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The Ground Effect and the corona leakage effect in correlation with the Polarity Effect in small rod-plate air gaps

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Abstract: In the present paper the Ground Effect of small rod–plate air gaps, which is observed due to the grounding of one of the electrodes, is investigated. Values of the field strength in the gap are recorded and analyzed for the two different arrangements, with the rod or the plate grounded. The distribution of the field along the axis of the gap is strongly affected by the geometry of the gap, and especially by the electrode chosen to be grounded. The Ground Effect also affects the breakdown voltage of the rod-plate air gaps but in a quite different way than the Polarity Effect does. The values of the breakdown voltage depend on the maximum value of the field strength in the gap, and the corona leakage current through the gap. According to the Polarity Effect the breakdown voltage is considerably higher in the arrangement with negative polarity on the rod because of the intensive corona effects. According to the Ground Effect the breakdown voltage is higher in the arrangement with the rod grounded because the maximum value of the field strength is lower. The Ground Effect is intense in small rod-plate air gaps, while the influence of the corona leakage current and the Polarity Effect appears in longer air gaps.

Key Words: Ground Effect**,** Polarity Effect, Corona, Simulation, FEM, Air Gaps, Field Strength.

1 Introduction

In every insulated arrangement and especially in air gap arrangements, where there is no symmetrical charging, because one of the electrodes is grounded and the other is electrically charged, differences of the electric field's distribution is observed in comparison to the case where both electrodes are electrically charged with opposite charges. The difference occurs due to the asymmetry that is caused by the grounding of one of the electrodes. The main factor that affects the differences in the field distribution is the geometry of the arrangement.
One of the most determinant factors of the dielectric strength of the insulating arrangements and especially of the air gaps is the field strength distribution inside the volume of the arrangement. The above differences in the field distribution influence the breakdown voltage of the arrangement accordingly, [1], [2], [3], [4], [5], [6], [7].
In symmetrical arrangements such as rod-rod air gaps the influence caused due to the grounding of one of the electrodes is rather small, resulting this way to small differences of the breakdown voltage between the two cases where the stressed voltage is of positive or negative polarity, [8]. This occurs because of the Polarity Effect which would not exist if the symmetrical arrangement was symmetrically charged, that is positive charge for one of the electrodes and negative for the other.
In non-symmetrical arrangements, such as rod-plate air gaps, the grounding's influence in the distribution of the field is significant, depending on the rod's and plate's size. This is easily revealed with the analysis of the field with the Finite Element Method. Respectively important can also be considered the influence of one of the electrode's grounding to the breakdown voltage of the gap, [4], [5], [6], [7].
This phenomenon is called the Ground Effect and is clearly different from the Polarity Effect although highly influenced by it, [5], [6], [7].
This paper investigates the Modelling and Analysis of the electric field distribution in rod-plate air gaps under different geometries and arrangements of the gaps, using the Finite Element Method. The Ground Effect is investigated as it concerns the field's distribution as well as the corona onset and the

breakdown voltage. The influence of the corona leakage current is also presented.
Software Quickfield developed by Terra Analysis has been used in the present paper for the simulation analysis. It is based on the Finite Element Method in order to solve two-dimensional problems, with plane and axisymetric models.
The program is based on Gauss's and Poisson's equations [8], [9].

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

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

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.
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 [7], [8].

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

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

2 The investigated arrangements.

The arrangements which have been drawn, analyzed, and experimentally studied are typical rod-plate air gap arrangements of different 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 50 - 200 mm in diameter. One electrode of each arrangement is stressed by high DC voltage of negative or positive polarity or AC voltage while the other is grounded. All the analyzed models are axisymetric, (figs 1, 2 and 3).
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 [8], [9], [10], [11], [12], [13], [14], [15], [16], [17]:

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

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

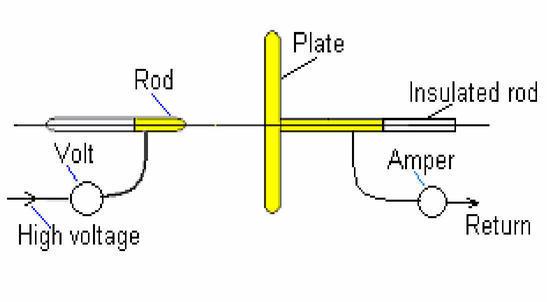


Fig 1. Rod - plate air gap, with grounded plate.

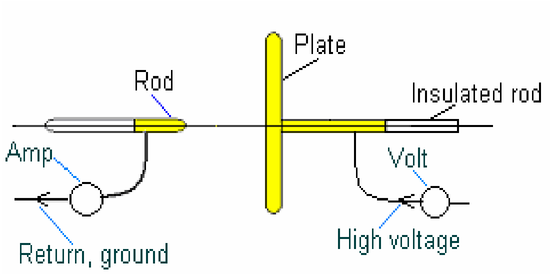


Fig 2. Rod - plate air gap, with grounded rod.

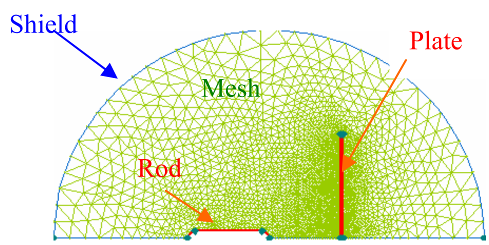
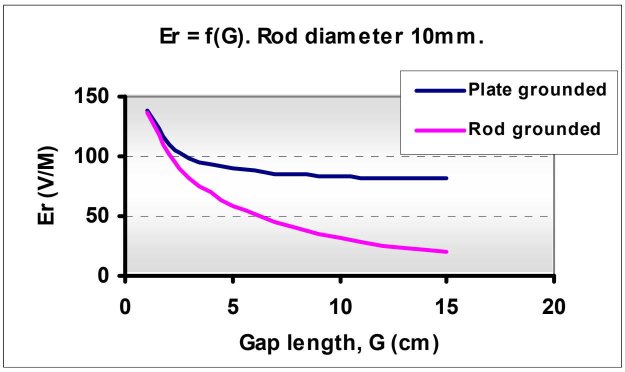


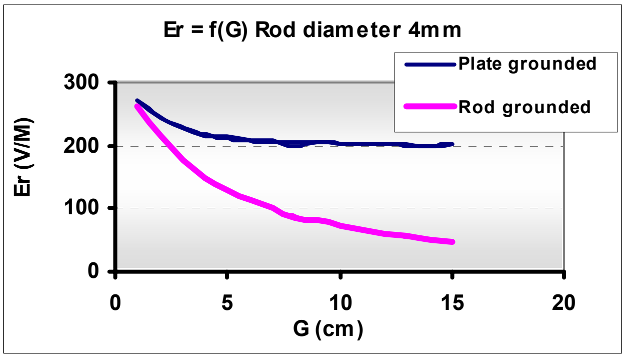
Fig 3. The analyzed model

3 The influence of the Ground Effect to the field distribution.

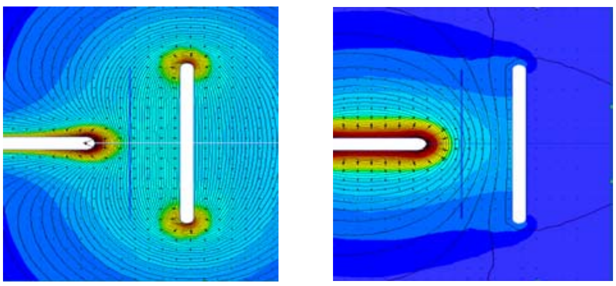
Rod-plate arrangements, with different grounded electrode, different dimensions of the plate and the rod, and different length of the gap have been modeled and analyzed. From the comparison between the two different cases of arrangement with the rod or the plate grounded it is resulted that the Ground Effect causes big differences in the field distribution between the two different arrangements.

The field distribution, the maximum value of the field strength in a rod – plate air gap and the field factor of the gap are demonstrated in figs 4, 5, 6, 7 and 8. It is obvious that the Ground Effect is intense in rod-plate air gaps.
In both arrangements, the maximum value of the field strength in the gap (field strength on the rod) decreases with the gap length. It is higher in the arrangement with the plate grounded and tends to get a steady value for each value of the rod's diameter when the gap is longer than 80% of the plate's diameter.
The corona electric charges in the gap are not taken into account in the analysis.

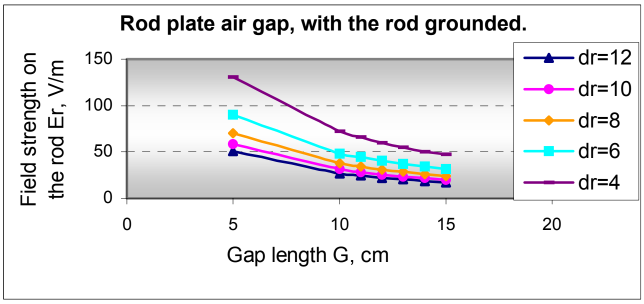




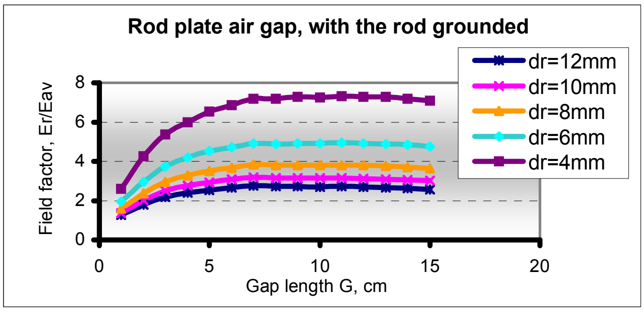
Figs 4. Rod - plate air gap. The maximum values of the field strength on the rod, Er, for the two different arrangements and two different diameters of the rod are shown in comparison. The plate's diameter is 100 mm.



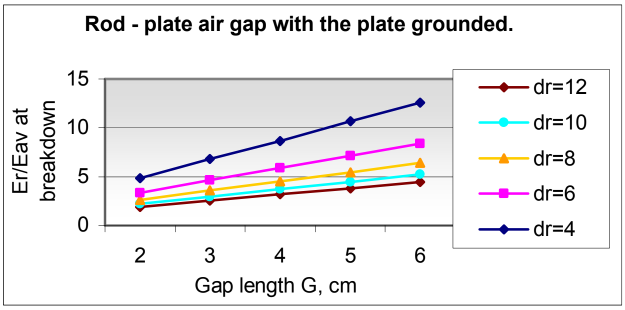
(a) The rod is grounded. (b) The plate is grounded
Figs 5. Field strength distribution in rod – plate air gap models from simulation analysis.



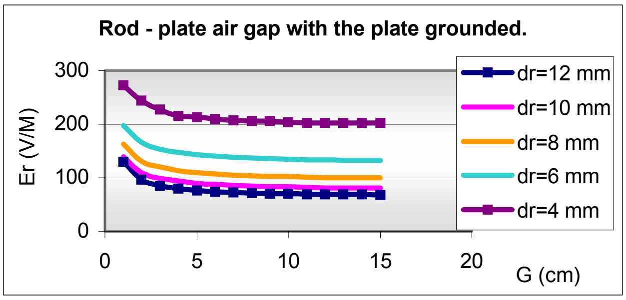
(a) Value of field strength on the rod.



(b) Field factor along the axis of the gap
Figs 6. Rod-plate air gap, with the rod grounded. The rod's diameter is dr, and the plate's diameter is 100 mm.



(a) The Field factor along the axis



(b) The field strength on the rod.
Figs 7. Rod-plate air gap, with the plate grounded. The rod's diameter is dr and the plate's diameter is 100 mm.

It is also resulted that the Field factor (n=Er/Eav) increases with the gap length. It takes lower values in the arrangement with the rod grounded and tends to get a steady value for each value of the rod's diameter when the gap length is longer than

80% of the plate's diameter, (fig 6b). In the arrangement with the plate grounded it increases continuously and is in complete agreement with equation 7, (fig 7a).

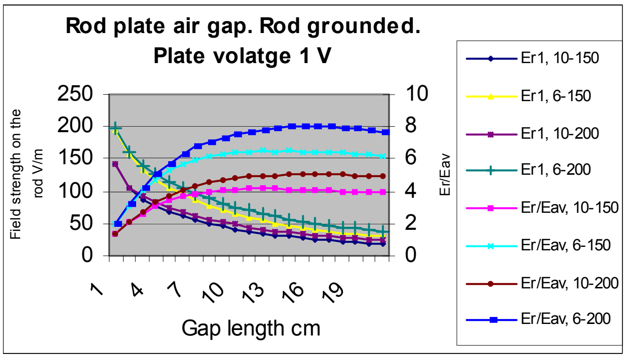
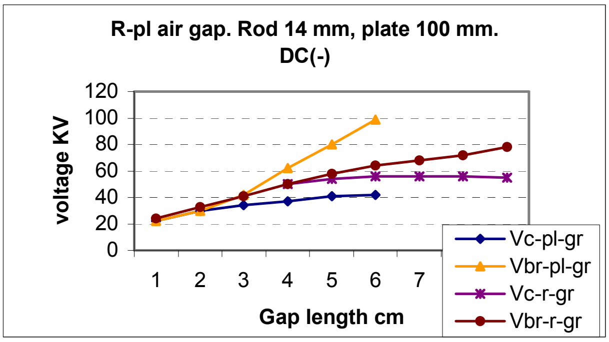
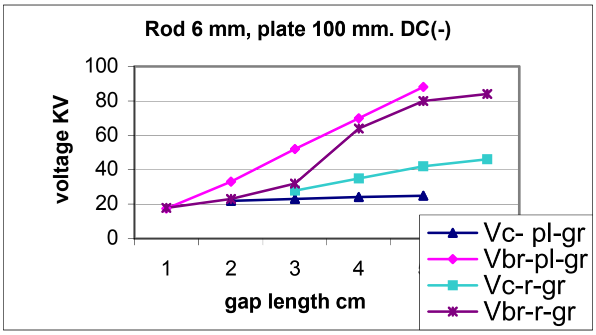


Fig 8. Rod - plate air gap, with the rod grounded. The maximum value of the field strength and the field factor along the axis of the gap for different values of the rod's diameter (dr), plate's diameter and gap length are shown. The applied Voltage is 1 V.

4 The influence of the Ground Effect to the corona onset and the breakdown voltage in rod – plate air gaps.



(a) Rod's diameter 14 mm.

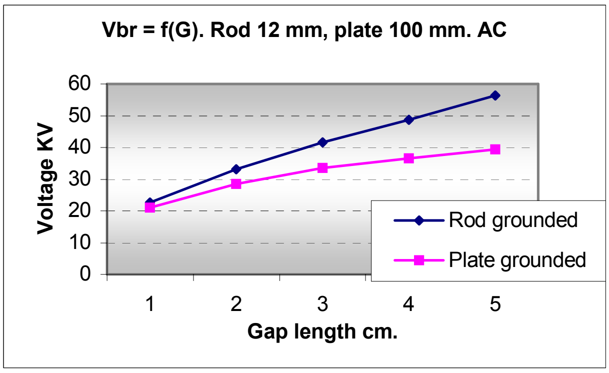


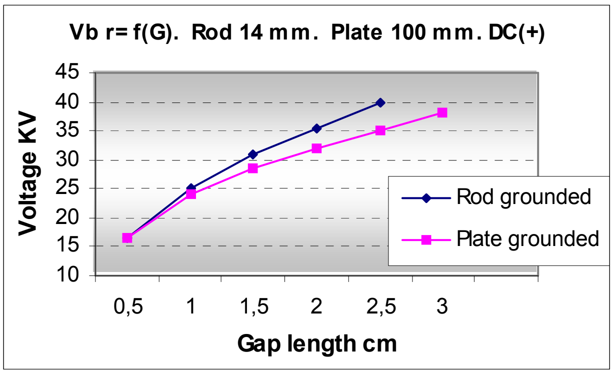
(b) Rod's diameter 6 mm.

Figs 9. Corona onset and breakdown voltage of rod – plate arrangements with the rod or the plate grounded. The applied voltage is negative DC voltage.

The Ground Effect influences the corona onset and the breakdown voltage of small rod-plate air gaps as it is resulted from figs 9 and 10.

The corona onset and breakdown voltage are higher for the arrangement with the rod grounded in small rod-plate air gaps. This is in full agreement with the results of the analysis, by which it is concluded that the maximum value of the field strength in the arrangement with the rod grounded is comparatively lower (figs 3, 4, 5, and 6). The results are also significant and clearer when the breakdown voltage is smaller than the corona onset voltage of the arrangement, and this happens when the gap length is relatively small.



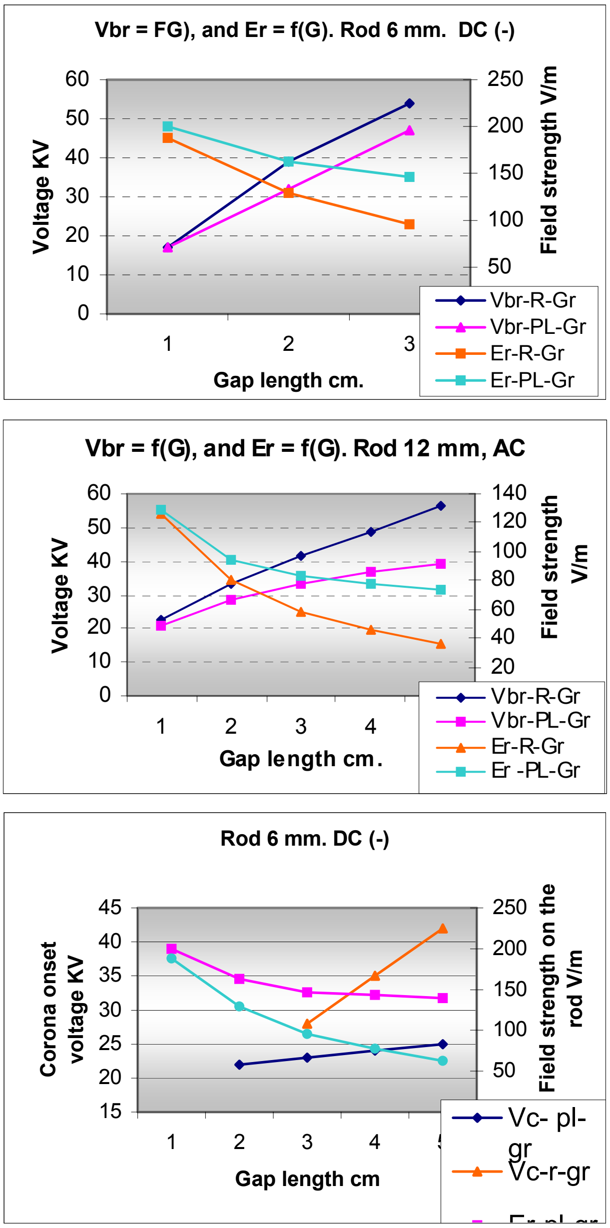


Figs 10. Breakdown voltage of rod – plate arrangements with the rod or the plate grounded for AC and DC positive applied voltage.

4.1 Connection between the breakdown voltage and the field distribution.

The most determinant factors that influence the breakdown voltage of an air gap are the field distribution in the gap and especially the maximum value of the field strength (usually on the rod), or the field factor, [1], [2], [3], [4], [5], [6], [7].

From figs 11 it is obvious that in the rod plate arrangements there is a clear connection between the maximum value of the field strength on the rod and the corona onset as well as the breakdown voltage of the gap. The smaller the field strength on the rod is, the higher the corona onset and the breakdown voltage are.



Figs. 11. The corona onset and the breakdown voltage in comparison to the maximum value of the field strength in rod-plate air gaps, for the two different arrangements with the rod or the plate grounded.

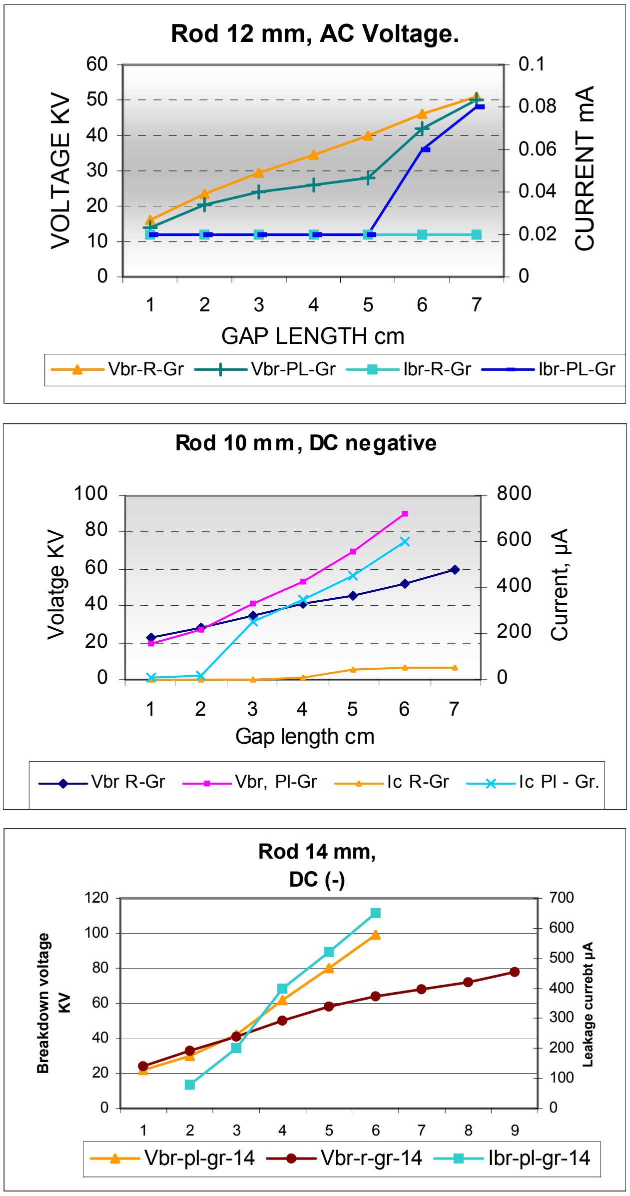
This relation is valid for small air gaps, for which the maximum value of the field strength on the rod is lower than the corona onset field strength, and can be given by equation:

$$\frac{V_1}{V_2} = A\left(\frac{E_2}{E_1}\right) \qquad (8)$$

, where V_1 and V_2 are the values of corona onset or breakdown voltage, and E_1 and E_2 the values of the field strength on the rod for the two different cases with the rod or the plate grounded. A is a coefficient, which's value depends on the gap length and the voltage's form.

The relation between the maximum value of field strength and the breakdown voltage seems to be stronger when the gap is stressed by positive DC or AC voltage and less strong when the gap is stressed by negative DC Voltage. This is due to the corona effects, which are more intensive when DC voltage of negative polarity is applied.

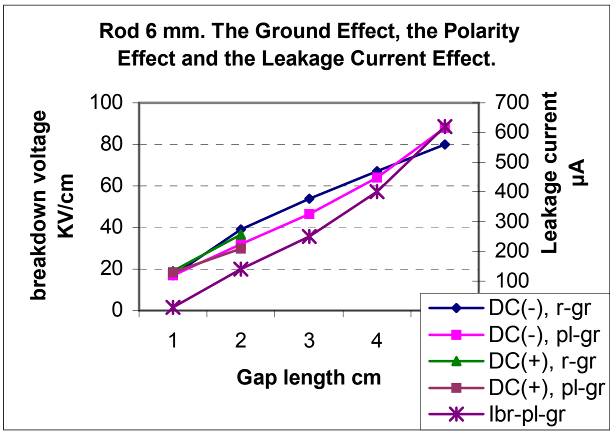
4.2 The Polarity Effect and the influence of the corona leakage current.

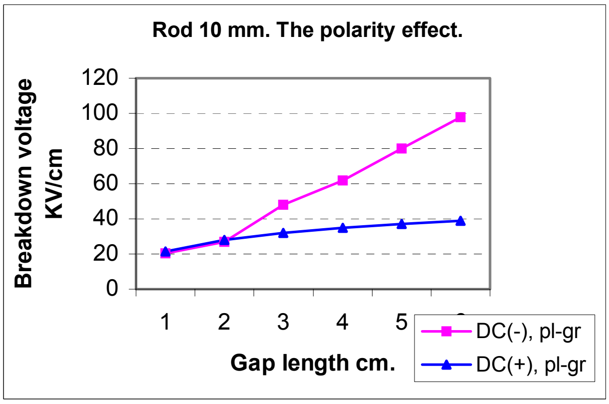


Figs 12. The breakdown voltage in connection to the corona leakage current in rod-plate air gaps for the two different arrangements with the rod or the plate grounded, and for DC and AC voltages.

When in a rod - plate air gap the plate is permanently grounded and the polarity of the applied DC voltage is changed, the Polarity Effect develops, [9], [10]. In this case the field's distribution in the gap is the same but with different direction, nevertheless the voltage polarity, and the Field Factor (=Emax/Eav) has the same value.

If the gap length is large enough the influence of the corona leakage current suppresses the Ground Effect, and the breakdown voltage is considerably higher in the arrangement with the plate grounded. We can say that the Ground Effect is overturned and the breakdown voltage increases significantly and becomes higher in the arrangement with the plate grounded, because of the influence of the corona leakage current (figs 13). The effect is stronger when the stressed voltage is DC negative and the rod's diameter is very small, because in this case the corona leakage current is a lot higher.





Figs 13. The Polarity Effect and the influence of the corona leakage current. DC voltage applied.

This is obvious in figs 13 where the breakdown voltage is higher for the arrangement with the rod grounded as far as the gap length is small enough (G<2 to 5 cm, depending on the rod's diameter and the form of the applied voltage), because of the Ground Effect. But for bigger gap length the breakdown voltage becomes higher for the arrangement with the plate grounded, because the leakage current is a lot higher. The polarity effect is also obvious from the same figs. We are led to the conclusion that the leakage current influences the field distribution in the gap greatly, lowers the maximum value of the field strength on the rod, and increases the breakdown voltage of the gap. This is the basic reason for the appearance of the Polarity Effect.

There is a relation between the value of the field strength, the breakdown voltage and the leakage current.

Equations (models) that can describe these relations are:

$$E_{br} = E_{th} - A_1 \cdot I_c \qquad (9)$$

and

$$V_{br} = V_1 + A_2 \cdot I_c \qquad (10)$$

, where: E_{br}, and E_{th} are the real and the theoretical, (without corona leakage current), calculated values of the field strength on the rod, at breakdown, V_{br} and V_1 are the real and the theoretical (if there was no leakage current) values of the breakdown voltage, and A_1 and A_2 are functions of the gap's dimensions and properties, with units Ω/m and Ω respectively

5 Conclusions

1. The influence of the Ground Effect to the field distribution is intense in all rod-plate arrangements, and it grows stronger when the rod's and the plate's diameter are decreased and when the gap length is increased. This means that the inhomogeneity of the electric field influences the Ground Effect. That leads the value of the field factor as well as the maximum value of the field's strength that usually appears on the rod to be high, and turn much higher when the arrangement is used with the plate grounded than with the rod grounded. The Polarity Effect makes no difference to the field distribution in small air gaps.
2. The Ground Effect influences the corona onset and the breakdown voltage of rod-plate air gaps strongly. In the arrangement with the rod grounded, where the maximum value of the field strength in the gap is lower, the corona onset voltage and the breakdown voltage are higher. The influence to the breakdown voltage is significant when the breakdown voltage is smaller than the corona onset voltage of the arrangement.
3. When the value of the breakdown voltage exceeds the corona onset voltage, the leakage current that is caused by the corona effects that take place in the gap, mainly influences the breakdown voltage, and the Ground Effect vanishes.
4. Attention should be given to the fact that the Ground Effect doesn't relate directly with the Polarity Effect, which only refers to the polarity

of the applied voltage. The Polarity Effect though influences the Ground Effect this way.

5. Future work will contain the full analysis of the Ground Effect for rod-plate air gaps of different geometries as far as the diameter of the rod and the plate is concerned, stressed by DC voltages of negative or positive polarity and AC voltages. The mathematical functions between the Field strength and the breakdown voltage (dielectric strength) of the air gaps, as well as between the Breakdown voltage of the gap and the corona leakage current through the gap will be also investigated..

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