Optimization and Prediction of Corona and Breakdown of Small Rod-plate Air Gaps Stressed by DC and Impulse Voltages

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***Abstract*— In the present paper methods of controlling Corona and breakdown in small rod-plate air gaps are investigated. Combining experimental and simulation-theoretical work, it is resulted that when the rod's diameter is bigger, the gap length larger and the rod is grounded the field is less inhomogeneous. Therefore the value of the dc breakdown voltage without Corona is higher. If Corona occurs then the values of the Corona onset voltage are higher, and the corona effects are not intense. The Corona effects, lead to a rise of the value of the dc breakdown voltage especially when the rod is negatively charged. Moreover an insulated thin barrier, when positioned near the rod increases the breakdown dc voltage to a maximum value, and minimizes the Corona effects. Especially for gaps stressed by impulse voltage the Corona effects, appearing with the form of electric current pulses, are influenced by the same factors with a different way. The values of the breakdown voltage in contrast to what happens with dc voltage are higher when the Corona effects are weaker, depending on the influence of the field's inhomogenity (geometry and effect of grounding). It is also resulted that a resistor connected in series with the gap decreases its maximum charging voltage and increases the value of the breakdown voltage) The average value of the field strength and the field factor across the axis of the gap are determinant factors of major importance for the phenomena of corona and breakdown in rod-plate air gaps. The inhomogeneity of the field determines the evolution of the dielectric behavior of the gap. The latter provides a new way of prediction of the dielectric behavior of the air gaps, with only the use of simulation analysis.**

Keywords— Corona; Breakdown; simulation; impulse; optimization; prediction; field strength.

I. Introduction

Air gaps are the most conventional insulating arrangements and thus are considered as one of the most important parameters for the design and dimensioning of insulating arrangements. In designing nearly every electrical arrangement, air gaps are essential components that arise necessarily in constructions, and especially in high voltages (switches, gaps between power lines, or power lines and earth, gaps between electrical and electronic components in most devices, etc.).

The mostly studied air gaps are the sphere-sphere, rod-rod and especially the rod-plate or point-plate air gaps mainly when the plate is grounded, because these gaps feature the least dielectric strength and the most intense Corona effects.

The basic effects which are referred as the dielectric behavior of an air gap are the Corona effects (electric charges in the gap) and the breakdown voltage [1-2]. The basic magnitudes which describe the dielectric behavior of an air gap are the Corona onset voltage, the Corona current in the form of current pulses and the Breakdown Voltage, [1-5].

The most known effects which influence the values of the above mentioned magnitudes are, the polarity effect, [1-2], and the barrier effect (composite insulation), [3]. Other lately investigated phenomena which have great influence on the dielectric behavior of the air gaps are the ground effect, that is the influence of the different electrode chosen to be grounded on the field distribution of a gap [4-5], and the Corona current effect, that is the influence of the Corona effects on the dc breakdown voltage of an air gap.

The polarity effect and its influence to the breakdown voltage have also been studied from many researchers involving arrangements with a grounded plate. The corona current effect combined with the polarity effect and ground effect has recently been an object of study mainly for arrangements stressed by dc voltage [4-5].

Air gaps with the rod grounded stressed by impulse voltages have not been investigated yet. In such arrangements the electric field in the gap is less inhomogeneous and the voltage needed for the Corona pulses to occur is higher and consequently the breakdown voltage is also higher, [6]. In the present paper the combined influence of the ground and the barrier effect on Corona and breakdown in rod-plate arrangements stressed by dc voltage, as well as the influence of the ground in combination to the Corona effects on arrangements stressed by lightning impulse voltage are investigated. The corona effects, which occur in air gaps before breakdown, when stressed by dc or low frequency ac voltages postpone the breakdown mechanism [6], while with impulse voltages they lead to breakdown [1,7].

The basic magnitude which influences the dielectric behavior of the air gaps is the field strength, and especially the maximum value of the field strength in the gap

$$E_{max} = n \cdot E_{av} \quad (1)$$

where $E_{av} = V/G$, V (V) is the applied voltage, G (cm) is the gap length, and n is the field factor of the gap. For a rod-plate air gap, with a very big plate, and r_r the rod's diameter the field factor is given by equation [1, 2]:

$$n = \frac{2G}{r_r \cdot \ln(G/r_r)}, \quad \text{if } G >> r_r, \quad (2)$$

The equations that calculate the values of the dc corona onset field strength on the tip of a rod are taken from bibliography, such as the empirical equation:

$$E_c = 22{,}4 \cdot \left[1 + \frac{1}{\sqrt[3]{r}}\right] \text{ (kV/cm) for dc voltage,} \quad (3)$$

where E_c (kV/cm) is the corona onset field strength on the tip of a rod with radius r (cm), that is located separately in the area, far from the grounded environment. It is understandable that the above equations cannot be fully implemented on inter – electrode air gaps, like the rod – plate gaps.

The Corona effect is one of the major factors that influence the operation of various installations and high voltage devices. Conductors and insulators, for example, experience intense Corona effects and in general partial discharges. This phenomenon leads to energy and electric charge losses, disturbance in wireless communications and ozone production. Thus it is very crucial to design common high voltage electric circuits and devices free from Corona effects, or partial discharges, when installed and activated with operating voltage. The optimization towards that direction is very important.

On the other hand many modern applications (electrostatic filters, electrostatic painting, electrostatic sound boxes, etc) rely on the existence and control of Corona effects in order to operate and function. In these cases the optimization towards the direction of controlling the Corona effects is of major importance.

The Corona effects and the breakdown of air gaps have been experimentally investigated by many researchers for the most commonly used arrangements where the gap is formed between two electrodes one of which is grounded and the other is stressed by high voltage. Especially in rod – plate air gaps the mostly used so far technique of the experimental work concerns arrangements where the plate electrode is grounded (pl-gr) and voltage is applied to the electrode of the rod [1-3].

Several methods for controlling the corona effects have been proposed. In the present paper a new method is investigated through experimental work, mathematical analysis and by simulation, based on the results given from the influence of grounding (ground effect) in connection to the barrier effect and the polarity effect.

II. The Procedure Followed

Experimental work has been carried out for air gap arrangements stressed by dc voltage and impulse voltage. The arrangements, which have been modeled, analyzed, and experimentally studied, are typical rod-plate air gap arrangements of different electrode geometry, and gap length. High dc or lightning impulse voltage of negative or positive polarity is applied to one electrode while the other is at earth potential (grounded).

The influence of the surrounding is minimized, by keeping relatively big distances between the models and the boundary shielding, as well as between the experimental arrangements and the grounded elements of the laboratory.

Mathematical models (Fig. 1) of the experimental arrangements have been designed, and the equation of initial conditions concerning the analysis of the electric field in the gaps, or the electric circuit, in connection to the ground, the polarity and the barrier effect has been formulated and analyzed. Appropriate models have been designed and simulation analysis has been held, with the use of special software (Fig. 2).

III. Theory of Field Analysis

Equations describing the initial conditions of rod plate air gaps without barrier and for the different arrangements with the plate or the rod grounded (Fig. 1a) are linear, presented in [7-8] and are described from basic equations (4), (5) and (10), (11).

In rod-plate air gaps with a barrier, the linearity of equations is not valid since the results depend on the position and the charging of the barrier. The surface of the barrier is charged through small partial discharges that occur in the gap. Thus there is a voltage developed on the surface of the barrier, resulting to the influence of the occurring electric field distribution in the gap. The latter is influenced differently in a rod-plate gap according to the electrode chosen to be grounded and its dielectric behavior is greatly affected.

a) For the arrangements in which the plate's voltage is V_{pl}, the barriers voltage varies linearly, the center of the barrier having voltage V_{bo}, the barriers edge V_{b1}, while the rod and the boundary shield are grounded the following equations are valid:

$$V(x,y) = 0, \text{ if } (x,y) \in R_1 \cup \Gamma \quad (4)$$

$$V(x,y) = 1, \text{ if } (x,y) \in P \quad (5)$$

$$V(x,y) = V_{b0} + |y| \cdot K_1, \text{ if } (x,y) \in S \quad (6)$$

$$V_{pl} \geq V_{b0} \geq 0 \quad (7)$$

$$V(x,y) = V_{b0} + |y| \cdot K_1, \text{ if } (x,y) \in S \quad (8)$$

and when the barrier is near the rod

$$V_{pl} \geq V_{b0} \geq 0 \quad (9)$$

b) For the arrangements in which the plate is grounded and the rod is stressed the following equations are valid:

$$V(x,y)=0,\ if\ (x,y)\in P\cup\Gamma, \tag{10}$$

$$V(x,y)=1,\ if\ (x,y)\in R_1\ , \tag{11}$$

and $V_{b0}\le 1$ (when the barrier is near the rod), (12)

where:

$$\Gamma=(x,y)\in\Re^2 : x^2+y^2=R^2 \tag{13}$$

$$R_1=\begin{Bmatrix}(x,y)\in\Re^2 : -r_r\le y\le r_r, \\ -a+r_r-G/2-\sqrt{r_r^2-y^2}\le x\le -r_r-G/2+\sqrt{r_r^2-y^2}\end{Bmatrix}, \tag{14}$$

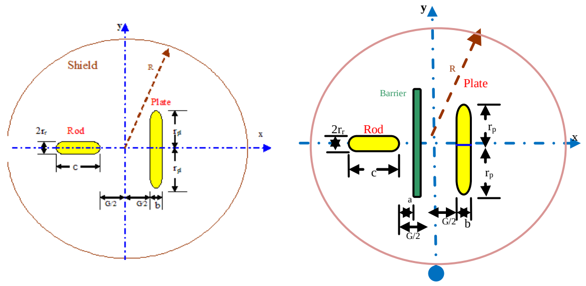
$$P=\begin{Bmatrix}(x,y)\in\Re^2 : \frac{G}{2}\le x\le\frac{G}{2}+b, \\ -r_p+\frac{b}{2}+\sqrt{\left(\frac{b}{2}\right)^2-\left(x-\frac{G}{2}-\frac{b}{2}\right)^2}\le y\le r_p-\frac{b}{2}-\sqrt{\left(\frac{b}{2}\right)^2-\left(x-\frac{G}{2}-\frac{b}{2}\right)^2}\end{Bmatrix}, \tag{15}$$

$$S=\begin{Bmatrix}(x,y)\in\Re^2 : x=-\frac{G}{2}+a, \\ -r_b\le y\le r_b\end{Bmatrix}, \tag{16}$$

$$K=\frac{V_{b0}-V_{b1}}{V_{b0}\cdot r_b}\qquad 0\le V_{b0}\le V\qquad K_1=\frac{V_{b1}-V_{b0}}{V_{b0}\cdot r_b} \tag{17}$$

a is the distance between the rod and the barrier and r_b the radius of the barrier (the plate and the barrier are in the form of a disc). Radius R is very big (Fig. 1).

It is resulted from comparison of equations (5), (6) and (10), (11) that there are significant differences between the arrangements with the rod or the plate grounded (ground effect), and are expected to lead to different dielectric behavior for the two arrangements



(a) Without barrier (b) With a barrier

Fig. 1 Theoretical models of rod-plate air gaps.

IV. The Simulation Results

The simulation analysis with the Finite Element Method and the use of special software has shown a significant influence of the effect of grounding and of the barrier on the field distribution in rod-plate air gaps. The differences between the arrangements, with the rod or the plate grounded, or with the existence of a barrier between the electrodes are obvious and shown in Figs. 2 and 3.

A. Rod-Plate Air Gaps Without Barrier

In rod plate air gaps without barrier the effect of grounding is intense when the gap length is relatively big (>2 cm) and the rod's diameters is relatively small (<12 mm).

In the rod grounded arrangements (r-gr) the field is less inhomogeneous than in the plate grounded (pl-gr) arrangements. The quantity of intensification is given by the maximum values of the field strength on the rod and the values of the field factor along the axis, which are lower in the arrangements with the rod grounded (r-gr) and higher in the arrangements with the plate grounded (pl-gr) (Fig. 2). The differences depend on the gap's geometry and rise to 70%, for a gap length up to 10 cm, when the rod's diameter is 10 mm, (Figs. 2 and 3).

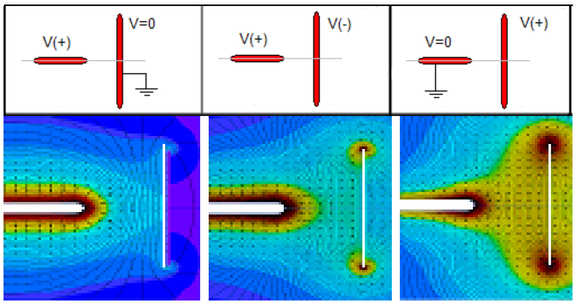


Plate-grounded. Symm. Charged Rod-grounded

Fig. 2 Field strength distribution in rod-plate air gap models for the different arrangements from simulation analysis. The effect of grounding is obvious. The value of the applied voltage is 1V for each of the three cases.

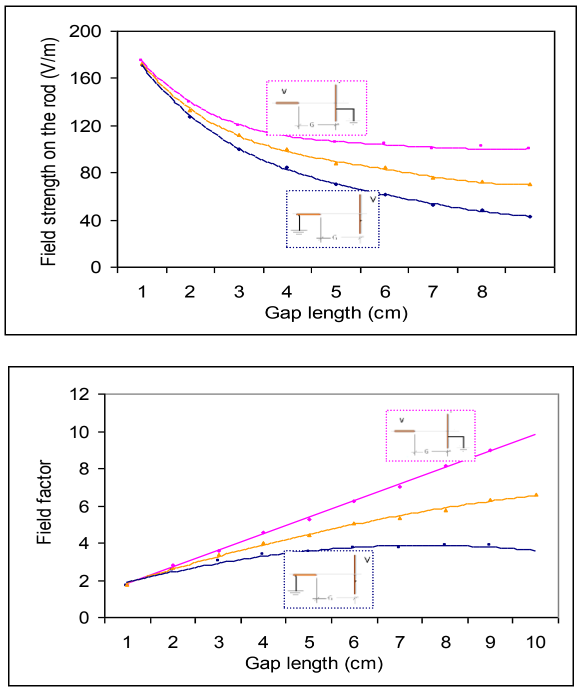


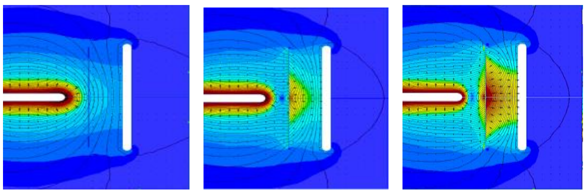
Fig. 3 The value of the field strength on the rod and the field factor along the axis of rod-plate air gaps, for the different arrangements with the rod (r-gr), or the plate grounded (pl-gr), either with symmetrically charged electrodes (symm.). The plate's diameter is 100 mm, and the rod's is 10 mm.

The curve of the values of the field strength as a function of the gap length seems to end asymptotically at the horizontal. The minimum value of the field strength on the rod appears when the gap length is big enough (>10 cm), for every grounding and charging condition of the arrangement, while the field factor seems to reach a maximum value only for the arrangement with the rod grounded, when the gap length is approximately 7 cm.

The influence of the grounded shield is negligible when the shield radius is more than 80 times bigger than the gap length (Fig. 4), and decreases when the diameter of the plate increases. The diameter of the rod used in the model is 10 mm, and the simulation voltage 1 V.

B. Rod – Plate Air Gaps with Barrier Stressed by DC Voltage

The barrier effect is well known to influence the breakdown voltage of the air gaps [3]. The models that were analyzed in the present paper were similar to the theoretical and experimental models. The results of the analysis revealed images of the field distribution in rod-plate gaps with barrier, stressed with voltage equal to or lower than the rod's voltage, or without additional charge. These results are shown in Figs. 5 and 6 for rod-plate gaps with either one of the electrodes grounded and with a barrier placed between them, perpendicular to the axis of the gap, and for different values of the voltage at the center of the barrier. It is clearly shown that the voltage on the barrier's surface influences the field distribution in the gap. The electric field becomes less inhomogeneous, and the charge accumulated on the surface of the barrier becomes a wall to the movement of the corona charges. The effect of grounding, influences the electric field distribution in the gaps with a barrier (Fig. 6), and hence their dielectric behavior.



$V_b=0$ $V_b=V_r/2$ $V_b=V_r$

Fig. 4 (5) The field strength distribution in rod plate gaps with the plate grounded and a barrier, for three different values of the voltage on the surface of the barrier. V_b is the voltage on the surface of the barrier (center) and V_r is the voltage of the rod. Vr=1 V, [17].

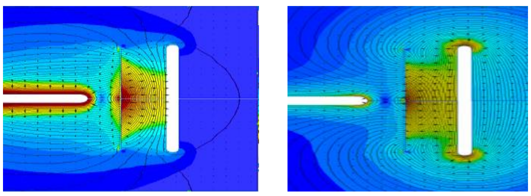


Plate grounded Rod grounded

Fig. 5 (6) The field strength distribution in a rod-plate gap with a barrier in comparison for the two different arrangements with the rod or the plate

IV. THE EXPERIMENTAL RESULTS

The influence of the ground effect and the polarity effect on the values of the corona onset voltage and the breakdown voltage, as well as on the Corona current were experimentally investigated for rod-plate gaps with or without barrier when stressed by dc or impulse voltages. The experimental arrangements were rod-plate air gaps with a rod diameter from 2 to 12 mm, and a plate diameter from 50 to 150 mm. The electrodes were made of brass, and the barrier was a plate made of prespan paper, 0.3 mm thick.

A. Rod – Plate Air Gaps without Barrier Stressed by DC Voltage

It is known that corona is ahead of breakdown, which follows. In relatively small gaps though (<3 cm), breakdown is possible to occur without the appearance of detectable corona effects, [4]. This in general happens when the field is less inhomogeneous, meaning small gaps, when the rod's diameter is relatively big (>8 mm) and especially in rod-plate gaps with the rod grounded, stressed by dc (-).

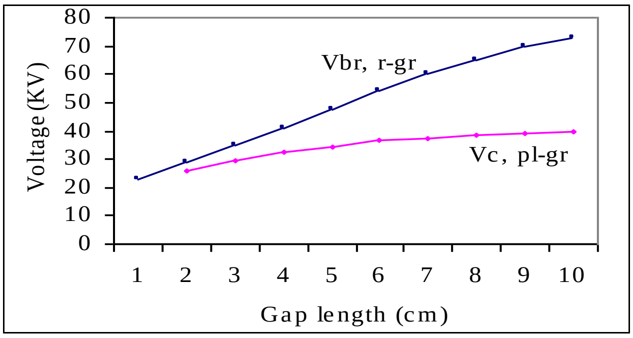


Fig. 6 The effect of grounding on the corona onset and the breakdown voltage of rod-plate air gaps 10-100 mm, stressed by dc negative voltage.

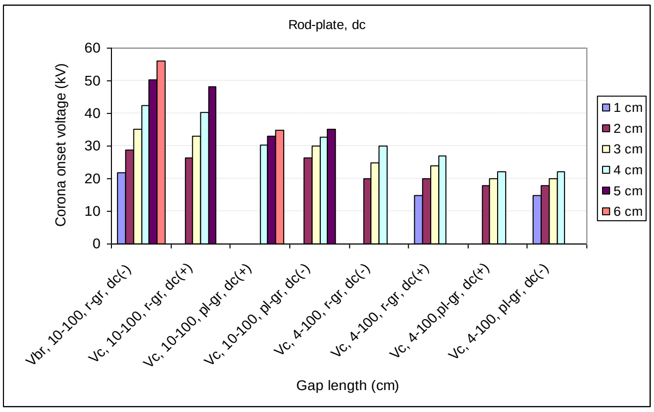


Fig. 7 The Corona onset voltage of rod-plate air gaps stressed by dc voltage, in combination with the ground effect.

In rod-plate air gaps with a rod's diameter of 10 mm and plate's diameter of 100 mm (10-100) with the rod grounded there are no corona effects before breakdown, and thus the breakdown voltage is taken into consideration, instead of the Corona onset voltage. In Fig. 6 the values of the corona onset voltage of the 10-100 mm arrangements with the plate grounded (pl-gr) are compared to the breakdown voltage of the arrangements with the rod grounded (r-gr). The influence of the ground effect is obvious; the breakdown voltage of the arrangements with the rod grounded is higher than the corona onset voltage of the air gaps with the plate grounded.

In air gaps stressed by dc voltages, Corona effects appear in the form of electrical pulses of significant value (up to some mA) and very small duration (a few ns) with high repetition frequency (every few μs or ms). The phenomenon is detected by dc electric current, which represents the average value of the Corona pulses, as well as by the Corona sound (squeak), or the Corona light and ultraviolet radiation. The frequency of the Corona sound depends on the air gap arrangement and the polarity and the value of the applied voltage. In the present experimental work, it was observed that in some cases there is no Corona sound, and it is resulted that this happens because the frequency of the Corona pulses belongs in the region of the ultrasonic sounds frequency.

The influence of the ground effect in connection with the gap's geometry on the Corona onset voltage is shown in Fig. 7. It is obvious that the Corona onset voltage is lower in the pl-gr arrangements with the smaller rod's diameter where the maximum value of the field strength is higher and the field is more inhomogeneous, while it is higher in the r-gr arrangements where the field is less inhomogeneous. It can be concluded that the Corona onset voltage is maximized when the rod is grounded for both voltage polarities, while it is minimized when the plate is grounded, and the rod's diameter is smaller, for both polarities as well.

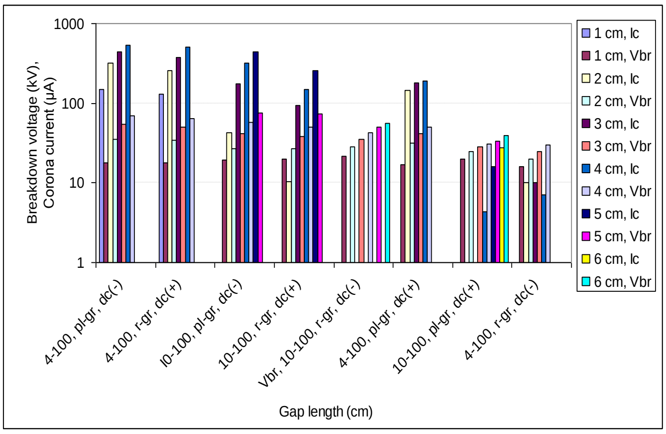


Fig. 8 The breakdown voltage of rod-plate air gaps stressed by dc voltage, in combination with the ground effect and the corona current effect.

Fig. 8 shows the values of the breakdown voltage of rod plate arrangements in combination with the ground effect and the polarity effect. It is resulted that the values of the breakdown voltage are higher in the arrangements with the negative and thinner rod, *r(-)*, and maximum in the arrangements with the plate grounded when stressed by dc(-), in which the Corona current is also maximum. Minimum values of the breakdown voltage appear in the gaps with the rod grounded when stressed by dc(-), that is in the arrangements with the minimum Corona current. The breakdown voltage is maximized in the arrangements with the plate grounded, stressed by dc(-) and minimized in the arrangements with the rod grounded and dc(-). The differences depend on the corona current in combination with the ground effect, the polarity effect and the gap's geometry (rod's diameter).

It is also resulted from Fig. 8 that the maximum values of the Corona current are observed in the air gaps with smaller rod's diameter and the plate grounded, and are minimized in small air gaps (<2 cm) with the rod grounded, while there are negligible Corona effects before breakdown when the rod with diameter of 10 mm is grounded.

The results for the rod-plate air gaps without barrier are presented in [8, 9]. It has been resulted that the minimum values of the Corona onset voltage and maximum values of the Corona current and breakdown voltage occur in air gaps with a thinner negative rod when the plate is grounded (pl-gr), (Fig. 7).

B. *Rod – Plate Air Gaps with Barrier Stressed by DC Voltage*

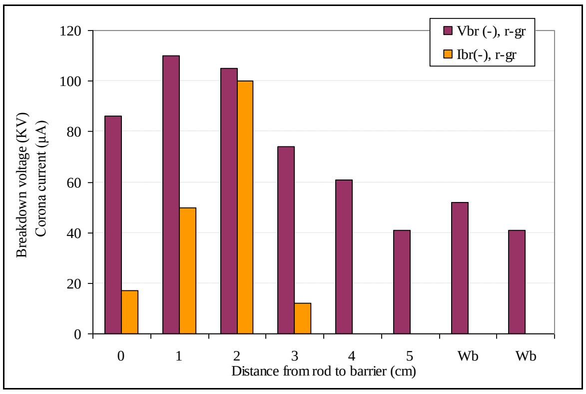
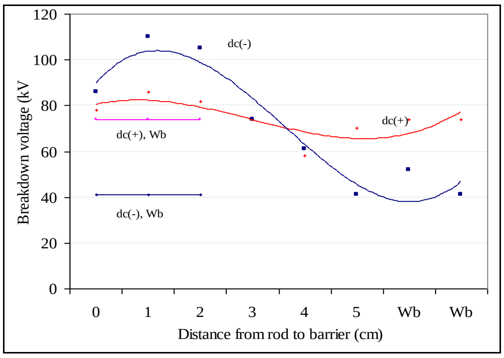
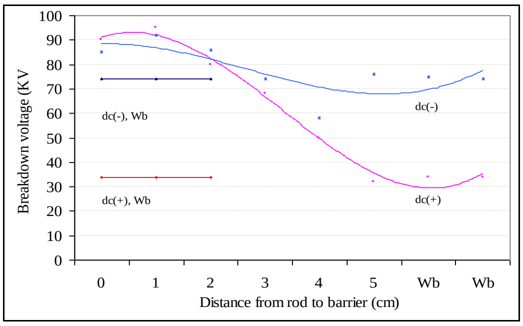


Fig. 9 The values of the breakdown voltage and the Corona current of rod-plate air gaps, 10-100 mm, 5 cm long, with a barrier, in comparison to air gaps without barrier (Wb). Applied voltage dc (-).



a) Arrangements with the rod grounded



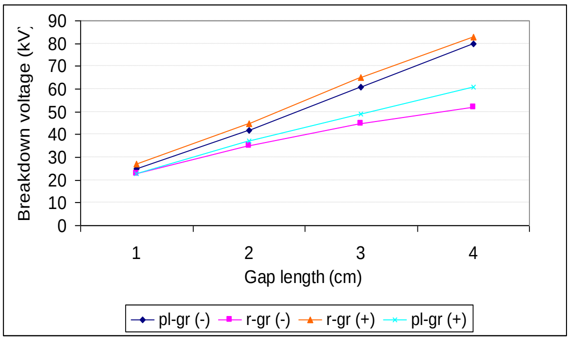
b) Arrangements with the plate grounded

Fig. 10 The values of the breakdown voltage of rod-plate air gaps, 10-100 mm, 5 cm long, with a barrier, in comparison to air gaps without barrier (Wb). Applied voltage is dc (-).

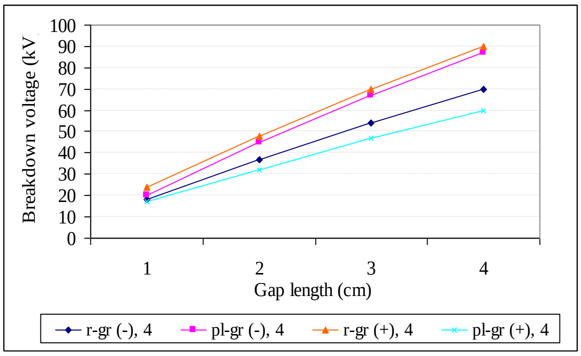
It is well known that the barrier effect influences the value of the breakdown voltage of air gaps [5-9]. It is resulted from the experimental work of the present research project that the barrier effect, in connection to the ground effect, influences greatly the values of the Corona onset and breakdown voltage and the Corona current as well, as it is shown in Figs. 9 and 10, in comparison to the values of the gaps without barrier (WB). It is obvious that the Breakdown voltage maximizes when the barrier is placed near the grounded rod. The Corona onset voltage is lower in the gaps with the barrier near the grounded electrode (rod or plate), but in the same time the Corona current is very lower and becomes negligible when the barrier is in specific positions, (Fig. 9). All the above results are also influenced by the geometry of the gap (gap length and electrodes dimensions).

B. Rod – Plate Air Gaps Stressed by Impulse Voltage

When the rod-plate air gaps are stressed by lightning impulse voltages the results are different from the results recorded with dc voltage [10]-[11]. The Corona effects appear in a form of one or rarely two partial discharge pulses of very short duration that occur before breakdown, and they greatly influence the values of the V50% of the breakdown voltage of the gap.



(a) The diameter of the rod is 10 mm and of the plate 100 mm



(b) The diameter of the rod is 4 mm and of the plate 100 mm

Fig. 11 The values of the breakdown voltage (V50%) of air gaps stressed by impulse voltage 1,2/50 μs in combination with the ground effect and the polarity effect.

From the comparison of Fig. 11 with Fig. 6 it can be concluded that the *V50%* values of the breakdown voltage of small air gaps are relatively higher than the breakdown voltage of the gaps stressed by dc voltage. Higher values of breakdown voltage appear in the arrangements with the rod grounded stressed by positive impulse voltage, or the plate grounded stressed by negative voltage (arrangements with negative rod), while lower values appear in the rod grounded gaps stressed by negative voltage, or the plate grounded stressed by positive voltage (arrangements with positive rod).

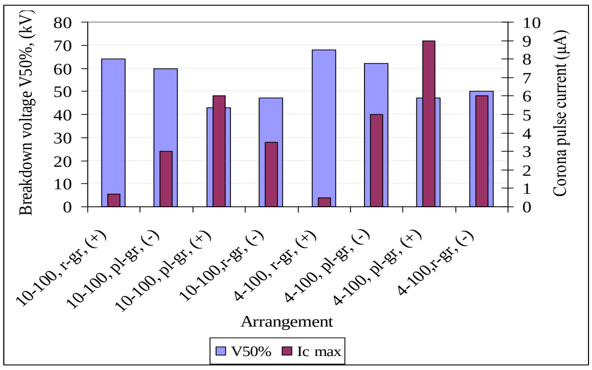
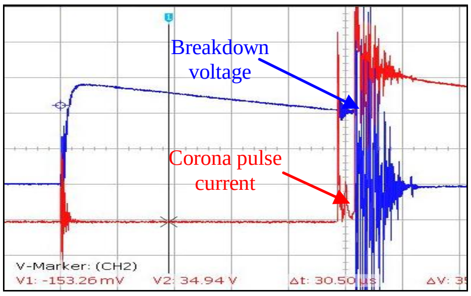
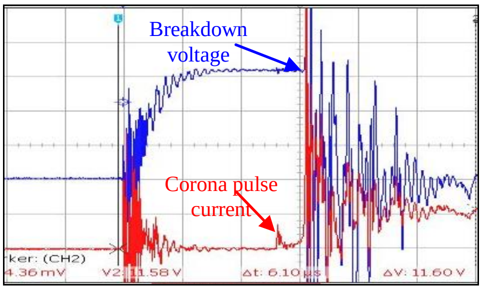


Fig. 12 The values of the breakdown voltage of air gaps 3 cm long stressed by impulse voltage 1,2/50 μs of both polarities, in comparison to the peak values of the Corona pulses occurred before breakdown.

These results are connected to the Corona effects (partial discharge pulses) as shown in the oscillograms of Figs. 13, 14, and 15. It is resulted that in the plate grounded arrangements, stressed by impulse (-), or in the rod grounded arrangements stressed by impulse (+), in which the rod is negative (*r* (-)), the magnitude of the corona pulses occurred before breakdown is higher and hence the value of the breakdown voltage is lower. In the rod grounded arrangements stressed by impulse (-), or in the plate grounded arrangements stressed by impulse (+), in which the rod is positive (*r* (+)), the corona pulses, when occurred before breakdown, are much smaller, and hence the value of the breakdown voltage is higher.



(a) Plate grounded air gap, large corona pulse.
20 kV/div, 0.8 A/div, 5μs/div



(b) Rod grounded air gap, very small corona pulse.
20 kV/div, 0.8 A/div, 1μs/div

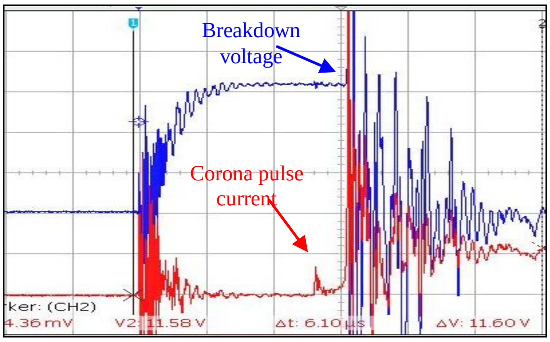
Fig. 13 Oscillogramms showing the breakdown positive impulse voltage and the Corona pulse occurring before breakdown for the 10-100 mm rod-plate air gaps, with a length of 3 cm.

The maximum values of breakdown impulse voltage occur in the plate grounded arrangement stressed by impulse (-), in which the minimum values of corona pulses are recorded, while the minimum values of the breakdown voltage occur in the plate grounded arrangements stressed by impulse (-) in which the maximum values of the corona pulses are recorded (Fig. 12). The differences depend on the intensity of the corona effects in combination with the ground effect and the gap's geometry and are bigger in the arrangements with the rod grounded, with smaller rod's diameter.

In the rod-grounded arrangements the field is less inhomogeneous and hence the values of the Corona onset voltage are higher the Corona pulses smaller and the breakdown voltage higher.

In the 4 -100 mm air gaps, the critical volume is smaller than in the 10-100 mm arrangements, and hence the values of the Corona onset voltage and the breakdown voltage are higher, but since the field is more inhomogeneous the Corona effects are more intense.

(a) Plate grounded air gap, large Corona pulse.
20 kV/div, 0.8 A/div, 2μs/div



(b) Rod grounded air gap, very small corona pulse.
20 kV/div, 0.8 A/div, 1μs/div

Fig. 14 Oscillogramms showing the breakdown positive impulse voltage and the Corona pulse occurring before breakdown for the 4-100 mm rod-plate air gaps, with a length of 3 cm.

V. PREDICTION

The average value of the field strength across the axis of a rod-plate air gap at corona onset or breakdown, given by equation (17), decreases as the gap length increases, the value also depending on the gap's geometry.

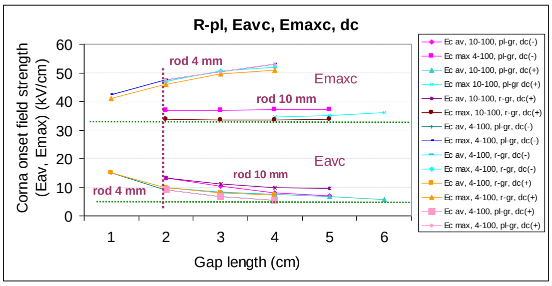
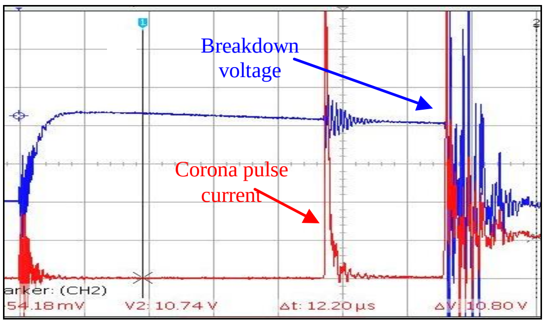
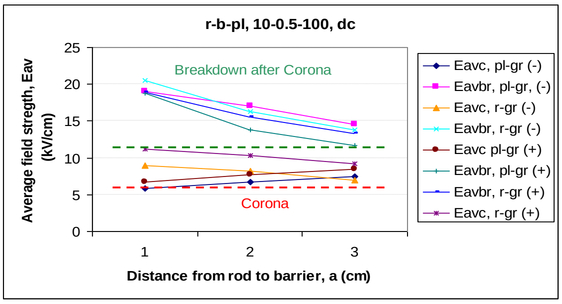


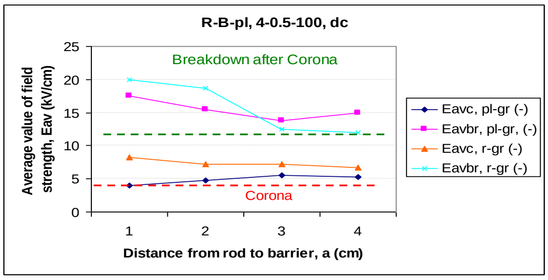
Fig. 15 The Maximum and average Corona onset field strength

From Fig. 16 it can be resulted and predicted that breakdown occurs without corona when the average value of the field strength across the gap is higher than a specific value Eav1>10 KV/cm. Otherwise, and under the circumstance that the maximum value of the field strength is higher than the appropriate value Ec, corona appears before breakdown. It can also be resulted that the breakdown occurs before corona when the gap's length is smaller than 2 cm, with the value also depending on the rod's diameter.





Rod 4 mm, plate 100 mm



Rod 10 mm, plate 100 mm

(a) Corona onset average value of the field strength in air gaps with a barrier.

Fig. 16 Corona onset field strength in gaps with a barrier

It can also be predicted that the minimum average value of field strength (Eav) across the gap without Corona is 4 kV/cm, and the minimum value of the Corona onset voltage (Ec) is 30 kV/cm. In the graphs of Fig. 9, two different areas can be clearly separated: the left area, in which breakdown is capable of occurring without corona, and the right area, where corona appears before breakdown.

It is resulted from Figure 16, and can be predicted that the Corona onset voltage starts when Eav is higher than 4 kV/cm, the exact value depending on the rod's diameter (inhomogeneity of the field), and the breakdown occurs when Eav>12 kV/cm. In the rod grounded arrangements and especially when the barrier is near the rod (a=1) the values are 10% to 100% higher, the differences depending on the position of the barrier.

The polarity of the applied voltage and the electrode chosen to be ground influence the results greatly.

VI. Conclusion

The dielectric behavior of an air gap stressed by dc voltage is characterized by less intense Corona effects when the electrode with the smaller dimensions is grounded (ground effect) and positively charged (polarity effect) in comparison to the other electrode. The insertion of an insulating paper sheet in a proper position between the electrodes maximizes the breakdown voltage (barrier effect) and minimizes the corona effects.

Simulation analysis with the FEM reveals that the ground effect and the barrier effect influence the electric field distribution in the air gaps. The field is less inhomogeneous in rod-grounded arrangements, and in the air gaps with a charged barrier.

Experimental results show that minimum values of the dc Corona onset voltage are recorded in the plate grounded air gaps without barrier, depending on the rod's diameter. Maximum values of dc breakdown voltage are recorded in the plate grounded air gaps without barrier, depending on the polarity of the applied voltage and the rod's diameter, and mainly on the intensity of the Corona effects occurring before breakdown. The larger the corona current is, the higher the breakdown voltage becomes.

In the air gaps with a barrier the values of the breakdown voltage are maximum in the rod grounded arrangements, stressed by dc (-), when the barrier is placed near the rod.

When lightning impulse voltage is applied on small air gaps without barrier, the results are different, due to the influence of the magnitude of the critical volume, in connection to the ground effect and the polarity effect. Maximum values of the Corona pulses and minimum values of the breakdown voltages are recorded in the plate grounded arrangements, when stressed by positive voltage (rod positive). On the contrary minimum values of the Corona pulses and maximum values of the breakdown voltages are recorded in the rod grounded arrangements when the plate is positively charged (rod negative). The differences are bigger in the rod grounded than in the plate grounded arrangements.

In the gaps without barrier breakdown occurs without corona when the average value of the field strength across the gap is higher than a specific value Eav>10 KV/cm, and the gap length is smaller than 2 cm. Otherwise Corona appears before breakdown, when Eav >4 kV/cm, and Emax>30 kV/cm.

In the gaps with a barrier Corona appears before breakdown when Eav>4 kV/cm and Emax> 22kV/cm while breakdown occurs after Corona when the average value of the field strength across the gap is higher than the specific value Eav>12 KV/cm.

The Corona current is relatively smaller in the air gaps with a barrier and significantly lower in the arrangements with the plate grounded.

VII. Acknowledgment

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