Polluted Barrier Effect on the Electric Field Distribution in Point-Plane Air Gaps under AC Applied Voltage: Based on Experimental Model

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Abstract− The aim of this paper is to study the effect of the surface condition of an insulating barrier on the electric field distribution in point-plane air gaps with the presence of a space charge, under AC voltage. The pollution was modelled as a uniform conductive layer on the barrier surface. Electric field analysis was carried out by changing the conductivity, permittivity, and thickness of the pollution layer. Using the Finite Element Method (FEM), the geometric model has been implemented in COMSOL Multiphysics software. This method is used to solve the partial differential equations that describe the field with the presence of space charge. The electric field increases when the conductivity and thickness of the polluted layer increases. Uniform pollution on the side of the high voltage point greatly reduces the insulation quality of the barrier. In addition, a limit level of pollution, from which its minimal electric strength is equivalent to that of a conductive barrier, has been determined. This model has been validated by comparing with the experimental results of a point-barrier-plane configuration with a distance between electrodes equal to 5cm. The distribution of the electric field predicted by the numerical model is in accordance with the experimental results. The latter indicate that this model has a great contribution in the physics of discharges in the air under various polluted environments.

Keywords− barrier surface condition, conductive layer, electric field, finite element, numerical method, point-plane air gap, space charge.

I. Introduction

The improvement of the dielectric strength of the non-uniform field air gaps by the insertion of insulating barriers has been well demonstrated under a clean and dry atmosphere and under AC, DC or impulse voltages [1-7].

In the high-voltage domain, pollution is a serious problem that must be taken into account when designing insulating systems. This is due to the formation of more or less conductive layers on the surface of the barriers, which used between electrodes in high voltage technique. These electrodes can be either the metal parts of different live equipment or the conductors of overhead lines or high-voltage terminals in testing laboratories. These polluting deposits covering the insulating surfaces can cause a considerable reduction in the dielectric strength of the high-voltage systems.

Knowledge of the degree of pollution is, therefore, a prerequisite and indispensable condition for a suitable insulation dimensioning.

Awad [8] studied the behavior of polluted barriers in point-point and point-plane air gaps of less than 12 cm in length. The voltages used were 50 Hz industrial frequency and switching impulse. It has been found that the breakdown voltage decreases when the surface conductivity increases and then tends to a constant value for a surface conductivity greater than or equal to 3 µS in the case where the polluted surface is in front of the point electrode.

In 1979, A. Boubakeur [9] studied the influence of a polluted barrier covered by a semiconducting or a conductive layer on the dielectric strength of a point-barrier-plane system. The semiconducting layers on the barrier correspond to the practice of using the barrier in polluted conditions. As soon as the surface conductivity of the semiconductor layers exceeds 1.6µS [10], the electrical discharge develops in two steps, as in the case of a metal barrier [11,12]. With a semiconductor surface barrier, the breakdown voltage of the point-plane air gaps varies between the values obtained with the insulating barrier with clean surfaces and those obtained with the metal barrier of the same shape.

The most recent works are those carried out by S. Mouhoubi [13,14] and concern the case of point-barrier-plane systems under DC and AC voltage. The pollution applied to the upper surface of the barrier facing the point causes an increase in the electric field at the plane, whatever the position of the barrier. Nevertheless, the completely polluted barrier causes a greater increase of the electric field, compared to the case where the barrier is only polluted on its upper surface.

With the growing development of computing electromagnetic software, it is now possible to obtain fast and accurate results. Among the numerical methods available and applicable to electromagnetic field calculations, the finite element method is the most used one. Thus, its use through the COMSOL Multiphysics commercial software was selected to carry out the various simulations.

In this work, the electric field distribution in a point-barrier-plane air gap was determined under an AC applied voltage. Conductivity, permittivity, and thickness of the pollution layer were varied to investigate their effect on the electric field distribution. The 2D model from COMSOL Multiphysics was used for modelling. To interpret the results

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of our model, the simulation results are compared with experimental data obtained by S. Mouhoubi [13,14].

II. SIMULATION MODEL

To simulate the electric field in the air, a drift-diffusion model is used. This model describes the generation, the annihilation and the movement of three species (electrons, positive ions, and negative ions) [15]. It includes a set of mass conservation equations for the charge carriers in the gas coupled with the Poisson's equation for the calculation of the electric field and is described by the equations (1) and (2) [15,16]:

$$\frac{\partial N_{e,p,n}}{\partial t} + \nabla.\left(-N_{e,p,n}W_{e,p,n} - D_{e,p,n}\nabla N_{e,p,n}\right) = R_{e,p,n} \quad (1)$$

$$(-\varepsilon_0\varepsilon_r\nabla V) = q\left(N_p - N_e - N_n\right),\ E = -\nabla V \quad (2)$$

The subscripts *e, p,* and *n* indicate the quantities related to electrons, positive ions, and negative ions, respectively. *N* stands for the charge carrier density, [m^{-3}]; D is the diffusion coefficient, [$m^2\ s^{-1}$]; $\boldsymbol{E}$ is the vector of electric field, [Vm^{-1}]; V is the electric potential, [V]. t stands for time, [s]; and R specifies source terms (rates of the processes in discharge plasma), [$m^{-3}\ s^{-1}$]; q = $1.6\cdot10^{-19}$ [C] is the elementary charge, and $\varepsilon_o = 8.854\cdot10^{-12}$ [Fm^{-1}] is the permittivity of vacuum [15].

The resulting process rates for the different charged particles can be expressed as follows [15,16]:

$$\begin{aligned} R_e &= R_{ion} + R_{det} + R_0 - R_{att} - R_{ep} \\ R_p &= R_{ion} + R_0 - R_{pn} - R_{ep} \\ R_n &= R_{att} - R_{det} - R_{pn} \end{aligned} \quad (3)$$

R_0 represents the rate of background ionization in zero field limit; $R_{ion} = \alpha N_e W_e$ is the rate of electron impact ionization (α stands for Townsend's ionization coefficient, m^{-1}); $R_{att} = \eta N_e W_e$ is the rate of electron attachment to electronegative molecules (η is attachment coefficient, m^{-1}); and $R_{det} = k_{det} N_e N_n$ is the rate of detachment of electron from negative ions (k_{det} is detachment coefficient, m^3/s).

Two types of recombinations are considered, electron-ion and ion-ion, with the rates $R_{ep} = \beta_{ep} N_e N_p$ and $R_{pn} = \beta_{pn} N_p N_n$, respectively ($\beta$ stands for corresponding recombination coefficient, m^3/s).

In our study, the used model parameters, the boundary and initial conditions used are adopted from [15,16] and are implemented in COMSOL Multiphysics.

A. Modeling of thin conductive layer

To study the influence of pollution on the distribution of the electric field, the pollution layer was modelled as a thin conductive layer uniformly distributed over the insulating barrier. The parameters of the polluted layer are given in the table 1.

Table. I

POLLUTION PARAMETERS

	Permittivity [F/m]	Conductivity [mS/cm]
Insulating barrier	5.8	0
Polluted barrier [17]	15 and 80	0.0235
		0.45
		1
		2

The used thickness for polluted layers are 0.1mm, 0.3mm and 0.5mm. The algorithm developed to calculate the electric field is represented in Fig 1. For our simulation, t_{out} is equal to 100 ms and the peak value of the AC voltage is used.

The input parameters for initializing calculations are the dimensions of the physical domain, gas pressure, potentials of the electrodes, number of nodes in the computational grid, desired output times and the initial distribution of space charges (if any).

The routine "Output Electric field" calculates data needed for the main solvers and calls subroutine "Resolution of the Poisson's equation", which solves the Poisson's equation (2). The output from it is the distribution of the electric field in the discharge gap (after the first call it gives the electrostatic field distribution if no space charge was set initially). Then the routine "Resolution of mass conservation equations" is called for solving system (1) – (3).

This routine calculates the time step advances the profiles of the densities of charged particles taking into account the source terms and computes the space charge density profiles using the electric field distribution obtained earlier. Then, the current time is updated and the routine subroutine "Resolution of the Poisson's equation" is called again to calculate the electric field corresponding to the new space charge distribution. If the current time is not greater than the desired output time, the loop "Resolution of mass conservation equations" – "Resolution of the Poisson's equation" is repeated until the condition is fulfilled [15].

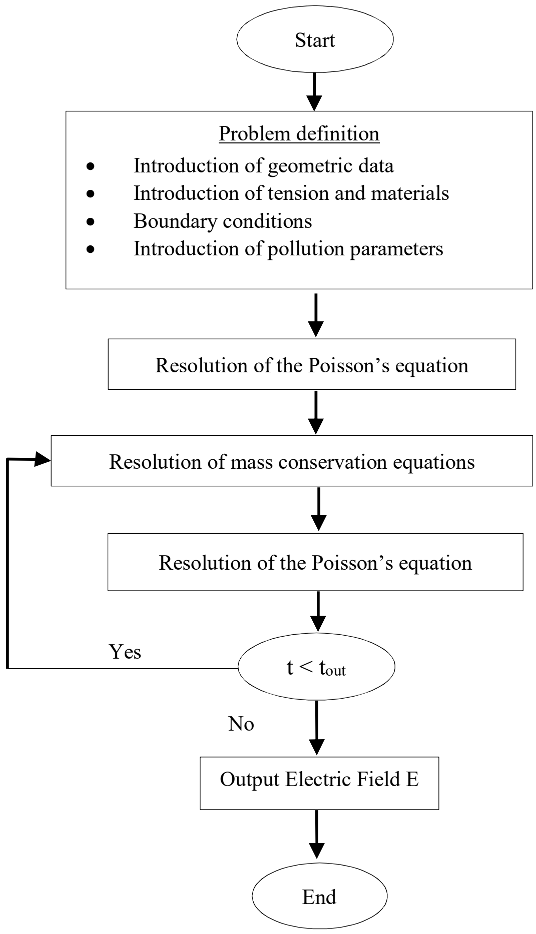

Fig.1: Simulation chart.

B. Implementation

In Fig 2, the geometry of the used point-plane electrode system with an insulating barrier is presented. To simulate our model, an AC voltage 50 HZ has been applied to the high-voltage electrode (point) and the plane is grounded considering that atmospheric conditions are normal.

A 2D simulation was performed for a point-plane electrode arrangement. The boundary conditions used in our simulation are given in Fig 3.

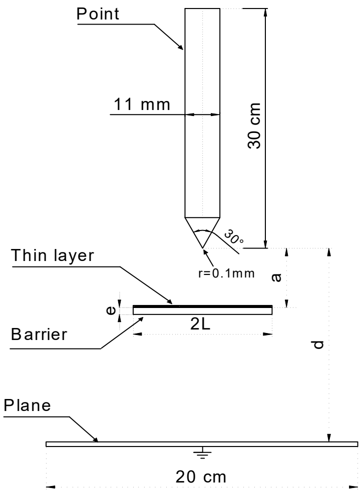

Fig.2: Point-barrier-plane configuration.

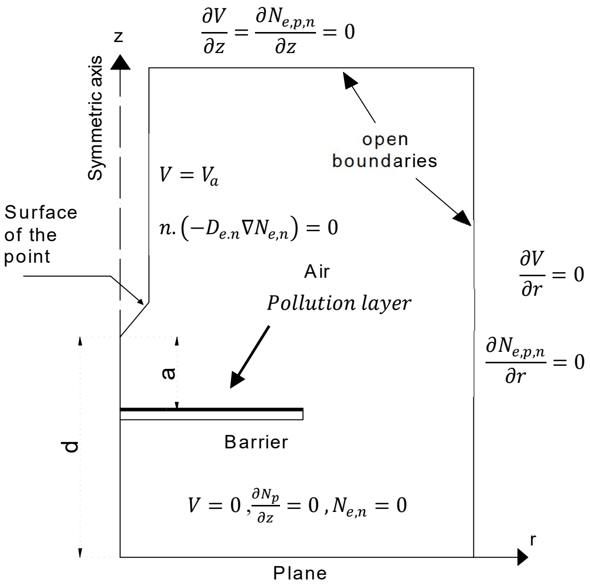

Fig.3: Computational domain, **n** is the unit vector normal to the boundary.

C. Validation of the model

To validate our model, a comparison is made with experimental results of investigations already performed using a capacitive probe carried out at the University of Cardiff by Mouhoubi and Boubakeur (Fig 2) [13,14].

D. Experimental Set-up and Measurement Method

The experimental set-up and measurement method are based on experiments measuring electric field under AC stress [13,14].

The capacitive probes is a portable probe, which is generally used for measurements of the electric field on site (apparatus, lines, stations, etc.). It consists of a surface element S isolated from the grounded circular plane (Fig 4). The S probe is connected to an electrical measuring circuit, introduced into a grounded housing, acting as a screen (Fig 5). Two 9-volt batteries power it. The design of the probe as well as elements of the electrical circuit is obtained by simulation using a software package Slim (Electromagnetic Engineering Alstom).

Considering equation (4), the electric field can be determined using a memory oscilloscope or a PC with an interface, which allows the V_c probe signal corresponding to the voltage across the capacitor C_{11} (Fig 6).

$$E = \frac{C_{11}.V_C}{\varepsilon_0.S} \qquad (4)$$

Where V_c is the voltage across the capacitance C_{11}.

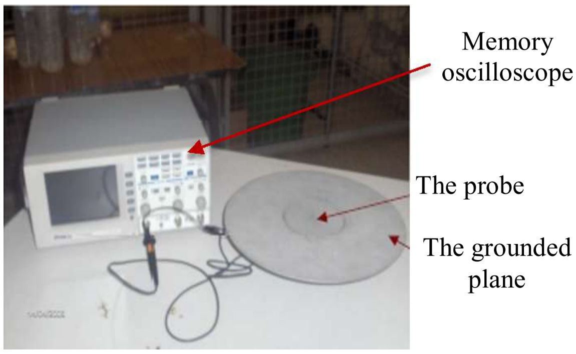

Fig.4: Photograph of the capacitive probe [13].

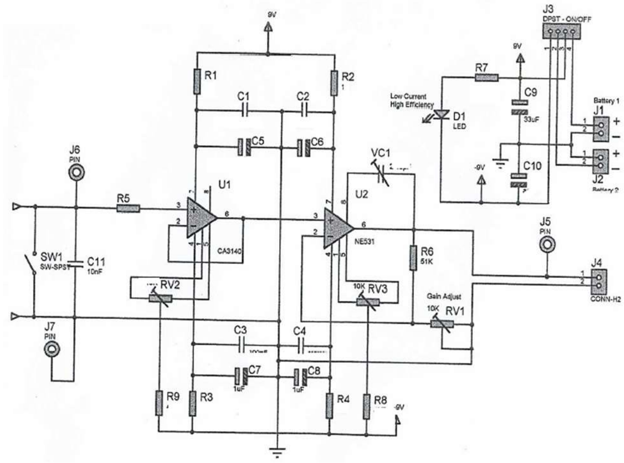

Fig.5: Electric circuit diagram of the capacitive probe [13].

Knowing the surface of the probe S as well as the value of the capacitance C_{11} :

$$E = 14.388 \times V_c \text{ (kV/m)} \qquad (5)$$

For a voltage of 10 kV applied to the high voltage electrode, the V_c voltage recorded across the capacitance of the probe is shown in Fig 6. The field probe schema as well as its characteristics used in the experimental tests are represented below (Fig 7):

- The radius of the probe (S_0): r = 2.235 mm.
- The inside radius of the electrode (E_1): re = 2,270 mm, which gives an air gap g = 0,035 mm and an effective radius of the probe rm = 2.2525 mm.

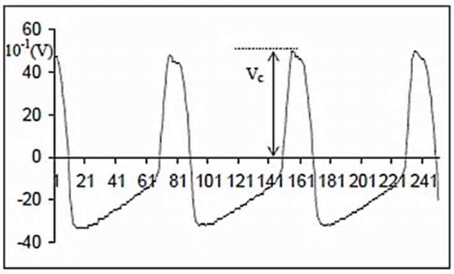

Fig.6: Oscillogram of the voltage V_c of the capacitive probe [14].

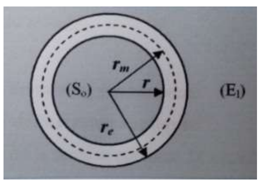

Fig.7: Field probe schema [14].

III. RESULTS AND DISCUSSIONS

The results in this work concern the electric field distribution at the plane in the presence of a space charge density in the medium, which varies from $[1 \div 50]\text{x}10^{-7}\text{C/m}^3$. This range of values gives better results compared to the experimental model. Several parameters, such as conductivity, permittivity, and thickness of the pollution layer are considered. We studied the influence of these parameters on one side of the barrier (in front of the point and in front of the plane) and on the two sides of the barrier. The influence of variation of the barrier length is not studied in this paper and is considered equal to 15 cm.

To better understand the performance of this method, an analysis that illustrates the relative error of the method compared to the experimental results in the calculation of the electric field at the plane was performed.

A. Influence of polluted barrier

We begin by studying the influence of a polluted barrier on its upper surface on the electric field at the plane in comparison with the experimental results obtained by Mouhoubi [13,14].

Fig 8 shows the influence of the polluted barrier on the variation of the electric field at the plane as a function of the voltage V. The electric field increases by increasing the applied voltage. We also note that the pollution increases the electric field at the plane [18]. A good correlation between experimental and calculated results for the insulating barrier (error < 6%), and a slight difference for the polluted barrier has been found (error < 10%).

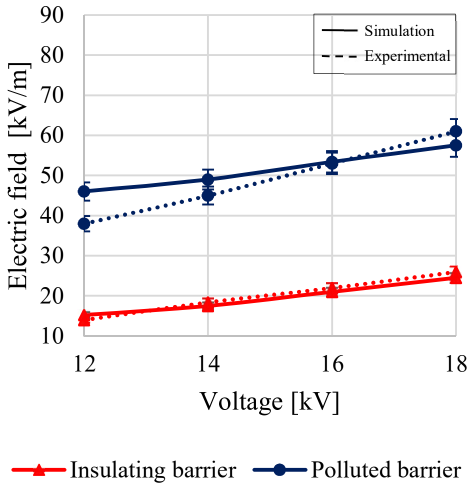

Fig.8: Influence of the polluted barrier on the variation of the electric field at the plane as a function of the voltage V (d = 5 cm, a/d = 0%, 2L = 15 cm, e=2.1mm, σ=0.45 mS/cm).

Fig 9 shows the variation of the electric field as a function of the applied voltage at the point, for two positions of the barrier, a/d = 0% and 20%, in the case of the polluted barrier facing the point.

The pollution applied to the upper face of the barrier causes the increase of the electric field at the plane, regardless of the position of the barrier [18]. It is useful to note that the electric field at the plane in the case of a polluted barrier, as for the clean barrier, increases by moving the barrier away from the point. Consequently, the dielectric strength decreases by increasing the ratio a/d [14].

There is a difference between the simulation results and the experimental data especially when the voltages are greater than 16 kV for the position a/d=0% and 14 kV for the position a/d=20%, and when the voltages are close to the indicated values, the simulation is closer to the experimental results.

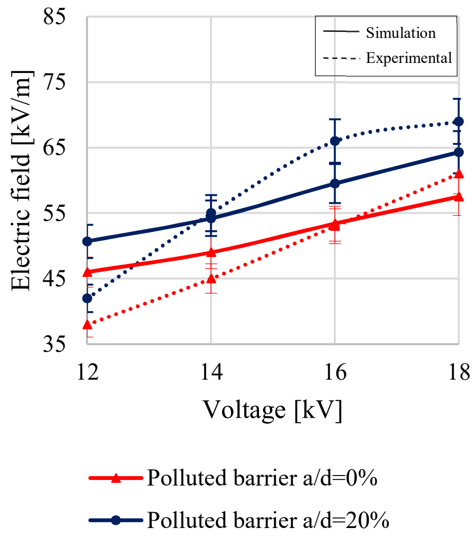

Fig.9: Influence of the position of the polluted barrier on the variation of the electric field at the plane as a function of the voltage V (d = 5 cm, 2L = 15 cm, e=2.1mm, σ=0.45 mS/cm).

B. Influence of pollution mode

The influence of the mode of pollution on the variation of the electric field at the plane as a function of the voltage V for a polluted barrier is shown in Fig 10.

From this figure, it can be observed that whatever the mode of pollution applied to the barrier, the electric field is higher than that of the clean barrier. In particular, the completely polluted barrier causes a greater increase of the electric field compared to the case where the barrier is only polluted on its upper surface [18]. For the insulating barrier, we observe that the simulation results are close to the experimental ones and the error is less than 5%. On the other side, for the polluted barrier, the experimental and the simulation data are within an error tolerance of +/- 10%. We also observe that the simulation results are close to the experiment ones, especially for high voltage values.

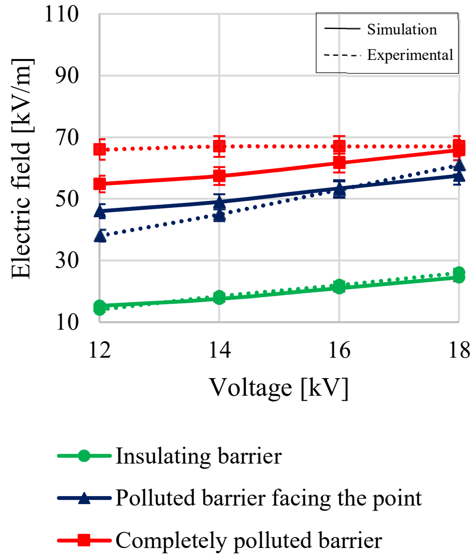

Fig.10: Influence of the pollution mode on the variation of the electric field at the plane as a function of the voltage V for a polluted barrier (d = 5 cm, a/d = 0%, 2L = 15 cm, e=2.1mm, σ=0.45 mS/cm).

C. Influence of layer conductivity

We examine now the effect of the layer conductivity on the electric field distribution at the plane for the three cases: polluted barrier facing the point, facing the plane, and completely polluted.

The x-axis (position on the plane) represents the distance between the center and the edge of the plane.

The results, presented in Fig 11,12 and 13, were obtained for an AC voltage equal to 22 kV, conductivity values of 0 S/m (clean barrier), 0.0235mS/cm, 0.45mS/cm, 1mS/cm and 2mS/cm, and for permittivity thin layer value of 80. Pollution layer thickness was kept constant at 0.1 mm.

From these figures, we note that the electric field depends on the pollution layer conductivity. As a first observation, a polluted barrier reduces the dielectric strength compared to that of the clean barrier, whatever the mode of application of the pollution but remains superior to that of the conductive barrier.

In Fig 11, the electric field distribution as a function of a polluted barrier facing the pointed electrode was presented. From this figure, we observe that when the conductivity of the pollution layer increases, the electric field increases [19].

The influence of the pollution layer facing the grounded electrode is presented in Fig 12. We notice the more the conductivity of the pollution layer increases, the electric field slightly increases but remain far from the case of the polluted barrier facing the point [19]. The pollution on the ground side does not significantly affect the dielectric strength of the system.

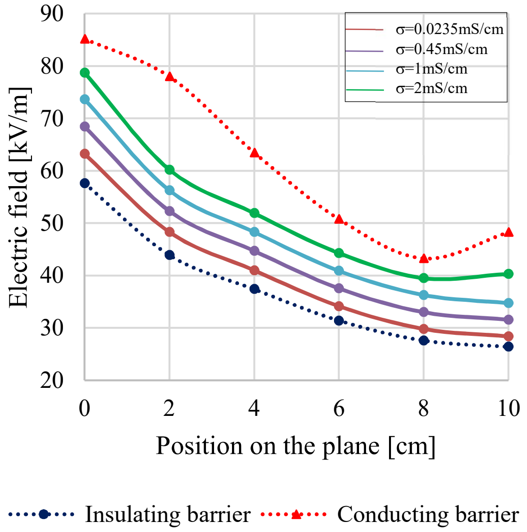

Fig.11: Distribution of the electric field at the plane (V=22kV, d = 5 cm, a/d = 0%, 2L = 15 cm, e=5mm, εr = 80, ep =0.1mm).

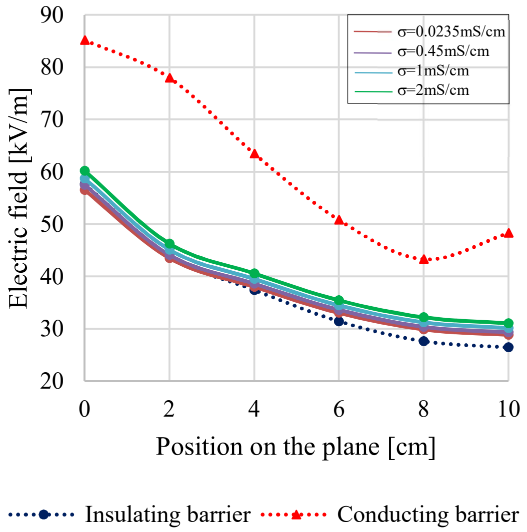

Fig.12: Distribution of the electric field at the plane (V=22kV, d = 5 cm, a/d = 0%, 2L = 15 cm, e=5mm, εr = 80, ep =0.1mm).

Finally, we tested the influence of a completely polluted barrier on the distribution of the electric field (Fig 13).

From this figure, we notice that the variation of the electric field is almost the same as the case of a polluted barrier facing the pointed electrode [19]. The pollution on the side of the point greatly reduces the insulation quality of the barrier.

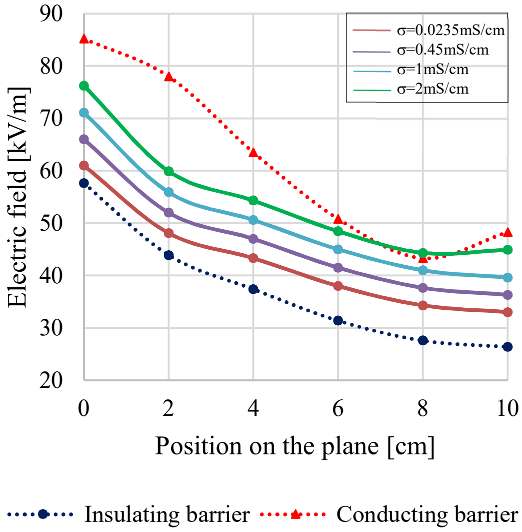

Fig.13: Distribution of the electric field at the plane (V=22kV, d = 5 cm, a/d = 0%, 2L = 15 cm, e=5mm, εr = 80, ep =0.1mm).

D. Influence of layer permittivity

In order to study the influence of the layer permittivity on the electric field distribution at the plane, two permittivity values: 15 and 80 respectively were used. We used also two conductivity values: σ=0.0235mS/cm and σ=1mS/cm, and the thickness of the pollution is equal to 0.1 mm.

Based on the simulation results (Fig 14), it has been observed that the influence of the permittivity on the electric field distribution at the plane is remarkable for low conductivity values. With the growth of the conductivity value, the effect of the permittivity decreases [18].

In fact, the thin layer becomes a better conductive layer entering in resistive regime making the electric field distribution uniform. In this type of regime, the influence of permittivity is not noticeable as we can observe when we compare the green curve, pollution conductivity of 1mS/cm and pollution permittivity of 80F/m, with the blue curve, pollution conductivity of 1 mS/cm and permittivity of 15F/m. These curves are substantially equal.

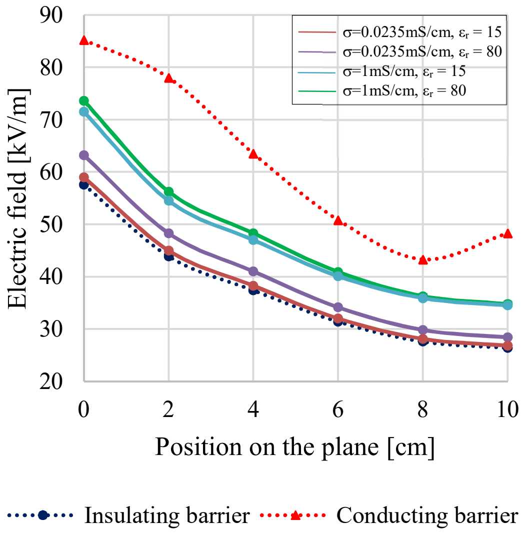

Fig.14: Distribution of the electric field at the plane (V=22kV, d = 5 cm, a/d = 0%, 2L = 15 cm, e=5mm, e_p =0.1mm).

E. Influence of layer thickness

The study of the effect of the thickness of pollution layers on the electric field distribution at the plane is of great importance to determine the dielectric strength of the point-barrier-plane arrangement.

To do this, three thicknesses e_p=0.1, 0.3 and 0.5mm were used. We also used two values of conductivity σ=0.0235 and σ=1mS/cm which represent two different levels of pollution. The value of the permittivity was kept constant and equal to 80.

From Fig (15,16), It can be observed that when the thickness of the pollution increases, the electric field increases. This increase in field strength is much greater when the conductivity of the pollution layer increases. For low values of conductivity and in the case of a polluted barrier on its upper surface (Fig 15), the electric field increases but remains far from that one obtained in the case of the conductive barrier.
If the conductivity and the thickness increase at the same time (Fig 16), the distribution of the electric field increases and converges towards the value of the conductive barrier [18].

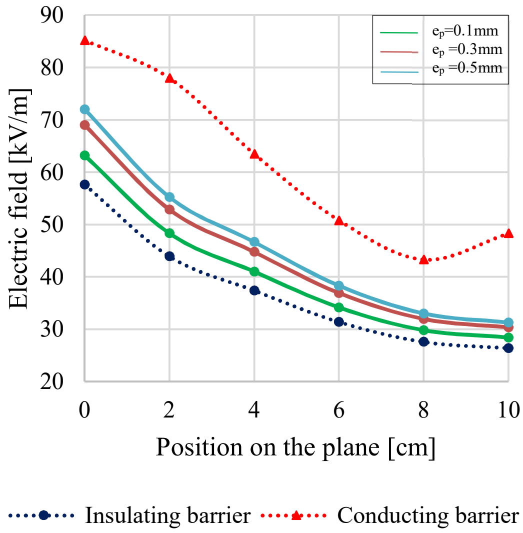

Fig.15: Distribution of the electric field at the plane (V=22kV, d = 5 cm, a/d = 0%, 2L = 15 cm, e=5mm, σ=0.0235mS/cm, εr = 80).

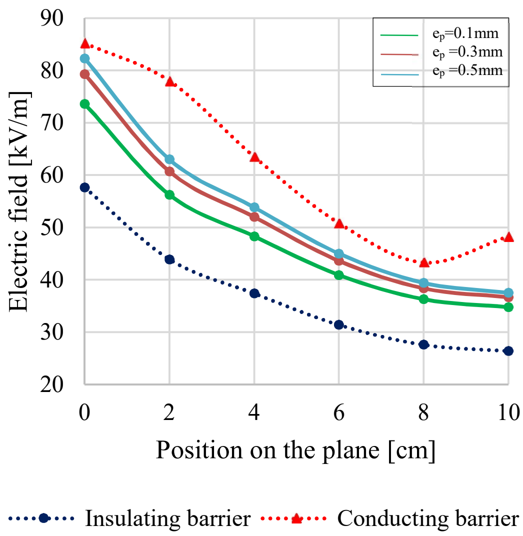

Fig.16: Distribution of the electric field at the plane (V=22kV, d = 5 cm, a/d = 0%, 2L = 15 cm, e=5mm, σ=1mS/cm, εr = 80).

F. Polluted barrier vs conductive barrier

To complete our study, the limit value of the conductivity from which the polluted barrier gives almost the same result as the conductive one in the case of polluted barrier facing the point was determined (fig 17).

From this figure, we observe that the polluted barrier has almost the same behavior in comparison with the conducting barrier for the position x=0 (center of the plane) and when the conductivity is close to 2.25 mS/cm [18].

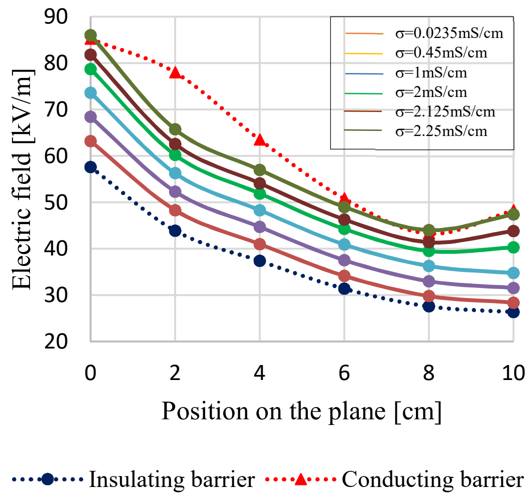

Fig.17: Distribution of the electric field at the plane (V=22kV, d = 5 cm, a/d = 0%, 2L = 15 cm, e=5mm, e_p =0.1mm).

IV. Conclusion

In this paper, electric field distribution in point-barrier-plane air gaps was investigated by using software package of COMSOL Multiphysics based on Finite Element Method (FEM). Comparison between the electric field in both clean and polluted cases was conducted.

The effect of the surface condition of the barrier on the electric field for a point-plane system gives the following results:

- The pollution on the side of the point greatly reduces the insulation quality of the barrier.
- The electric field of the point-barrier-plane configuration increases with increasing conductivity of the pollution layer covering the barrier.
- The influence of the thin pollution layer permittivity on the electric field is remarkable for the small values of the conductivity.
- From our results with different pollution layer thicknesses, we can deduce that this parameter has an important influence on the distribution of the electric field and therefore the dielectric strength of the system.
- There is a limit value of the conductivity from which the polluted barrier gives almost the same result as the conductive barrier. In our study, this value is equal to: 2.25 mS/cm.

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