Abstract. A new approach of the Polarity Effect in connection to the Corona Current and the Ground Effect in small rod-plate and rod-rod air gaps is presented. The influence of the polarity of the applied voltage to the corona onset voltage or the breakdown voltage of small rod-plate and rod-rod air gaps is investigated. The influence of the grounding of one of the electrodes, to the field distribution, and consequently to the corona onset and the breakdown voltage of small air gaps, is also investigated by simulation analysis along with experimental work. This phenomenon is the Ground Effect, and is quite different from the Polarity Effect, though slightly influenced by it. The inhomogeneity of the electric field and the maximum values of the field strength in a rod-plate and rod-rod air gap are analogically higher when the plate is grounded and lower when the electrodes are symmetrically charged, or the rod is grounded. The values of the corona onset and the breakdown voltage in small air gaps are analogically lower for the arrangement with the plate grounded. Correspondent relations are valid for the rod-rod arrangements. In longer air gaps the corona current appears, the Polarity Effect becomes very intense and the Ground Effect is overlapped. Relations between the values of the breakdown voltage, the polarity of the applied voltage, the corona current through the gap and the way the gap is grounded are established. The principle of action-reaction is valid. “The corona current reacts against the action of the field to produce corona charges and makes the field less inhomogeneous”.

1 INTRODUCTION

The air gaps are very important insulating arrangements for high voltage applications (power lines, electrostatic filters, electrostatic painting, etc.). The mostly used air gaps are the sphere-sphere, the rod-rod (or point-point), and the rod-plate (or the point-plate) air gaps with one electrode grounded. In the rod-plate air gaps the plate is usually grounded [1] - [9].

The most determinant factor for the dielectric behavior and especially for the dielectric strength of an air gap is the inhomogeneity of the electric field, and especially the maximum value of the field strength in the gap, which usually appears on the sharper edge of the electrodes, mostly on the tip of a rod. Other factors are the polarity and the form of the applied voltage as well as the corona effects, which take place when the field strength exceeds some specific value [4] - [12].

In less homogenous electric fields like the small air gaps with relatively big diameters of the electrodes, the corona effects do not appear before breakdown. The values of the breakdown voltage depend on the grade of the field’s inhomogeneity, and especially on the maximum value of the field strength. The more inhomogeneous the field is the lower the breakdown voltage becomes, [19], [20].

In longer air gaps the field is more inhomogeneous and corona effects and hence a corona current through the gap occur before the breakdown. The intensity of the corona effects depends on the grade of the field’s inhomogeneity, and especially on the maximum value of the field strength. The more inhomogeneous the field is the lower the Corona Onset Voltage becomes. The Corona Current influences the breakdown voltage positively, [16]-[18].

The inhomogeneity of the electric field in the air gaps depends mainly on the dimensions of the electrodes and the length of the gap. An important factor that influences the inhomogeneity of the electric field in the air gaps is the grounding of one of the electrodes. In the rod-plate air gap also important is the electrode that is chosen to be grounded, [16]-[19].

In most applications the air gaps are used with one electrode stressed by high voltage, while the other is grounded (at earth potential). Particularly the rod-plate arrangements are usually connected with the plate grounded [3]-[12]. In such geometry, a different distribution of the electric field and different maximum values
of the field strength are observed in comparison to the arrangement where both electrodes are electrically charged with opposite charges [15]-[18]. This phenomenon is the Ground Effect and is quite different from the Polarity Effect, although it is affected by it.

The Polarity Effect is known as the phenomenon that influences the dielectric behavior of relatively longer rod-plate air gaps with the plate grounded, when the polarity of the applied DC voltage is changed. According to the Polarity Effect the values of the breakdown voltage of the gaps are analogically higher when the polarity of the applied DC voltage is negative.

The corona effects are more intense and the corona current through the gap is also analogically higher when the polarity of the voltage is negative.

Generally the corona current and the breakdown voltage of longer rod-plate air gaps are analogically higher when the polarity of the rod’s voltage is negative in comparison to the plate’s polarity [18], [19].

In this paper the influence of the grounding of one of the electrodes (the Ground Effect), as well as of the corona charges to the field distribution and the maximum values of the field strength in rod-plate and rod-rod air gaps, is investigated by simulation analysis using the Finite Element Method. The influence of the Ground Effect to the Corona Onset, the Corona Current, and the Breakdown voltage of small rod-plate and rod-rod air gaps stressed by DC or impulse voltage is experimentally investigated. A connection between the breakdown voltage and the Corona Current, as well as the Polarity Effect and the Corona Current in longer air gaps is established, and a new principle of action-reaction is formulated.

Special software has been used in the present paper for the simulation analysis of the air gap models. It is based on the Finite Element Method with the use of Poisson’s equation \( \nabla^2 V = 0 \) and the Dirichlet boundary conditions \( V = 0 \), in order to solve two-dimensional problems of axisymmetric models.

### 2 THE INVESTIGATED MODELS AND ARRANGEMENTS

The arrangements, which have been modeled, analyzed, and experimentally studied, are typical rod-rod and rod-plate air gaps of different electrode geometry and of 1 to 10 cm in 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), or both electrodes are symmetrically charged with opposite and equal voltages. All the analyzed models are axisymmetric with a spherical boundary shield big enough in diameter at earth potential, “Figures 1, and 2”.

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

\[
E_{av} = \frac{V}{G}
\]

(1)

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:

\[
n = \frac{E_{max}}{E_{av}}
\]

(2)

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

\[
n = \left[ \left( \frac{G}{D} + 1 \right) + \left( \frac{G}{D} + 1 \right)^2 + 8 \right]^{0.5} / 4,
\]

(3)

or

\[
n = \frac{G}{2D}, \quad \text{if} \quad G \gg D,
\]

and for a rod-plate air gap, with a very big plate, the field factor is given by:

\[
n = \frac{2G}{r \cdot \ln(G/r)}, \quad \text{if} \quad G \gg r,
\]

(4)

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, \( D \) is the diameter of the sphere, and \( r \) is the radius of the rod’s tip.
3 THE GROUND EFFECT

Air gap arrangements, with one electrode grounded or not, with different dimensions of the plate and the rod, and different gap lengths have been modeled, analyzed, and experimentally investigated. From the comparison between the different arrangements with one electrode grounded, or with symmetrical charging of the electrodes, it is resulted that there are big differences in the field distribution in the air gaps of the three different arrangements. These differences are due to the Ground Effect, which is quite different from the Polarity Effect, and is valid for both polarities of DC voltage, as well as for AC and impulse voltages.

3.1 The rod-plate air gaps

The rod electrode is a cylinder long enough, with a relatively small diameter (2-14 mm) and a hemisphere tip, and the plate electrode is a disk plate of more than 100 mm in diameter (Figure 1).

3.1.1 The simulation results

The distribution of the electric field in a rod-plate air gap is different for the three different arrangements the one with the plate grounded (Pl-gr), the other with symmetrical charging of the electrodes (symm), and the third with the rod grounded (R-gr). The field is less inhomogeneous when the rod is grounded “Figure 2”.

The maximum value of the field strength in the gap (the value of the field strength at the tip of the rod) and the value of the field factor “(2)”, decrease analogically with the gap length. They are analogically bigger in the arrangement with the plate grounded (Pl-gr) and turn much bigger as the length of the gap increases, “Figure 3”. The rod’s diameter of the model is 10 mm, the plate’s 100 mm, and the applied voltage 1V.

![Figure 2. The field strength distribution of the electric field in a rod-plate air gap.](image)

![Figure 3. The values of the field strength and the field factor of rod-plate air gaps, in function to the gap length.](image)

(a) The maximum value of the field strength on the rod.
(b) The field factor along the axis of the gap.

When the plate’s diameter is big enough the differences of the values of the field strength on the rod for the three different arrangements are smaller and tend to minimize, “Figure 4”.

3.1.2 The experimental results for the Corona Onset and the Breakdown voltage.

The values of the corona onset voltage in rod-plate air gaps are higher for the arrangement with the rod grounded (R-gr), as expected, and shown in “Figure 4”.

In small rod-plate air gaps with less inhomogeneous electric field there are no corona effects before breakdown. The values of the breakdown voltage of these air gaps are higher for the arrangements with the rod grounded, as shown in “Figures 4 and 5”. It is also easy resulted that the Ground Effect is quite different from the Polarity effect, since it is observed when the rod is negatively charged in comparison to the plate.
(a) Stressed by negative DC voltage

(b) Having the same polarity (+) or (-) on the rod, in comparison to the plate.

Figure 4. The influence of the Ground Effect to the corona onset \( V_c \) and the breakdown \( V_{br} \) voltage of rod-plate air gaps for the different arrangements of grounding and charging.

(a) Negative Impulse voltage 1,2/50 \( \mu \)s.  
(b) Positive and Negative Impulse voltage 1,2/50 \( \mu \)s

Figure 5. The influence of the Ground effect to the breakdown impulse voltage 1,2/50 \( \mu \)s. Rod-plate, 10-100 mm

3.1.3 The experimental results for the DC Corona Current.

The Values of the Corona current through the rod-plate air gap is greatly influenced by the Ground Effect, as it is shown in Figure 6. It is higher when the plate is grounded and lower when the rod is grounded, as it is expected according to the analysis results. The graphs in Figure 6 are for DC voltage of either positive or negative polarity. But in both graphs of the same figure the rod has the same Polarity positive or negative in comparison to the plate.
The Ground effect is also valid for AC voltages in rod-plate air gaps, as concerns the Corona Onset Voltage, the Breakdown voltage and the Corona Current

3.2 The rod-rod air gaps

The electrodes are cylinders long enough, with a relatively small diameter (2-14 mm) and hemisphere tips (Figure 1).

3.2.1 The simulation Results

The distribution of the electric field in a rod-rod air gap is different for the two different arrangements, the one with one rod grounded (R-gr) and the other with symmetrical charging of the electrodes (symm). The field is more inhomogeneous when one rod is grounded “Figure 7(a)”. The maximum value of the field strength in the gap (the value at the tip of the stressed rod) increases with the gap length while the field factor, “(2)”, decreases. They are analogically bigger in the arrangement with one rod grounded (R-gr) and turn much bigger as the length of the gap increases, “Figure 7(b)”. The rod’s diameter of the model is 10 mm, and the applied voltage is 2 V.

3.2.2 The experimental results for the Corona Onset and the Breakdown Voltage.

The values of the corona onset voltage are lower for the arrangement with one rod grounded (R-gr), as expected from “Figure 7”, and shown in “Figure 8”. In small rod-rod air gaps with less inhomogeneous electric field the values of the breakdown voltage are lower for the arrangements with one rod grounded, as shown in “Figure 8”. The rod’s diameter is 10 mm.

The values of the Corona Onset field strength on the stressed rod are almost the same for the two different arrangements, as expected.
4 THE INFLUENCE OF THE CORONA CURRENT TO THE FIELD DISTRIBUTION AND TO THE GROUND EFFECT

In longer air gaps, where the corona effects appear before breakdown, small corona current flows through the gap. The current increases with the magnitude of the voltage, and differentiates the distribution of the field in the gap. It reacts and makes the electric field less inhomogeneous.

(a) No space charges. (b) With Corona charges.

The Field strength distribution in the gap

The value of the Field strength on the rod

Figure 9. The influence of the corona charges to the Field strength distribution in a rod-plate air gap model.

The analyzed model in “Figure 9” is a rod-plate arrangement of 6 cm in length, with a rod’s diameter of 10 mm and a plate’s diameter of 100 mm. The plate is grounded; the negative DC breakdown voltage is 90 KV, and the Corona charges correspond to a current of 440 μA. It can easily be observed that the field is less inhomogeneous when the corona charges appear in the gap. The maximum value of the field strength in the gap is much lower when space charges are taken into account during the analysis, “Figure 9”.

The principle of action-reaction (Newton’s third law, law of inertia, Lenz’s law) is evident in this case. We can define the following statement: “The inhomogeneity of the field produces the Corona Effects, and the Corona charges tending to oppose to the reason that causes them try to make the field less inhomogenous, decreasing the maximum value of the field strength”.

(a) The rod is negative in comparison to the plate
(b) The applied voltage is negative

Figure 10. The influence of the Corona current to the Ground Effect. The applied voltage is DC; the rod’s diameter is 10 mm, and the plate’s 100 mm.

When the gap length is long enough and the corona effects are intense, the influence of the corona current suppresses the Ground Effect, and the breakdown voltage becomes higher in the arrangement with the plate
grounded, “Figure 10”.

The Corona current through the gap influences the values of the breakdown voltage, which increase analogically. The bigger the corona current is the higher the value of the breakdown voltage becomes, as it is resulted from “Figure 10”.

The corona effects and their influence to the air gap’s dielectric behavior are stronger when the rod is stressed by DC negative voltage or when its diameter is very small.

In these longer air gaps the Corona Current influences and overlaps the Ground Effect resulting the breakdown voltage to be higher in the arrangement with the plate grounded, instead of the arrangement with the rod grounded. A correspondent relation between the breakdown voltage and the Corona Current seems to be valid, according to the equation (9).

\[ V_{\text{br}_{\text{pl}} - \text{gr}} - V_{\text{br}_{\text{r}} - \text{gr}} = B \left( I_{\text{br}_{\text{pl}} - \text{gr}} - I_{\text{br}_{\text{r}} - \text{gr}} \right) \]  

(9)

where \( B = f (d_r, d_{pl}, G) \) is a function parameter of the rod’s \( d_r \) and plate’s \( d_{pl} \) diameter, and the gap’s length \( G \).

5 THE POLARITY EFFECT AND THE CORONA CURRENT

In the rod-plate air gaps with the plate grounded the corona current is bigger and the breakdown voltage higher when the polarity of the applied voltage is negative, “Figure 11”. This is the well-known Polarity Effect.

A relation between the values of the breakdown voltage \( (V_{\text{br}}) \) and the corona current through the gap \( (I_{\text{br}}) \), exactly before breakdown, arises. The equation (model) that can describe this relation is:

\[ V_{\text{br} - \text{r}} - V_{\text{br} - \text{+}} = A \left( I_{\text{br} - \text{r}} - I_{\text{br} - \text{+}} \right) \]  

(10)

where \( A = f (d_r, d_{pl}, G) \) is a function parameter, a little different (bigger) from the parameter \( B \) of equation (9), mainly because of the Ground Effect. In “Figure 11(b)” the parameter \( A=\Delta V/\Delta I \) seems to be linear in function to the gap length, where \( \Delta V = V_{\text{br} - \text{r}} - V_{\text{br} - \text{+}} \), and \( \Delta I = I_{\text{br} - \text{r}} - I_{\text{br} - \text{+}} \).

The rod’s diameter is 10 mm and the plate’s diameter 100 mm, in the simulation and experimental models.

In small air gaps, where the electric field is less inhomogeneous the breakdown may take place before the corona effects appear. In these cases the Ground Effect influences the breakdown voltage, which does not depend on the polarity of the voltage applied on the rod “Figure 4”. This happens due to the absence of corona current through the gap. When the gap becomes longer the corona current in the arrangement with the plate grounded takes considerable values and the breakdown voltage for this arrangement becomes higher.

6 CONCLUSIONS

1) The inhomogeneity of the electric field and the maximum value of the field strength in rod-plate and rod-rod air gaps are strongly affected by the geometry of the electrodes, the length of the gap, and the corona charges.

2) There are significant differences, as far as the electric field distribution, the Corona Onset and the Breakdown Voltage of the air gap arrangements is concerned, between the different arrangements, with one electrode grounded or with symmetrical charging of the electrodes (Ground Effect).

3) There is a connection between the breakdown voltage and the corona current through the gap just before breakdown. An equation model can describe this connection.
4) The Polarity of the applied voltage produces small differences to the values of the corona onset voltage. In less homogenous fields as the electric field of a rod-plate air gap with the rod grounded, the breakdown appears before the corona effects for gap lengths less than 10 cm. In these cases the values of the breakdown voltage depend mainly on the gap’s geometry, as well as the way the gap is grounded and charged, since there are no corona effects.

5) The Polarity of the applied voltage influences the values of the breakdown voltage in longer air gaps (Polarity Effect). It is proved that the Polarity Effect is clearly connected to the corona current through the gap just before breakdown. The Corona Current is higher when the rod is negatively charged, and so is the value of the breakdown voltage. An equation model can describe this connection.

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