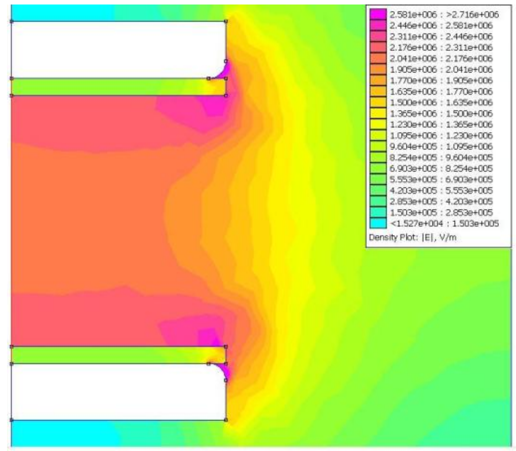


Fig. 7. Electric field distribution for case of insulating barriers on the electrodes

The maximum electric field intensity is observed around the plane electrodes and increases when the insulating barriers are not in contact with the surface of electrodes (Fig. 7-8). In the presence of double insulating barriers, the electric field distribution between the electrodes seems to be more proper the case that the upper barrier hanging on the air. The color variation that represents the change of electric field intensity appears to be constant within certain limits.

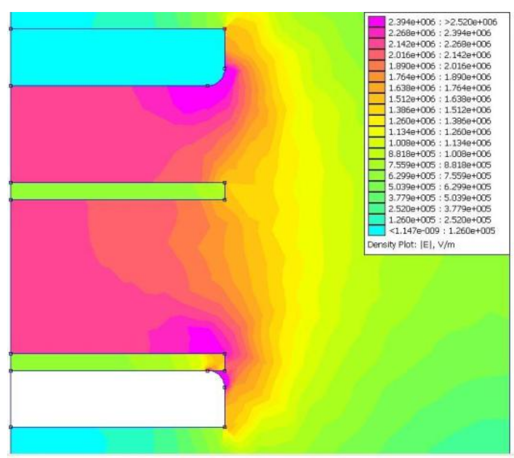


Fig. 8. Electric field distribution for case of one of the barriers located between the electrodes

Each insulating barrier causes a strong electric field fluctuation and a correspondingly sharp change in potential distribution across the layers. Ions and electrons that enter the barrier layer are accelerated, decelerated, or reflected by the electric field change. In the presence of a dielectric barrier in the gap, the maximum field intensity increases comparatively. As seen in Figure 8, barriers placed in different locations cause quite different electrostatic characteristics.

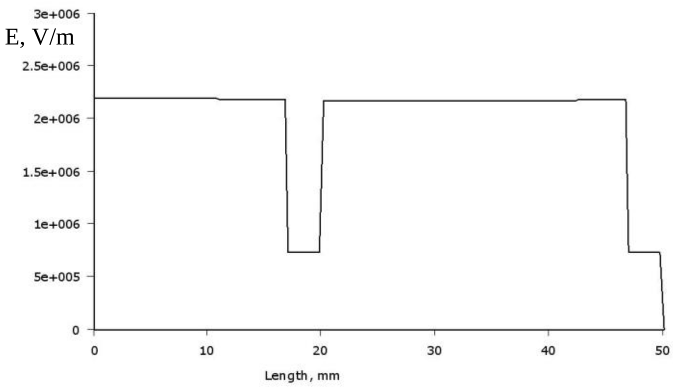


Fig. 9. Variation of electric field intensity along gap length for case of one of two barriers located on the electrode.

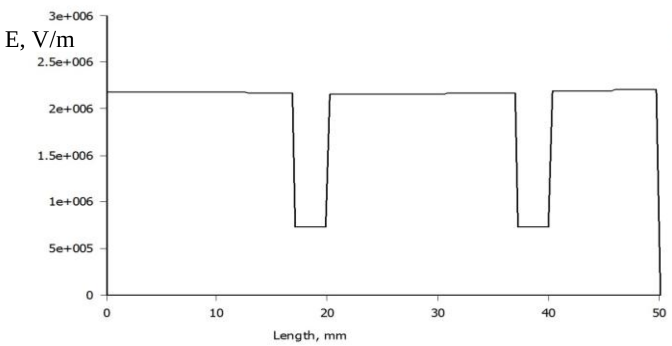


Fig. 10. Variation of electric field intensity along gap length for case of the barriers located between the electrodes

In Figure 9 and 10, it can be easily observed that the insulating barriers cause notable changes on the electric field intensity. The barrier acts by making the electric field between the electrodes, uniform. On the other hand, the electric field intensity on the surface of the both electrodes decreases considerably.

V. CONCLUSIONS

This paper concerns the influence of the second insulating barrier on the breakdown voltage of a plane-to-plane electrode configuration under DC withstand voltage tests. The effect of second insulating barrier on the breakdown voltage of air is increasing with the increase of the electrode gap. There seems to be two main reasons for the performance of the double-layer insulating barrier. The first is by increasing the discharge path the breakdown voltage values become higher and the second is to prevent the system against the charging of upper barrier as the same polarity with high voltage electrode. The improvement of the dielectric strength in the presence of the second barrier is also verified by the computer analysis. It also alters the space charge distribution and then the electric field. The space-charge field in the dielectric barrier, the main dielectric properties and the inhomogeneous polarization play an important role in the barrier effect. Good correlation between the experimental data and the computer analysis about the barrier effect in the air gap for non-uniform electric field is obtained. As a result, the electrostatic field between the insulating barriers and the electrodes becomes uniform and the breakdown voltage increases.

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