Optimization of Corona Onset and Breakdown Voltage of Small Air Gaps Stressed by DC and Impulse Voltages

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Abstract—The present paper aims to the investigation of the methods used to minimize or maximize the values of the Corona onset and Breakdown voltage in small rod-plate air gaps when stressed by dc or impulse voltages. The main factors which influence greatly the distribution of the electric field in the gap, and hence the above values are the geometry and the selection of grounding and charging of the electrodes, (ground effect), the gap length, the existence of barrier in the gap (barrier effect), and the Corona effects appearing prior to breakdown.

Combining theoretical, simulation and experimental work, it is resulted that: a) The electrode chosen to be ground, strongly influences the distribution of the field and the Corona effects and hence the values of the Corona onset and breakdown voltage. When the rod is grounded and the plate is negatively charged the value of Corona onset voltage is higher, the corona effects are less intense and dc breakdown voltage, without Corona, is higher. When the plate is grounded and the rod is negatively charged the value of the Corona onset voltage is lower, the corona effects are more intense and hence the dc breakdown voltage is higher. b) A dielectric barrier, when placed in specific positions in the gap, decreases the Corona effects and raises the breakdown dc voltage. c) In air gaps stressed by impulse voltages the results are very different. The corona onset and the breakdown voltage are maximum when the rod is grounded and positive leading to more intense Corona effects.

Keywords: air gap, Corona, breakdown, high voltage, field, FEM

I. INTRODUCTION

Air as an insulator is the most used in various arrangements and probably the best conventional solution for the majority of the high voltage applications. The air gap thus is considered as one of the most important parameters for the design and dimensioning of insulating arrangements, in almost every electrotechnical application.

In designing nearly every electrical arrangement, air gaps are essential components that arise necessarily in constructions (switches, gaps between power lines, or power lines and earth, gaps between electrical and electronic components in most devices, etc.).

In the last decades air gaps are necessary and operational components of modern constructions and devices, while their dielectric behavior is the basis of their operation, [1]-[2].

The basic effects which are referred to as the dielectric behavior of an air gap are the Corona effects and the breakdown voltage [1-2].

The equations that calculate the values of the corona onset field strength on the tip of a rod are taken from bibliography, such as the empirical equation [1],

\[ E_c = 30 \cdot \left[ 1 + \frac{0.3}{\sqrt{r}} \right] \] (kV/cm) for ac voltage, \hspace{1cm} (1)

as well as the empirical equation :

\[ E_c = 22.4 \cdot \left[ 1 + \frac{1}{\sqrt{r}} \right] \] (kV/cm) for dc voltage, \hspace{1cm} (2)

where \( E_c \) (kV/cm) is the corona onset field strength on the tip of a rod with radius \( r \), which is located separately and far from the grounded environment.
The above equations are not applicable for the inter-electrode air gaps, like the rod-plate gaps.

The most known effects which influence the values of the above mentioned magnitudes are the polarity effect, [1]-[3], and the barrier effect, [5]-[8].

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 of the gap chosen to be grounded on the field distribution and hence the dielectric behavior of a gap [8]-[9].

The Corona current effect, that is the influence of the Corona current on the value of the breakdown voltage of a gap when stressed by dc voltage, [10]-[11].

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 voltages. Especially in rod – plate air gaps the used so far technique of the experimental work concerns arrangements where the plate electrode is grounded and voltage is applied to the electrode of the rod, [1]-[6]. Arrangements symmetrically charged have been just lately investigated, as well as rod – plate air gaps with the rod grounded and the plate stressed by high dc or ac voltages, while a suggestion to be referred to as “the ground effect” has been proposed, [7]-[9].

It is well known that air gaps present a very different dielectric behavior when stressed by impulse voltages, due to the influence of the critical volume in the area of the rod electrode and the required time lag, [2].

Several methods for controlling the breakdown voltage have been proposed, [2]-[3]. In the present paper a new method is investigated based on the results given from the influence of grounding (ground effect) in connection to the barrier effect and the polarity effect either under dc voltages, or impulse voltages of both polarities.

There are no bibliographic references on the influence of the grounding on the rod-plate air gaps stressed by impulse voltages. This effect is investigated for the first time in the present paper.

The models used for the optimization of the dielectric behavior of air gaps, concerning the increase in the values of breakdown voltage combined with a variation of the Corona effects, are essential for every application using High Voltages. These models cover economic and safety issues and their use raises advantages since it helps avoid destruction of the insulated materials of the devices, or improves the operation of others.

II. THE PROCEDURE FOLLOWED

Mathematical models of the experimental arrangements have been designed, and the equation of initial conditions concerning the analysis of the electric field in the gaps, in connection to the ground and the barrier effect has been formulated and analyzed. Appropriate models have been designed and simulation analysis has been held, with the use of the Finite Element Method. The values of the voltage, the field strength in specific positions in the gaps, under different conditions, and in combination with the effects of grounding and barrier have been recorded and processed. All the analyzed models are axisymmetric, with a spherical boundary shield big enough in diameter.

Special software Quickfield, from Terra Analysis, Denmark, commercially available, has been used for the simulation analysis of the air gap models. It is based on the Finite Element Method with the use of Poisson’s equation:

\[ \nabla^2 V = -\rho \epsilon / \epsilon , \]

and the Dirichlet boundary conditions \( V = 0 \), where \( V (V) \) is the applied voltage, \( \rho (C/m^3) \) the space charge density, and \( \epsilon (F/m) \) the dielectric constant of the air or the gas used.

A. Rod – Plate Air Gaps Without Barrier

The initial conditions of a rod-plate air gap are given by the following equations (Fig. 2).

For the arrangements with the rod grounded, while the plate is stressed by 1 V (\( p = 0 \)):

\[ V(x, y) = 0, \text{ if } (x, y) \in R \cup \Gamma , \]

\[ V(x, y) = 1, \text{ if } (x, y) \in P \]

For the arrangements with the plate grounded, while the rod is stressed by 1 V (\( p = 0 \)):

\[ V(x, y) = 0, \text{ if } (x, y) \in P \cup \Gamma , \]

\[ V(x, y) = 1, \text{ if } (x, y) \in R , \]

where:

\[ \Gamma = (x, y) \in \mathbb{R}^2 : x^2 + y^2 = R^2 , \]

\[ R = \left\{ (x, y) \in \mathbb{R}^2 : -G/2 \leq x \leq r_p , -G/2 \leq y \leq r_p , \right\} \]

\[ P = \left\{ (x, y) \in \mathbb{R}^2 : G/2 \leq x \leq G/2 + b , -G/2 \leq y \leq G/2 \right\} \]

\[ V \text{ is the applied voltage, } G \text{ is the gap length, } r_p \text{ is the radius of the plate, } r_e \text{ is the radius of the rod, } R \text{ is the radius of the shield, } a \text{ is the length of the rod, and } b \text{ is the thickness of the plate.} \]

The significant differences between equations (4), (5) and (6), (7) lead to significant differences of the dielectric behavior between the two arrangements.

Fig. 1 Theoretical models of rod-plate air gaps
B. Rod-Plate Air Gaps with Barrier

In the 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 voltage develops on the surface of the barrier, resulting to the influence of the 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 $V_{b1}$, while the rod and the boundary shield are grounded, equations (4), (5) are valid, as well as equations:

$$V(x,y) = V_{a0} + \left\{ \begin{array}{ll}
K_1 & \text{if } (x,y) \in S, \\
0 & \text{if } (x,y) \notin S
\end{array} \right. \tag{11}$$

$$V_{a0} \geq V_{b1} \geq 0 \tag{12}$$

$$V(x,y) = V_{a0} + \left\{ \begin{array}{ll}
K_2 & \text{if } (x,y) \in S, \\
0 & \text{if } (x,y) \notin S
\end{array} \right. \tag{13}$$

$$V_{a0} \geq V_{b2} \geq 0. \tag{14}$$

b) For the arrangements in which the plate’s voltage is $V_{pl}$, the rod is stressed equations (6), (7) are valid, in combination with equations:

$$V(x,y) = V_{b1}(1-\frac{1}{G})K_3, \text{if } (x,y) \in S \tag{15}$$

and (when the barrier is near the rod) $V_{b1} \leq 1$, (16) where:

$$S = \left\{ (x,y) \in \mathbb{R}^2 : x = -\frac{G}{2} + a, \right. \left. 0 \leq y \leq r_b \right\}, \tag{17}$$

$$0 \leq V_{b1} \leq V \quad K_3 = \frac{V_{b1} - V_{b2}}{V_{a0} - V_{b1}} \quad K = \frac{V_{b0} - V_{b1}}{V_{a0} - V_{b0}} \tag{18}$$

where $a$ 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). There are significant differences between equations (4), (5), (11), (12) and (6), (7), (13), (14), because of the ground effect.

### III. THE INVESTIGATION ARRANGEMENTS

The arrangements, which have been modeled, analyzed, and experimentally studied, are typical rod-plate air gap arrangements of different electrode geometry and gap length. The rod electrode is a hemispherical capped long cylinder with a relatively small diameter (4-10 mm), and the plate electrode is a disk of 100 mm in diameter, both made of brass. 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 rate of dc voltage rise is approximately 2 kV/s.

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. All the analyzed models are axisymmetric with a spherical boundary shield big enough in diameter (at least 200 times bigger than the gap’s length) at earth potential.

The average value of the field strength, along the axis of an air gap is defined by equation:

$$E_{av} = \frac{V}{G} \tag{19}$$

The field factor (or efficiency factor) $n$ is a net number, which defines the inhomogeneity of the field in the gap and is expressed by equation:

$$n = \frac{E_{max}}{E_{av}} \tag{20}$$

For a sphere-sphere air gap the field factor is calculated from equation:

$$n = \left[ \frac{(G/D + 1) + [(G/D + 1)^2 + 8]^{0.5}}{4} \right] \quad \text{or} \quad n = G/(2D), \quad G > D, \quad \text{if} \quad G > D \tag{21}$$

where $V$ is the applied voltage, $G$ is the gap length, $E_{max}$ is the maximum value of the field strength (on the rod), $E_{av}$ is the average value of the field strength along the axis of the gap, and $D$ is the diameter of the sphere.

The values of the field strength at corona onset are affected by the polarity of the applied voltage (polarity effect), [1], [10].

The corona onset voltage, the corona current and the breakdown voltage of the correspondent experimental horizontal arrangements have been measured. The results show the influence of the grounding on the corona current, the corona onset and the breakdown voltage of small air gaps. The maximum and minimum values have been recorded.

### 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).

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 [6]. The models that were analyzed in the present paper were similar to the 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 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.
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, [9]. 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. 7 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.](image)

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. 7 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 Ampere) and very small duration (a few ns) with high repetition frequency (every few μs). 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 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.

The influence of the ground effect in connection with the gap’s geometry on the Corona onset voltage is shown in Fig. 8. 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 Corona onset voltage of rod-plate air gaps stressed by dc voltage, in combination with the ground effect and the Corona current effect.](image)

Fig. 9 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.

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

![Graph](image1)

Fig. 10 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 (-).

The barrier effect influences the value of the breakdown voltage of air gaps [5-9]. This is common mostly for average and big rod plate grounded, and rod-rod gaps. For the arrangements though of rod-plate gaps where the rod is grounded and the plate is stressed with high voltage, leading to a less inhomogeneous field, the barrier effect hasn’t been investigated and as appears from the present paper the results of its influence on the breakdown voltage of the gap are different compared to the ones from the arrangement with the plate grounded, (Fig. 12), creating phenomena that maximize or minimize the Corona onset voltage and the corona current.

The values of the corona current in rod-plate gaps with rod’s diameter of 10 mm and plate’s diameter of 100 mm respectively with or without barrier were recorded and the results are shown in the curves of Fig. 10.

It is resulted from Figs. 10 and 11 that the breakdown voltage is higher in the arrangements with a barrier and the rod grounded, with the differences depending on the diameter and the polarity of the rod, as well as the distance between the rod and the barrier. Maximum values of the breakdown voltage appear when the rod is grounded and the barrier is near the rod.

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 [13]-[14]. 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.

![Graph](image2)

Fig. 11 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 (-).

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![Graph](image3)

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

Fig. 12 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.
Breakdown voltage $V_{50\%}$, (kV)

<table>
<thead>
<tr>
<th>Arrangement</th>
<th>Breakdown voltage $V_{50%}$ (kV)</th>
<th>Corona pulse current ($\mu A$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10-100, r-gr, (+)</td>
<td>60</td>
<td>5</td>
</tr>
<tr>
<td>10-100, pl-gr, (-)</td>
<td>50</td>
<td>3</td>
</tr>
<tr>
<td>10-100, pl-gr, (+)</td>
<td>40</td>
<td>2</td>
</tr>
<tr>
<td>4-100, r-gr, (-)</td>
<td>30</td>
<td>1</td>
</tr>
<tr>
<td>4-100, pl-gr, (-)</td>
<td>20</td>
<td>0.5</td>
</tr>
</tbody>
</table>

From the comparison of Fig. 12 with Fig. 7 it can be concluded that the $V_{50\%}$ 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).

These results are connected to the Corona effects (partial discharge pulses) as shown in the oscillograms of Figs. 14, 15, and 16. 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.

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. 13). 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.
the rod grounded and a length of 3 cm. The Corona pulse occurring before breakdown for the rod-plate air gaps, with

Fig. 16 Oscillograms showing the breakdown negative impulse voltage and the rod-grounded arrangements when the plate is positively charged. Minimum values of the Corona pulses and maximum voltage are recorded in the plate grounded arrangements, with or 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 rod grounded arrangements, 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. The values of the Corona onset voltage, the corona pulse current, and the breakdown voltage are relatively higher in the arrangements with smaller rod’s diameter.

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