The influence of the Ground Effect to the corona leakage current in small air gaps

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Abstract: The Ground Effect is the phenomenon that occurs due to the different way an air gap is grounded while stressed by high voltage. This phenomenon influences the distribution of the field in the gap, the corona onset voltage and the breakdown voltage in small gaps. In longer air gaps, the Ground Effect influences the Corona Effects and consequently the values of the Corona Current through the gap. The corona leakage current is higher in a rod-plate air gap with the plate grounded, because in such an arrangement the electric field is more inhomogeneous. This is valid for both polarities of DC voltage and AC voltage as well. In a rod-rod air gap the values of the corona current appear differences between the two polarities of DC voltage. When the corona current becomes high enough it decreases the inhomogeneity of the field and influences the values of the breakdown voltage. 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"

Key Words: Corona Current, Ground Effect, Polarity Effect, FEM, Air Gaps, Breakdown.

1 Introduction

The air gaps are very important arrangements in modern electrical applications. They are used in ozone production and chip construction, in electrostatic filters, electrostatic painting, loudspeakers, etc. Consequently the dielectric behavior of these arrangements is of great importance.

The mostly used air gaps are the rod-plate (or the point-plate), and the rod-rod (or point-point) air gaps, [1] - [9].

The most determinant factor for the dielectric behavior and especially for the dielectric strength of an air gap is the inhomogeniety 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 [5] - [14].

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 in the field. The more inhomogeneous the field is the lower the breakdown voltage becomes, [15[, [16].

In longer air gaps the field is more inhomogeneous and corona effects and hence a Corona Current through the gap occur before breakdown. The intensity of the corona effects depends on the grade of the field's inhomogeneity. The more inhomogeneous the field is the higher the Corona Current becomes. The Corona Current influences the breakdown voltage positively, [16]-[19].

The inhomogeneity of the electric field in the air gaps depends mainly on the dimensions of the electrodes and the length of the gap.

Another 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 gaps it is also important which electrode is chosen to be grounded [16]-[20].

In most applications the air gaps are used with one electrode stressed by high voltage, while the other is grounded (at earth potential). 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 [16]-[20]. Especially in the rod-plate air gaps the differences are a lot bigger between the two different arrangements with the rod or the plate grounded. This phenomenon is the Ground Effect and is quite different from the Polarity Effect, although it is connected with it.

The Polarity Effect, the Corona Effects and the Corona Current through the gap are well known phenomena thoroughly studied, and their influence to the dielectric behavior of air gaps has been investigated for many applications.

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.

In the present paper we have analytically and experimentally investigated the influence of the grounding of one of the electrodes (Ground Effect), as well as the Polarity of the applied voltage (Polarity Effect), to the dielectric behavior and especially to the leakage corona current in rod-plate and rod-rod air gaps. We also investigated the influence of the Corona Current to the breakdown voltage of the air gaps.

Special software Quickfield from Terra Analysis 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 axisymetric models.

The program is based on Gauss's and Poisson's equations:

$$E = -\nabla V \qquad (1)$$

$$\nabla D = -\rho \qquad (2)$$

or

$$\nabla^2 V = -\frac{\rho}{\varepsilon} \qquad (3)$$

where E is the field strength, ρ is the space charge density in C/m^3, ε is the dielectric constant of the medium, V is the voltage, and $D=\varepsilon E$ is the dielectric displacement [1], [2].

The electric charge density, and the total electric charge on a particular surface S, or in the volume included in surface S, is calculated by equations [1], [2].

$$q = \Delta D_n, \quad \text{and} \quad Q = \int_s D_n \cdot d_s \qquad (4)$$

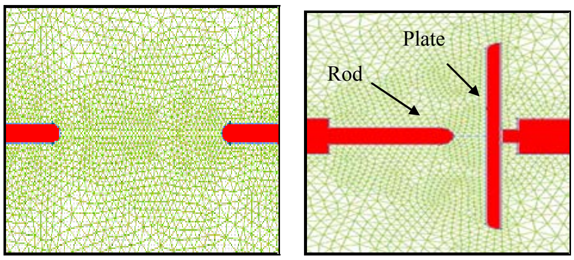
The boundary conditions and the mesh density used for the analysis are of great importance for accurate results.

2 The investigated arrangements.

The arrangements, which have been modeled, analyzed, and experimentally studied, are typical rod-plate air gap arrangements of different electrode geometries. The rod electrode is a cylinder long enough, with a small diameter (2-14 mm) and a hemisphere tip. The plate electrode is a disk plate of a 100 mm in diameter. High DC voltage of negative or positive polarity or AC voltage is applied to one electrode while the other is at earth potential (grounded). All the analyzed models are axisymetric, with a spherical boundary shield big enough in diameter, "figs 1 and 2".

(a) Rod-rod (b) Rod-plate

Fig. 1: The experimental arrangements.



(a) Rod-rod (b) Rod-plate

Fig. 2: The simulated models.

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

$$E_{av} = \frac{V}{G} \qquad (5)$$

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:

$$n = \frac{E_{max}}{E_{av}} \qquad (6)$$

For a rod-plate air gap the field factor is given by equation [1], [2]:

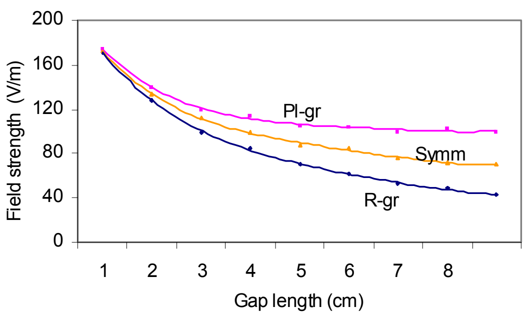
$$n = \frac{2G}{r \cdot \ln \frac{4G}{r}} \qquad \text{If } G>>r \qquad (7)$$

where V is the applied voltage, G is the gap length, Emax is the maximum value of the field strength (on the rod), Eav is the average value of the field strength along the axis of the gap, and r is the radius of the rod's tip. The plate's diameter is big enough.

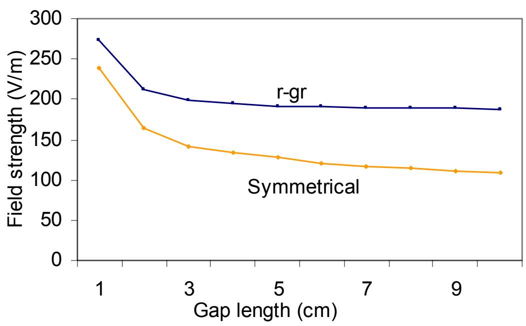
3 The influence of the Ground Effect to the dielectric behavior of small air gaps

The Ground Effect influences the field distribution and the maximum value of the field strength in the air gaps, as well as the values of the Corona Onset voltage, the Breakdown voltage and the corona current through the gap.

3.1 The influence to the field distribution



(a) Rod-plate



(b) Rod-rod

Fig. 3: Maximum values of the field strength on the rod, in rod – plate, and rod-rod air gaps, from simulation analysis.

Rod-plate arrangements, with one electrode grounded or not, with different dimensions of the plate and the rod, and different length of the gap have been modeled and analyzed. From the comparison between the different arrangements with the rod or the plate grounded, either with symmetrical charging of the electrodes, it is resulted that the Ground Effect causes big differences in the field distribution in the air gap of different arrangements.

The field distribution and the maximum value of the field strength (Er) in the gap for the three different arrangements with the rod grounded (r-gr), or the plate grounded (pl-gr), either with symmetrical charging of the electrodes (symm.) is shown in comparison in "figs 3 and 4". It is obvious that the Ground Effect is intense in rod-plate air gaps.

In all air gap arrangements (with the rod grounded, or the plate grounded, either with symmetrical charging of the electrodes) the maximum value of the field strength in the gap (field strength on the rod) depends on the gap length. It is higher in the arrangement with the plate grounded (pl-gr) and turns much higher as the length of the gap increases.

In rod-rod arrangements it is higher in the arrangement with one of the electrodes grounded.

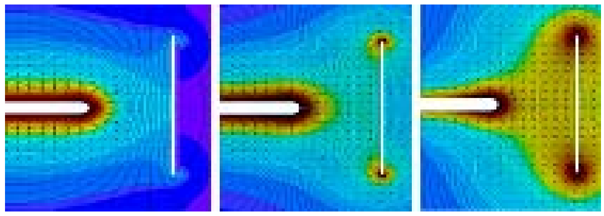
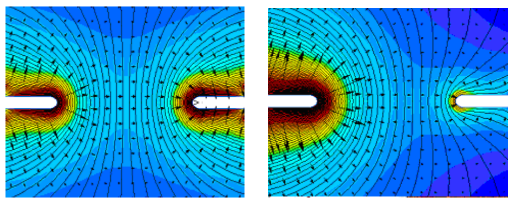


Plate grounded Symmetrical ch. Rod grounded

(a)Rod-plate



Symmetrical charging One rod grounded

(a)Rod-rod

Fig. 4: Field strength distribution in rod-plate and rod-rod air gap models for the different arrangements from simulation analysis.

3.2 The influence to the Corona Onset and Breakdown Voltage

The grounding of one of the electrodes influences the corona onset voltage significantly depending on the gap length, as well as the rod's diameter.

The Corona Onset Voltage is higher for the arrangement with the rod grounded, in comparison to the arrangement where the electrodes are symmetrically charged, or the plate is grounded, and it grows much higher as the gap length increases. “fig 5”.

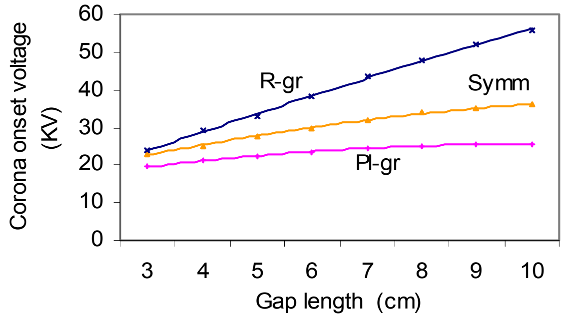
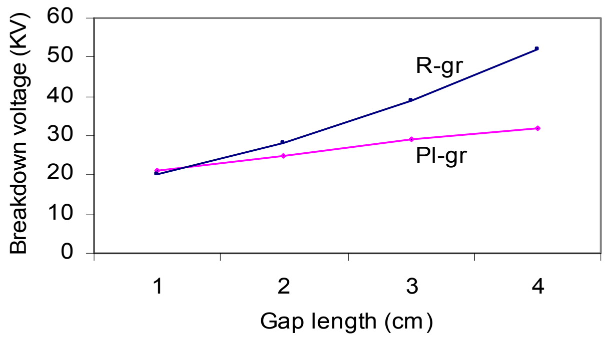
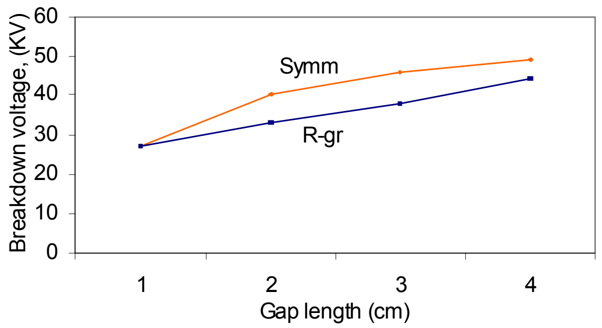


Fig. 5: The influence of the Ground effect to the Corona Onset Voltage of rod-plate air gaps, in function with the gap length, for DC voltage.



(a) Rod-plate air gaps



(a) Rod-rod air gaps

Fig. 6: The influence of the Ground Effect to the Breakdown Voltage of small rod-plate and rod air gaps, in function with the gap length, stressed by DC voltage.

The relation between the field strength on the rod (Ec, maximum value of field strength in the gap) and the corona onset voltage (Vc) is:

$$V_{c\text{-}r\text{-}gr} / V_{c\text{-}pl\text{-}gr} = A^*(E_{r\text{-}pl\text{-}gr} / E_{r\text{-}r\text{-}gr}), \qquad (8)$$

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

The Ground Effect influences the breakdown voltage in small rod-plate air gaps. The breakdown voltage is higher for the arrangement with the rod grounded, as it is shown in “figs 6, and 7”. The experimental models are rod-plate air gaps with a rod’s diameter of 10 mm, and a plate’s diameter of 100 mm, stressed by DC voltage. This is in full agreement with the results of the analysis, “fig 3”.

The influence is valid when the breakdown appears before the corona effects, and this happens when the gap length is relatively small, or when the gap is stressed by positive voltage. In longer air gaps the Corona Current influences the breakdown voltage.

Correspondent relations are valid for the rod-rod air gaps.

4 The influence of the Ground Effect to the Corona Current

In longer air gaps, where the corona effects appear before breakdown, small electric current flows through the gap.

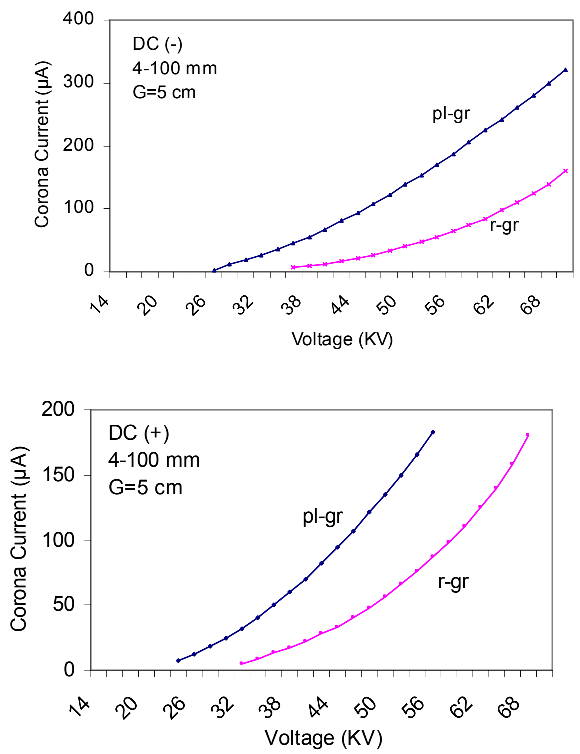
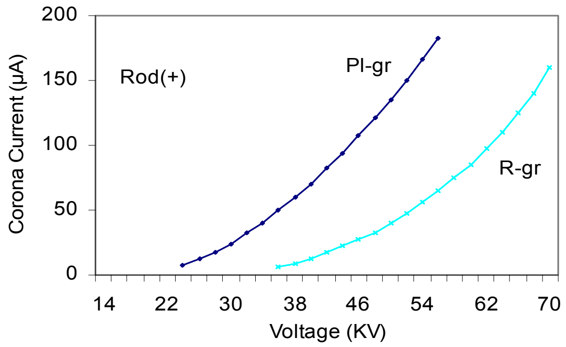
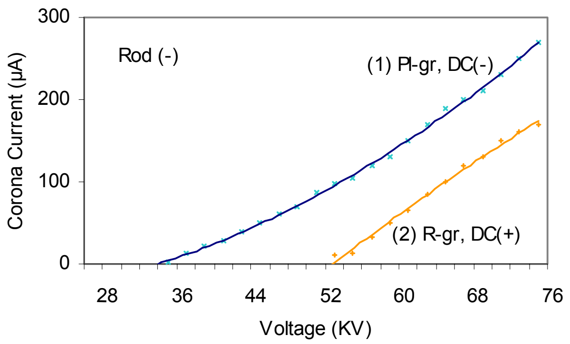


Fig 7 The influence of the Ground Effect to the Corona Current for DC positive and negative voltage.

The Ground Effect influences the values of the Corona Current through a rod-plate air gap greatly, as it is shown in ‘fig 7’. They are 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 "fig 7" are for DC voltage of either positive or negative polarity. In "figs 8" in both graphs the rod has the same polarity, positive or negative, in comparison to the plate.



(a) Rod-plate, 4-100 mm



(b) Rod-plate, 10-100 mm

Figure 8. The influence of the Ground Effect to the Corona Current for DC voltage, G=5 cm.

The values of the Corona Current depend mainly on the values of the maximum values of the field strength in the gap. This is obvious from "fig 9". For the same value of the field strength the values of the Corona Current are the same in the two different arrangements (with the plate and the rod grounded). This is valid when the applied voltage is relatively small. For higher voltages the surrounding influences the Corona Current, and the connection is not clear.

The Ground effect is also valid for AC voltages in rod-plate air gaps, as far as the Corona Onset Voltage, the Breakdown voltage and the Corona Current are concerned "fig 10".

A rod-rod air gap arrangement may be mechanically symmetrical, but, when one rod is grounded and the other is charged, it is not electrically symmetrical, due to the Ground Effect. Thus when the Polarity of the applied voltage is changed the values of the Corona leakage current are different, because of the influence of the Polarity Effect "fig. 11".

This is good verification that the Ground Effect is valid.

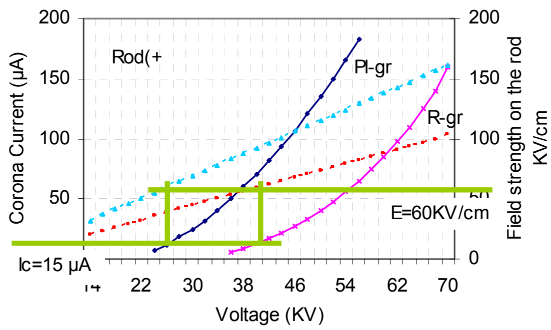


Fig. 9. The connection between the Field strength and the Corona Current in a rod-pate air gap, 4-100 mm, 5 cm.

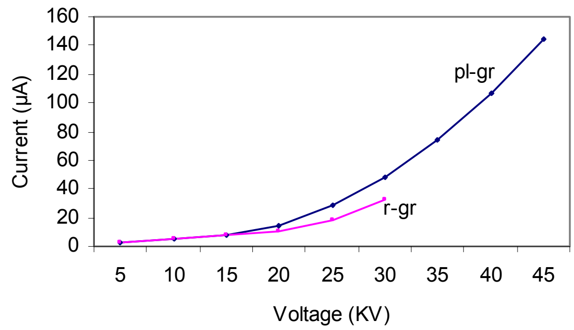


Figure 10. The influence of the Ground Effect to the Corona Current of rod-plate air gaps (4-100 mm) for AC voltage.

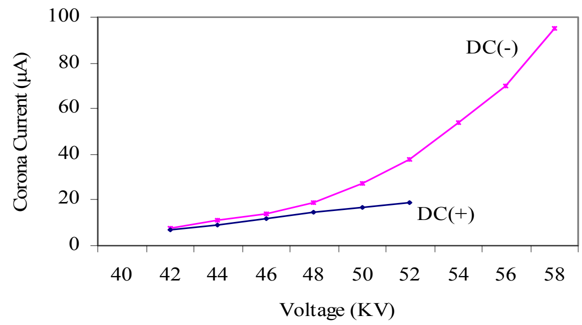


Fig.11. The influence of the Ground Effect to the Corona Current in rod-rod air gaps. The rod's diameter is 4 mm, the applied voltage is DC voltage.

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, "fig. 12".

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 values of the breakdown voltage become, as it is resulted from "figs 12 and 13".

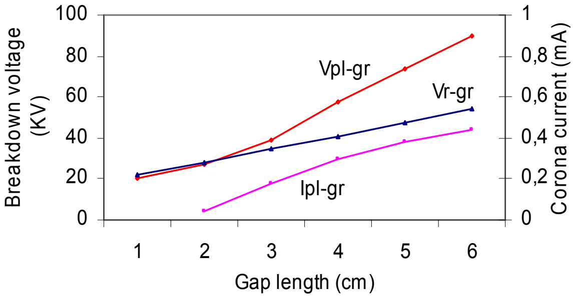


Fig. 12: The inversion of the Ground Effect by the Corona current in rod-plate air gaps. Negative DC voltage is applied.

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 "fig. 11". A correspondent relation between the breakdown voltage and the Corona Current seems to be valid, according to equation (9).

$$V_{pl-gr} - V_{r-gr} = B\left(I_{pl-gr} - I_{r-gr}\right) \quad (9)$$

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

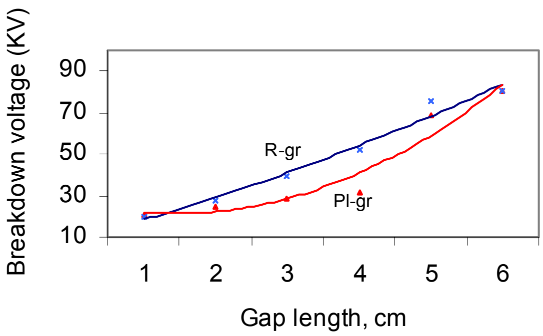


Fig. 13: The influence of the corona current to the Breakdown voltage of rod-rod air gaps. Positive DC voltage is applied.

6 Conclusions

1) The Ground Effect influences the distribution of the field and hence the Corona Onset and the Breakdown voltage of small air gaps.
2) In longer air gaps with smaller rod's diameter, the field is more inhomogeneous and the corona effects appear before breakdown. The value of the Corona Current, which depends on the field inhomogeneity is influenced by the Ground Effect greatly.
3) The Corona Current is higher in the arrangements with the plate grounded, where the field is more inhomogeneous. This is valid for both polarities of the applied DC voltage as well as for AC voltage.
4) A connection between the Corona Current and the maximum value of the field strength in the gap appears.
5) A relation between the breakdown voltage and the corona current arises, as well. The principle of action-reaction (Newton's third law) is valid. "The corona current reacts against the action of the field to produce corona charges, and opposes to the increase of the maximum value of the field strength, reducing the inhomogeneity of the field".

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