Electrical discharge reproduction in rod-barrier-plane system

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ABSTRACT

The present paper deals with new modeling to reproduce the electric discharge in the rod-plane air gap system with rubber insulating barrier under AC and impulse voltage. This model considers the randomness character of discharge evolution which is governed by the electric field. The discharges shape obtained by this model are compared with ones given by experimental tests. The established model reproduces correctly the forms of discharges obtained by experimental tests under AC voltage. It is found that the behavior of the electrical discharge depends not only on the dimension (thickness and width) of the insulating barriers but on its positions in the air gap as well. It is to highlight that the mode of applied voltage is of key importance barrier. Experimental investigation shows that the developed arc can evolve on 1 to 4 channels. The generated discharges in AC voltage distinguish by the formation of a multiple-channel arc. Whereas, the discharge under lightning impulse voltage found to progress in a single channel whatever the barrier position and dimensions. The model confirms that electric field is the most important factor in the behavior of the rod-insulating barrier-plane system submitted to high voltage.

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1. INTRODUCTION

Insulating barriers are widely used in many high voltage devices, especially in circuit breakers, disconnectors and insulation bushings. Their primary function is to improve insulation performance and increase the breakdown voltage of air or oil-filled gaps [1]–[4]. The presence of an insulating barrier between two electrodes changes the initial gap into a stratified system made up of two dielectric media (air or liquid and the barrier material) that has higher dielectric strength. This improvement in dielectric strength depends on the position of the barrier, its dimensions (thickness and width) and its material.

Indeed, given the resulting elongation of the channel of the electric discharge in such systems, the distribution of the electric field is also strongly modified [1]–[5]. Several experimental and theoretical investigations have been carried out to improve the understanding of the mechanisms governing the breakdown phenomenon and electrical discharges in non-uniform field systems [6] and [7], especially in rod-barrier-plane systems [1]–[5], [8]–[30]. These studies noted that the breakdown voltage is a function of the distance between the electrodes and their shape, the dimensions, the nature and position of the barrier and the applied voltage type [12], [26]. The investigations were conducted using three types of voltage: DC voltage [16], [18], [24]–[26], AC voltage [1], [15], [17], [26] and impulse [8]–[10], [19]. The maximum disruption voltage is often obtained when the barrier is placed close to the sharp electrode (up to 25% of the studied interval length) [1], [8], [11], [26]. Bako [2] showed that, in oil, the nature and thickness of the insulating barrier, the applied voltage, the polarity of the electrodes and the pressure play an important role in the generation, propagation and general form of the electrical discharge. He also noted that the final length of discharge increases linearly with applied voltage and barrier permittivity and decreases with increasing thickness. The final discharge length is significantly higher under AC compared with the cases of impulse and direct voltages (for the same voltage magnitude) and, therefore, the flashover voltage is higher under AC. Polytechnique [26] further indicated that breakdown voltage increases under AC and DC voltage due to the elongation of the discharge channel, emphasizing the role of width. However, an increase in the barrier thickness does not lead to the elongation of the discharge channel. Guerbas *et al.* [31] confirmed that the discharge can present two forms: (i) discharge that originates from the rod electrode terminating the edge of the barrier and then progressing onto the plane electrode, and (ii) discharge that initiates at the rod towards the center of the barrier slides on its surface towards the edge before finally jumping to the plane electrode.

For polluted barriers having a surface conductivity of 1.6 µS, the discharge develops in two steps similar to a metal barrier: it advances from the rod to the center of the polluted barrier and then from the edge of the barrier towards the plane. To estimate the optimal position of the barrier [8], they presented a model that takes into account the surface charge density on both sides of the barrier. Fofana *et al.* [11] have established an analytical model to describe the experimental observations in a rod insulating barrier-plane system, for large air gaps under positive lightning impulse voltage. The developed model reproduces the experimental observations but does not simulate well barriers placed near the rod. It is important to emphasize that sliding electrical discharges on the surface of the barrier were not considered in this model.

All previously cited studies, regarding the influence of the insertion of an insulating barrier in a rod-plane electrode system, assessed the dielectric strength and noted that the trajectory of the electrical discharge is highly dependent on dimensions, nature and position of the barrier. In addition, it was demonstrated that the increase in the breakdown voltage is closely related to the elongation of the principal discharge channel. Nevertheless, the authors did not dwell on the arc shape obtained and the number of channels that can appear during the discharge as well as the possibility of formation of multiple arcs. Modeling and numerical simulation, an essential complement to experimental investigations, play an important part in the analysis of electrical discharge phenomena as described in [8], [10], [11], [13], [20], [21], [23], [32].

This work is a contribution to enhance the flashover voltage prediction by proposing a new approach aiming to reproduce random electric arc propagation throughout the rod- insulating barrier-plane system. In fact, a new concept of numerical simulation based on the effect of electric field magnitude is proposed to predict the different electrical discharge forms and steps in atmospheric air. The rod electrode is subjected to direct high voltage of AC and lightning impulse voltage. Indeed, it considers that the discharge develops from the rod where the electric field magnitude is highest and then progresses randomly towards the neighbouring points. In addition, this model considers the electro-geometric parameters of the system (gap distance, rod electrode radius, width, thickness, nature and position of the barrier). The shape of discharges obtained by simulation, using the established model represents in a very satisfactory way these observed during the tests.

2. EXPERIMENTAL TECHNIQUE

The experimental model in Figure 1, consists of a rod-plane gap using brass electrodes, the gap length is d. The rod electrode is obtained by machining a rod of 1.2 cm diameter and 1.5 cm long to obtain a sharp shape having a 45° angle finished with a half-sphere radius rp=500 µm. The rod is then connected to the high voltage through a threaded longer cylindrical conductor rod, which also allows adjusting the vertical inter-electrode distance. The plane electrode is a 15 mm thick circular plate of 90 mm diameter and having a Rogowski electrode profile. The plane electrode fixed to the test bench and grounded to the experiment earth point. The insulating barrier, which inserted between these two electrodes at a position x from the rod electrode, is of a circular shape having a radius Lb/2, a thickness e, and a relative permittivity εr. For the experiments conducted in this work, the silicone rubber barriers were manufactured in the laboratory by mixing a base resin host matrix (600 A), a hardener (600 B) using in-house molding, and vacuum casting facilities. The physical properties and dimensions of these studied barriers are summarized in Table 1.

The tests were carried out at Cardiff University's High Voltage Laboratory using two types of voltage sources: a 50 Hz transformer for AC tests (50 kV, 2.5 kVA, 50 Hz) and a lightning impulse generator (1.2/50 µs, 300 kV maximum peak voltage). To measure the breakdown voltage, AC voltage was applied with a ramp of 2 kV/s whilst, for the lightning impulse, the up and down method with 30 tests was adopted.

The barriers were checked and cleaned with isopropyl alcohol after each discharge, after each test in AC voltage and after each series of 30 tests for the impulse voltage. The shape of the discharge is recorded using a fast camera (lightning RDT 16,000 color playback type). The images representing the discharges are extracted from the obtained film. The test circuit used for experimental tests is illustrated in Figure 2.

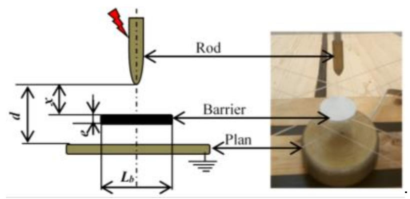


Figure 1. Electrodes configuration

Table 1. Physical properties and geometry of the studied systems

Material	εr	Lb (cm)	D (cm)	E (mm)	x/d (%)
Silicone rubber	2.9	2	5	2	0
	2.9	4	5	4	0.2
	2.9	6	5		0.4
					0.5
					0.8
					1

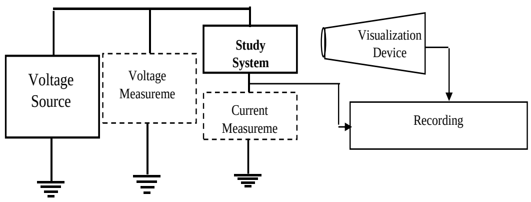
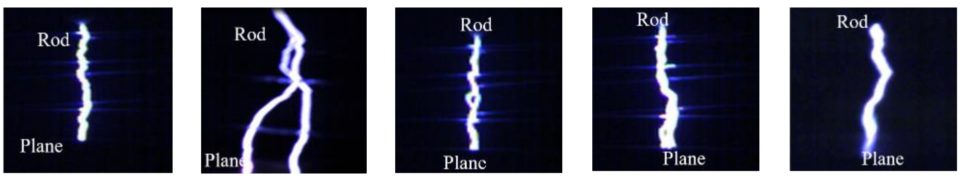


Figure 2. Schematic of an experimental laboratory set up

3. EXPERIMENTAL RESULTS: FORM OF ELECTRIC DISCHARGE

3.1. Rod-plane electrode system (without barrier)

Figure 3 displays discharges recorded for an air rod-plane electrode system with a gap length of d=5 cm. Specifically, Figures 3(a) to 3(d) depict discharges recorded under AC voltage, while Figure 3(e) illustrate discharges under lightning impulse. As can be seen on the pictures, irrespective of voltage type, the discharge appears to start from the rod and propagates randomly with a tortuous path to a point near the center of the plane. The number of channels is, however, dependent upon the type of applied voltage. For the lightning impulse, the discharge has a single channel as can be observed in Figure 3(e). In contrast, under AC voltage, up to three channels can be created, as captured in Figure 3(d). From this result, it is inferred that the type of voltage application is a dominant factor in determining the shape of the discharge. For the lightning impulse, the discharge starts from the rod electrode and stops only if it reaches the plane electrode. In AC, the time being longer than the impulse, the discharge starts from the rod and can evolve into several channels. Arc extinction and re-ignition phases may also appear in AC.



(a) (b) (c) (d) (e)

Figure 3. Electrical discharges forms for a rod-plane electrode system with d=5 cm: (a) AC voltage, (b) AC voltage, (c) AC voltage, (d) AC voltage and (e) lightning impulse voltage

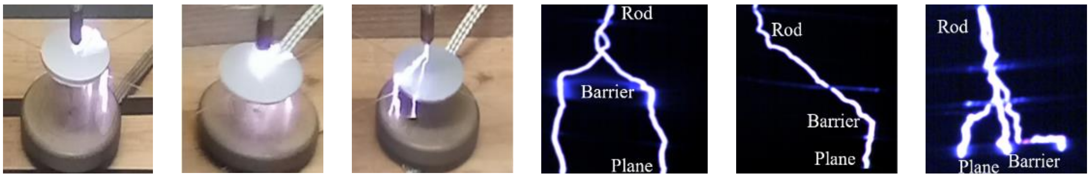
3.2. Rod-insulating barrier-plane electrode system

The introduction of a barrier within the gap between the rod and plane electrodes induces changes in the electrical discharge shape depending on the position, width of the barrier. Furthermore, it is noteworthy that both the gap length and applied voltage serve as influential factors in shaping the observed discharges. The interactions between these parameters contribute to the nuanced behavior of the discharge phenomenon in the rod-plane electrode system.

3.2.1. Influence of the insulating barrier position

A. Under alternating voltage

A silicone rubber barrier characterized by a width (Lb=6 cm) and a thickness (e=4 mm) is investigated for different positions, as illustrated in Figure 4. For insulating barrier positioned in contact with the rod electrode, the electric discharge slides over the barrier surface to reach the plane electrode Figure 4(a). When the barrier is moved away from the rod electrode, the electric discharge takes a new orientation. It can be a sliding discharge for (x=20%) Figure 4(b) or a diagonal arc which starts from the rod and goes straight to the barrier edge for (x=40%, x=50%, and x=80%), corresponding to Figures 4(c) to 4(e) respectively. For a barrier sitting on the plane electrode, two trajectories of the discharge can be seen occurring simultaneously (multiple discharges) sliding and diagonal Figure 4(f). The discharge shapes can progress in a single or two arc channels, starting from the initiation point (rod electrode) or at other positions along the arc.

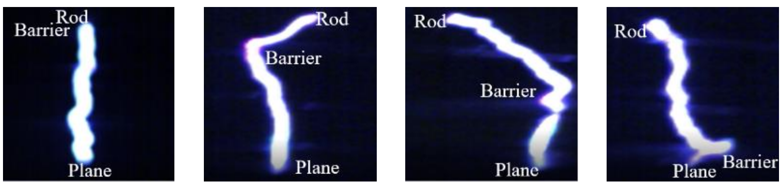


(a) (b) (c) (d) (e) (f)

Figure 4. Electric discharges forms (silicone rubber, Lb=6 cm, e=4 mm and d=5 cm) AC voltage, x: relative position: (a) x=0%, (b) x=20%, (c) x=40%, (d) x=50%, (e) x=80%, and (f) x=100%

B. Under lightning impulse voltage

The results for the silicone barriers at different positions in a 5 cm gap are illustrated on Figure 5 as can be observed, the discharge shape depends on the barrier position. For a barrier close to the rod, the discharge slides on the barrier surface to reach the edge before jumping to the ground electrode edge Figure 5(a). For a barrier placed at 20%, the discharge advances towards the barrier edge then onto the plane Figure 5(b). For x=50%, the discharge progresses towards the barrier center then slides on its surface to the edge, a second discharge onset from the barrier low center Figure 5(c). For a position further away from the rod x=100% of the gap distance, the discharge advances towards barrier edge then onto the plane electrode Figure 5(d).



(a) (b) (c) (d)

Figure 5. Electric discharges forms (silicone rubber, Lb=4 cm, e=4 mm, d=5 cm) lightning impulse voltage x: relative position: (a) x=0%, (b) x=20%, (c) x=50%, and (d) x=100%

3.2.2. Influence of insulating barrier width

Figures 6-8 reproduce records of discharge shapes obtained for silicone rubber barrier, using different widths of barrier thicknesses and positions under AC and lightning impulse voltage. In these experiments, a gap distance of 5cm is used. Investigating diverse parameters, notably the dimensions of the barrier, offers valuable insights into the discharge behavior within the rod-plane electrode system.

A. Under alternating voltage

Figures 6 and 7 subjected to alternating voltage, the discharge develops from the rod electrode and advances towards the center of the barrier, then slides over its surface towards the edge of the plane electrode Figures 6(a), 6(b), 6(c), and 7(a). Or jumps diagonally towards the barrier edge then into the plane electrode Figures 7(b) and 7(c). The records showed that the electric discharge advances in 1 or in multipath, up to 4 channels.

(a) (b) (c)

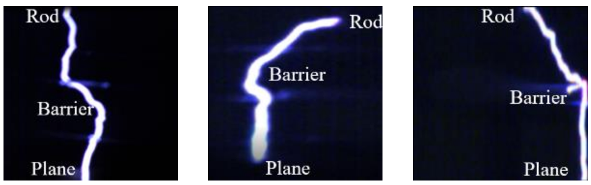
Figure 6. Electric discharges forms (silicone rubber, e=4 mm and d=5 cm, x=0%) AC voltage, Lb: width: (a) Lb=4 cm, (b) Lb=6 cm, and (c) Lb=8 cm

(a) (b) (c)

Figure 7. Electric discharges forms (silicone rubber, e=4 mm and d=5 cm, x=40%) AC voltage, Lb: width: (a) Lb=4 cm, (b) Lb=6 cm, and (c) Lb=8 cm

B. Under lightning impulse voltage

For lightning impulse voltage applications using a silicone rubber barrier Figure 8, the discharge is seen to propagate in a single channel, and it develops directly from the rod towards the barrier edge and then onto the plane electrode using a barrier diameter of Lb=4 cm and 6 cm as illustrated in Figures 8(a) and 8(b) respectively. Otherwise, it occasionally slides over the surface of the barrier to reach the plane electrode for a barrier width Lb=8 cm Figure 8(c). These results prove that the distribution of the electric field between the rod electrode and the insulating barrier plays an important role in the behavior of the electric discharge. The electric field between the barriers tends to become uniform as reported by Béroual and Boubakeur [8].

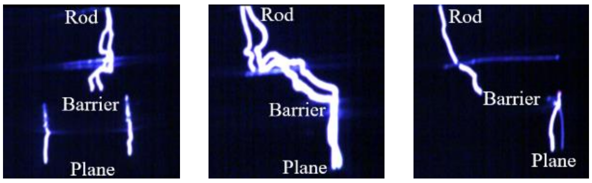


(a) (b) (c)

Figure 8. Electric discharges forms (silicone rubber, e=4 mm and d=5 cm, x=40%) lightning impulse voltage, Lb: width: (a) Lb=4 cm, (b) Lb=6 cm, and (c) Lb=8 cm

3.3. Rod-polluted barrier-plane electrode system

In the purpose to investigate condensation effects on the dielectric performance, the barrier was sprayed with tap water. The utilized barrier, with thickness e=2 mm and width Lb=6 cm, was setting at position x=50%. Noted that AC voltage was applied and the tests were repeated three times, as illustrated in Figure 9. The electrical discharge was observed to always to propagate of the barrier surface. The presence of water droplets causes electric field enhancement, creating a preferred discharge path. This is seen as disconnections in the electric discharge path as illustrated in Figure 9(a) and 9(b) first and second test respectively. In third test Figure 9(c), the electric discharge propagates from the rod electrode to the edge of the barrier then onto the plane electrode. Under these conditions, several channels were recorded. This result is in agreement with that obtained for insulating barriers.



(a) (b) (c)

Figure 9. Electric discharges forms (polluted silicone rubber, e=2 mm, Lb=6 cm and d=5 cm, x=50%) AC voltage: (a) first test, (b) second test, and (c) third test

4. MODELLING OF THE DISCHARGE

A model is generated to reproduce the discharge shape. A number of assumptions were considered in this model. The discharge is assumed to initiate at the rod electrode and progresses towards the plane electrode. In addition to being random in its development, its progression is always taken as moving from the highest field points towards the points of lower potential. Assuming that the discharge channel is a good conductor (the whole charge is accumulated in the channel), the drop voltage between the ends of the channel is zero.

The discharge is assumed to develop steps towards 5 possible points Figure (10): D (right), C (center), G (left), DH (horizontal right) and GH (horizontal left). The discharge completes its path when the E field condition in (1) is satisfied:

$$E_{target} \geq E_{max}.\delta \qquad (1)$$

where: E_{target}: designates the field at the targeted point (D or C or G or DH or GH), E_{max}: the maximum field calculated at each stage of development, δ: random variable generated by the uniform law (random). It varies between 0 and 1.

When dealing with applications involving extra low-frequency AC (at 50/60 Hz) or DC voltages, challenges can be approached as an electrostatic field issue. In this context, the electric and magnetic field components are often examined independently, allowing calculations based on static field principles. Maxwell's equations govern other electromagnetic fields, while in electrostatic (and quasi-static) scenarios, these equations, along with constitutive equations, simplify to the following form.

$$\vec{\nabla}\mathrm{x}\vec{E} = 0 \qquad (2)$$

$$\vec{\nabla}.\vec{D} = \rho \qquad (3)$$

$$\vec{D} = \varepsilon\vec{E} \qquad (4)$$

Where E is the electric field intensity, D is the electric displacement, ρ is the space charge density, ε is the dielectric permittivity of the material. Based on (2), electric field intensity is introduced by the negative gradient of the electric scalar potential V in (5).

$$\vec{E} = -\vec{\nabla}V \qquad (5)$$

By substituting in (4) and (5) into (3) and considering a homogenous material, poisson's scalar equation is obtained in (6):

$$-\vec{\nabla}.\left(\varepsilon\vec{\nabla}V\right) = -\vec{\nabla}.\left(\varepsilon_0\varepsilon_r\vec{\nabla}V\right) = \rho \qquad (6)$$

where ε_0 is vaccum permittivity, εr = εr is the relative permittivity and ρ is the space charge density. For a homogenous material permittivity ε is constant and the (6) becomes:

$$\vec{\nabla}^2V = \Delta V = -{}^{\rho}/_{\varepsilon} \qquad (7)$$

For space devoid of charge (ρ = 0), the field is defined by Laplace's as in (8):

$$\Delta V = 0 \tag{8}$$

V: is the electric potential.

Once the condition is satisfied, a line joining the two points (the considered point and the targeted point) is achieved. These points, in turn, become new points from which the discharge can advance. It results in the potential difference between the ends of the channel to be zero [32]. The electric field is computed using the FEMM software [33] under the MATLAB environment considering a Neumann boundary condition ∂V/∂n=0 on a rectangular border surrounding the system [34]. After each evolution, the electric field is recalculated taking into account the newly formed discharge channels. Figure 10 illustrates a sketch of the resulting arc path.

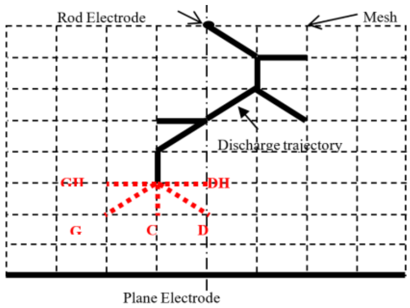
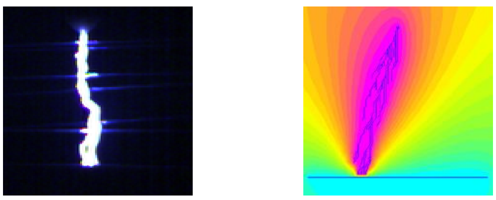


Figure 10. The discharge progression

5. MODELLING RESULTS

Figures 11-14 show a comparison between experimental and simulated discharges for different configurations. In all the cases examined, it can be seen that the discharges obtained by simulation of the established model reproduce faithfully the discharges recorded during the experimental tests thus confirming the important role of the electric field in the initiation and propagation of the electric discharge. Figure 11 shows compare experiment Figure 11(a) and model results Figure 11(b) with the rod-plane electrode system without barriers. From the figure, it can be observed that the discharge starts from the rod electrode and advances directly towards the plane center. The introduction of an insulating barrier changes the electric discharge shape and path. For an insulating barrier close to the rod electrode, a sliding discharge on the surface is seen as illustrated in Figure 12 shows (experimental results Figure 12(a) and model results Figure 12(b)) shows. When the barrier is placed at x=50%, the discharge starts at the rod electrode and heads for the barrier edge and then to the plane electrode Figure 13(a) and 13(b). It can also end up at a point near the barrier edge to extend along the barrier surface before finishing at the plane electrode Figure 13(c) and 13(d). For a barrier in contact with the plane electrode, case shown in Figure 13 for d=5 cm, this discharge can develop as a single channel Figure 14(a) and 14(b), 2 paths Figure 14(c), 14(d) or 3 paths Figure 14(e) and Figure 14(f). The simulated electric discharges forms are consistent with those obtained experimentally. The agreement obtained between the experimental and modelling results helps to validate the developed model, which takes into account the system geometry (gap length, rod electrode radius), the barrier dimensions (width and thickness) and its position.

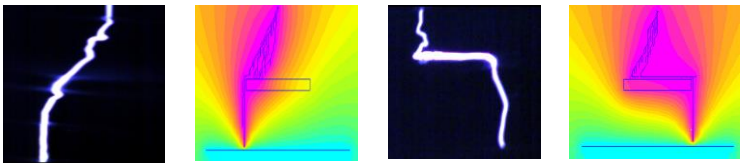


(a) (b)

Figure 11. Comparison of predicted model arc shapes with arcs recorded during tests, without barrier, d=5 cm (a) experimental results and (b) their simulation results respectively

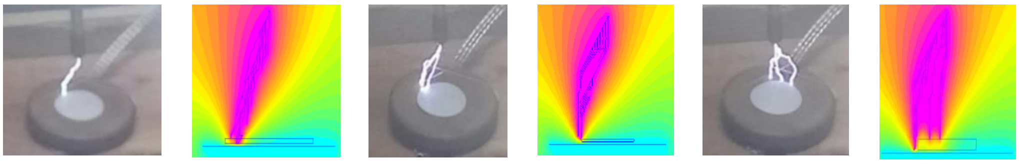
(a) (b)

Figure 12. Comparison of predicted model arc shapes with arcs recorded during tests, x=0%, e=2 mm, Lb=4 cm, d=5 cm (a) experimental results and (b) simulation results



(a) (b) (c) (d)

Figure 13. Comparison of predicted model arc shapes with arcs recorded during tests, x=50%, e=2 mm, Lb=4 cm, d=5 cm: (a) experimental result, (b) its simulation result, (c) experimental result, and (d) its simulation result



(a) (b) (c) (d) (e) (f)

Figure 14. Comparison of predicted model arc shapes with arcs recorded during tests, x=100%, e=2 mm, Lb=4 cm, d=5 cm: (a) experimental result, (b)its simulation result, (c) experimental result, (d) its simulation result, (e) experimental result, and (f) its simulation result

6. CONCLUSION

In this work, the influence of the Silicone rubber insulating barrier in a rod-plane air gap was investigated under lightning impulse (1.2/50 µs) and AC voltages (50 Hz) to determine its effects on the electrical discharge propagation and shape. Furthermore, a numerical model, reproducing satisfactorily the electrical discharge shapes in the rod-barrier-plane system, was developed. From the obtained shapes under AC voltage, the generated discharges are distinguished by the formation of a multiple-channel arc. In contrast, under lightning impulse voltage the discharge progresses in a single channel whatever the position and dimensions of the barrier, with clean and polluted barrier. These discharges were recorded, and various paths are found as follow: i) diagonal discharge advances from the rod electrode to the barrier edge and then onto the plane; ii) discharge advances from the rod towards the barrier center then propagates on its surface to finish on the plane electrode especially at x=0%; iii) diagonal and sliding discharge at the same time in the case of AC voltages; iv) discontinuous discharge; for a wetted barrier with some tap water droplets, the discharge is always along the surface and the presence of water droplets on the barrier surface causes disconnections in the electrical discharge. The electric field repartition plays an important role in the initiation and propagation of electrical discharge. In the presence of an insulating barrier, the distribution of the electric field between barrier and plane electrode is almost uniform. The distribution of the electric field between the rod electrode and the insulating barrier guides the discharge in its evolution therefore impose its shape. The developed model reproduces satisfactorily the discharges shapes recorded during the experimental tests. This model takes into account the geometry of the system (gap length), the dimensions of the barrier (width and thickness) and its position. Finley, this study can be useful for various applications, we recommend utilizing our model to study and assess the electrical discharge behavior of high-voltage transformers, current transformer, power transformer, circuit breakers and disconnect switch, with full credibility.

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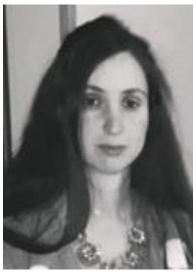

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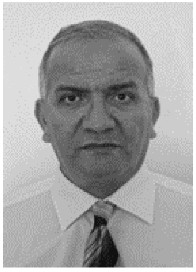

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