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Modeling and analysis along with experimental investigation of the Ground Effect in rod-plate air gaps with or without barrier.

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Abstract. One of the most determinant factors of the dielelectric strength of the air gaps is the field strength distribution in the gap. The corona space charges in the gap influence also the distribution of the field strongly and hence the breakdown voltage of the gap. In the present paper the arrangements rod-plate air gaps with or without a barrier for the two different cases with the rod or the plate grounded are experimentally investigated and analyzed with the aid of special simulation software, using the Finite Element Method. Values of the field strength in the gap, while stressed by the breakdown voltage are recorded and analyzed. The results show that the distribution of the field along the axis of the gap is strongly affected by the geometry of the gap, and especially by the grounded electrode (Ground Effect). The value of the breakdown voltage depends on the maximum value of the field strength in the gap as well as the value of the corona leakage current through the gap. A charged barrier between the electrodes influences the distribution of the field significantly, as well as the breakdown voltage.

Key Words: Ground Effect, Barrier Effect, Simulation, FEM, Air Gaps, Field Strength.

1 Introduction

In every insulated arrangement and especially in air gap arrangements, where one of the electrodes is grounded and the other is electrically charged, so there isn't any symmetrical charging, a difference of the electric field's distribution is observed in comparison with the case where both electrodes are electrically charging with opposite charges. The difference occurs due to the asymmetry that is caused by the grounding of the one electrode, because in that way every grounded surface around the arrangement functions more or less as grounded electrode of the arrangement.

The two factors that regulate how different the distribution of the field becomes are the geometry of the arrangement as well as the size and properties of the boundary surface. One of the most determinant factors of the dielectric strength of the insulating materials and especially of the air gaps is the field strength distribution inside the mass of the materials. The above difference in the field distribution accordingly influences the breakdown voltage of the insulator or the gap [1], [2], [3], [4], [5].

In symmetrical arrangements such as rod-rod air gaps the influence caused by the grounding of the one electrode, is rather small resulting this way to small differences between the two cases where the applied voltage is of positive or negative polarity, [6]. This is 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. A rod-rod arrangement with one electrode grounded functions like a rod-plate arrangement, providing that the plate is of a small diameter.

In non-symmetrical arrangements, such as rod-plate air gap arrangements, the ground's influence in the distribution of the field is significant, depending on the rod 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 the one electrode's grounding to the breakdown voltage of the gap, [4], [5].

This phenomenon is called the Ground Effect and is clearly different from the Polarity Effect although highly influenced by it, [5].

This paper investigates the Modelling and Analysis of the electric field distribution in rod-plate air gaps with or without a barrier under different geometries and arrangements of the gaps, using the Finite Element Method. The Ground Effect is fully investigated as far as the field's distribution and the breakdown voltage are concerned. The influence of the corona leakage current is also presented.

Software Quick field 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 [7], [8].

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

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

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 the 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 that have been drawn, analyzed, and experimentally studied are typical rod-plate air gap arrangements of different geometries.

One electrode of each arrangement is stressed by high voltage and the other is grounded. The insulating barrier is a dielectric disk plate perpendicular to the axis of the gap. All the analyzed models are axisymetric, (figs 1 and 2).

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

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

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 gap the field factor is given by equation [7], [8]:

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

, where V is the 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.

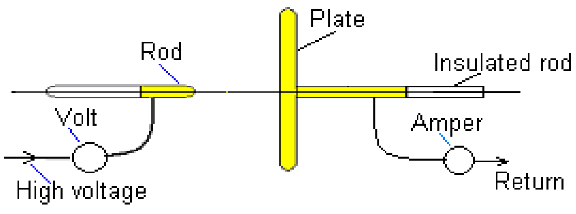
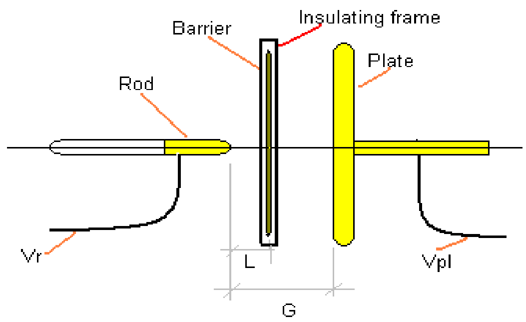
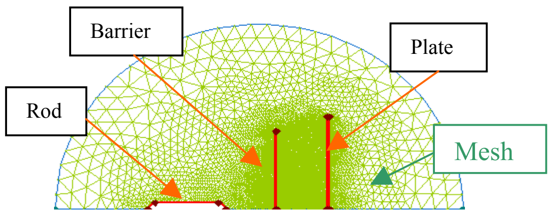


Fig 1. Rod - plate air gap.



(a) The experimental arrangement



(b) The analyzed model

Fig 2. The Rod - plate air gap with a barrier

3 The Ground Effect on the field distribution.

Rod-plate arrangements, with different grounded electrode, different dimensions of the plate and the rod, different length of the gap, with or without barrier between the electrodes have been modeled and analyzed. The comparison between the two different cases of arrangement, the one with the rod and the other with the plate grounded, results that the Ground Effect gives big differences between the two different arrangements.

3.1 The Arrangements of rod – plate air gaps without barrier.

The field distribution, the maximum value of the field strength in a rod – plate air gap without barrier and the field factor of the gap are demonstrated in figs 3, 4, 5, 6 and 7. The influence of the Ground Effect is very obvious.

In both arrangements, the maximum value of the field strength in the gap (field strength on the rod) decreases with the gap length. In the arrangement with the plate grounded it is higher 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.

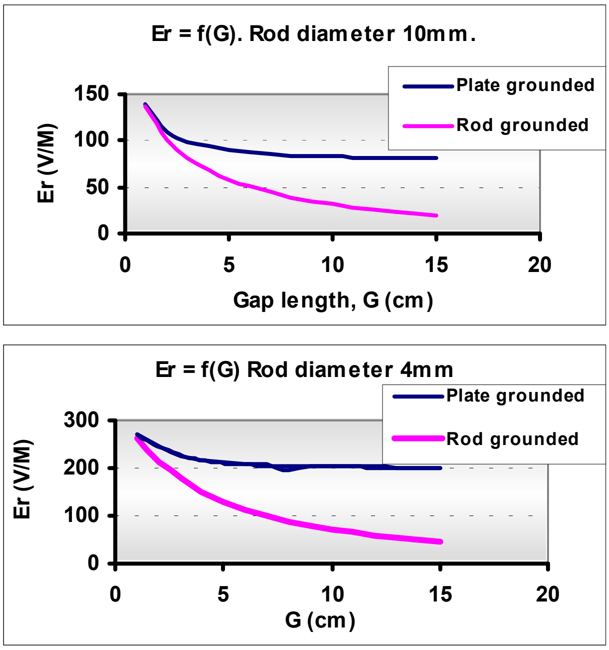
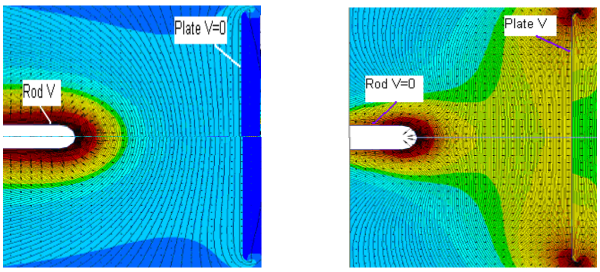
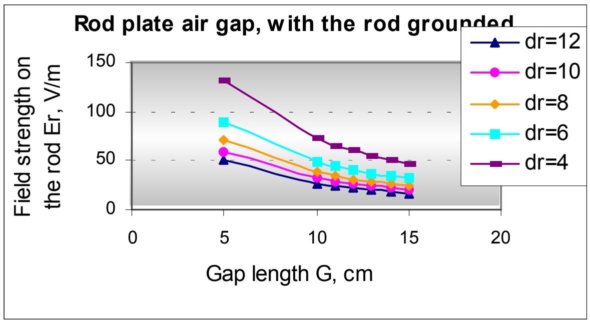


Fig 3. Rod - plate air gap. The maximum values of the field strength on the rod, Er, for the two different arrangements and two different diameters of the rod are shown in comparison. Plate diameter is 100 mm.

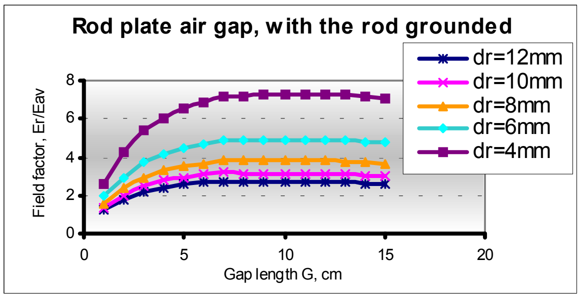


(a) The Plate is grounded. (b) The rod is grounded
Fig. 4. Field strength distribution in rod – plate air gap models from simulation analysis.

It is also shown that the Field factor (n=Er/Eav) increases with the gap length. In the rod grounded arrangement (fig 5a) it has lower values 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. In the plate grounded arrangement (fig 6a) it increases continuously and is in complete agreement with equation (7).

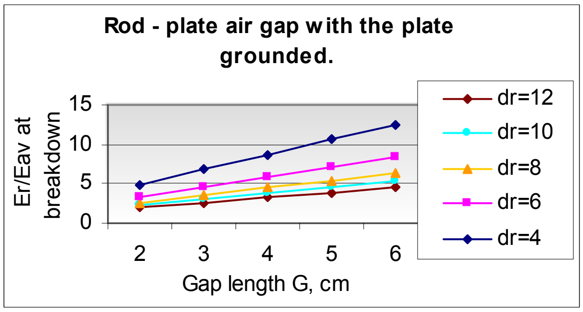


(a) Value of field strength on the rod.

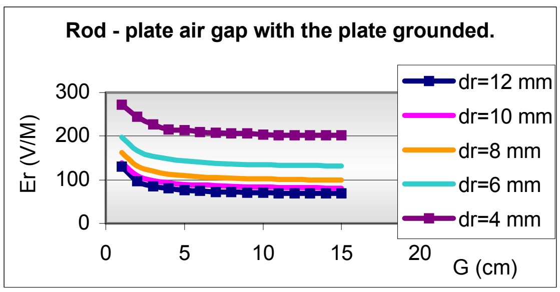


(b) Field factor along the axis of the gap

Fig 5. 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.

Fig 6. Rod-plate air gap, with the plate grounded. The rod's diameter is dr and plate's diameter is 100 mm.

3.2 Arrangements of air gaps with a Barrier.

A basic composite insulation arrangement is that of a rod- plate with a dielectric plate called barrier placed between the electrodes.

The dielectric barrier separates the air gap in two different parts, which function differently. The first part between the stressed electrode and the barrier behaves like a rod - plate arrangement and the second part between the barrier and the grounded electrode behaves like a plate – plate arrangement [1], [2], [3], [4], [5], [9], [10], [11], [12], [13], [14], [15].

When a rod-plate air gap with a barrier is stressed by high voltage corona space charges drift through the air to the barrier and accumulate on the surface facing the rod electrode (fig 7). The charge is distributed linearly on the surface of the barrier. The distribution of the electric charge on the barrier influences the field distribution in the gap strongly, thus influencing the value of the breakdown voltage of the gap. The influence depends on the gap length, the position of the barrier in the gap and the dimensions of the barrier. This is called the Barrier Effect, [1], [2], [3], [4], [9], [10], [11], [12], [13].

The voltage on the barrier is directly proportional to the charge density on its surface, depending on the position of the barrier in the gap, [1], [2], [3], [4].

The field strength distribution along the axis of the gap for different values of the barrier's voltage and different positions of the barrier in the gap is shown in figs 8 and 9. The two different cases of the arrangements with the rod grounded or the plate grounded have been investigated.

The maximum value of the voltage at the center of the barrier influences the distribution of the field along the axis of the gap greatly, and thus the breakdown voltage.

As the charge on the barrier increases, the field strength on the barrier and the average field strength of the whole gap increase significantly. The average field strength in the part between the barrier and the plate increases as the charged barrier moves towards the plate.

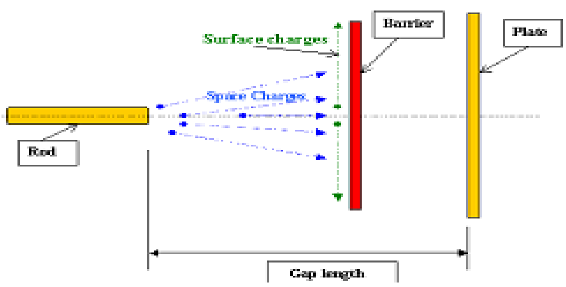
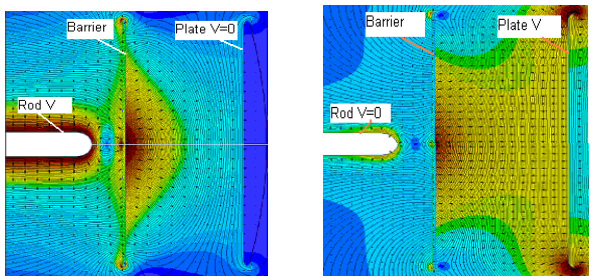


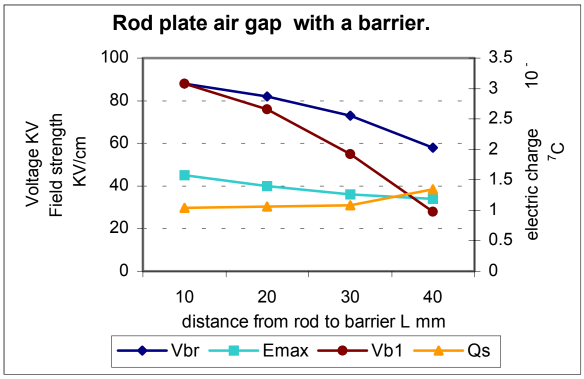
Fig 7. Rod-plate air gap stressed by high voltage. Electric charge is accumulated and distributed on the barrier.

It is resulted that the field strength values on the rod and the barrier in the first part between the rod and the barrier increase significantly when the charge on the barrier increases. The space charge and the electric leakage current through the air of the gap limit the value of the field strength at the part between the rod and the barrier.

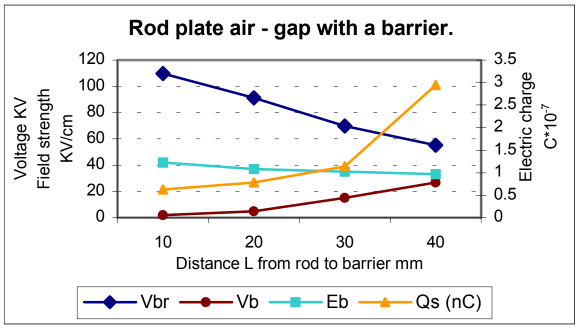


The plate is grounded. The rod is grounded.

Fig 8. The field strength distribution in a rod-plate air gap with a charged barrier, from simulation analysis with the Quickfield.



(a) The Plate is grounded, Vr=Vbr.



(b) The Rod is grounded, Vr=0.

Fig 9. Rod-plate air gap 50 mm long with a charged barrier at different positions. The breakdown voltage (Vbr), the value of the voltage on the barrier (Vb), the field strength at the center of the barrier (Eb), and the electric charge on the barrier (Qs) are shown. The applied voltage is DC voltage.

The field strength on the barrier, at fig 9, has a typical value between 30 KV/cm and 40 KV/cm, which is the expected value at breakdown for the part of the gap

between the barrier and the plate, [12], [13]. It is also shown from the same figure that the values of the voltage at the center of the barrier are different from the values of the voltage of the rod. The difference depends on the position of the barrier in the gap.
Thus it is resulted that the prevalent view, [9], [10], [11], [12], [13], that at breakdown, the value of the voltage at the center of the barrier is equal to the value of the voltage on the rod, is not exactly correct. This is usually valid when the barrier is near the rod.
It is also resulted from analysis with FEM, (figs 8 and 9), that the Ground Effect is also valid in the rod-plate arrangements with a barrier. The field distribution is much different for the two different arrangements, [4], [5].

4 The Ground Effect on the breakdown voltage in rod – plate air gaps with or without a barrier.

The Ground Effect influences the breakdown voltage of rod-plate air gaps with or without a barrier as it is shown in figs 10 and 11.
The breakdown voltage is higher for the arrangement with the rod grounded. This is in full agreement with the results of the analysis, in which it is concluded that the maximum value of the field strength in the arrangement with the rod grounded is comparatively lower (fig 3, 4, and 5). The influence is stronger and clearer in the air gaps without barrier. It is 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 small enough. With positive DC, or AC applied voltage the Ground Effect is more effective than with negative DC voltage. The Ground Effect has less influence to the arrangements with a barrier.

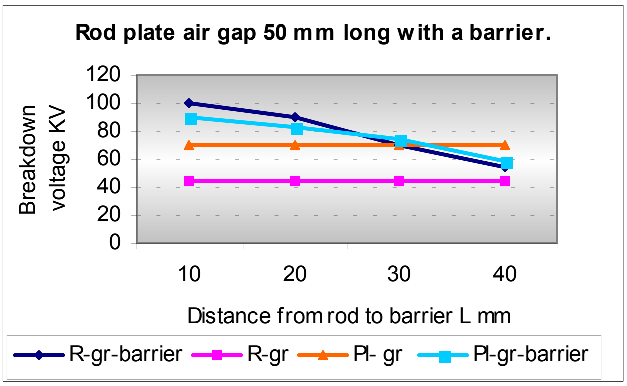


Fig 10. Rod-plate air gap of a 50 mm length, with a barrier at distance L from the rod. Rod's diameter 10 mm., plate's diameter 100 mm. The applied voltage is negative DC voltage.

The insertion of the barrier influences more the arrangement with the rod grounded, increasing the breakdown voltage significantly

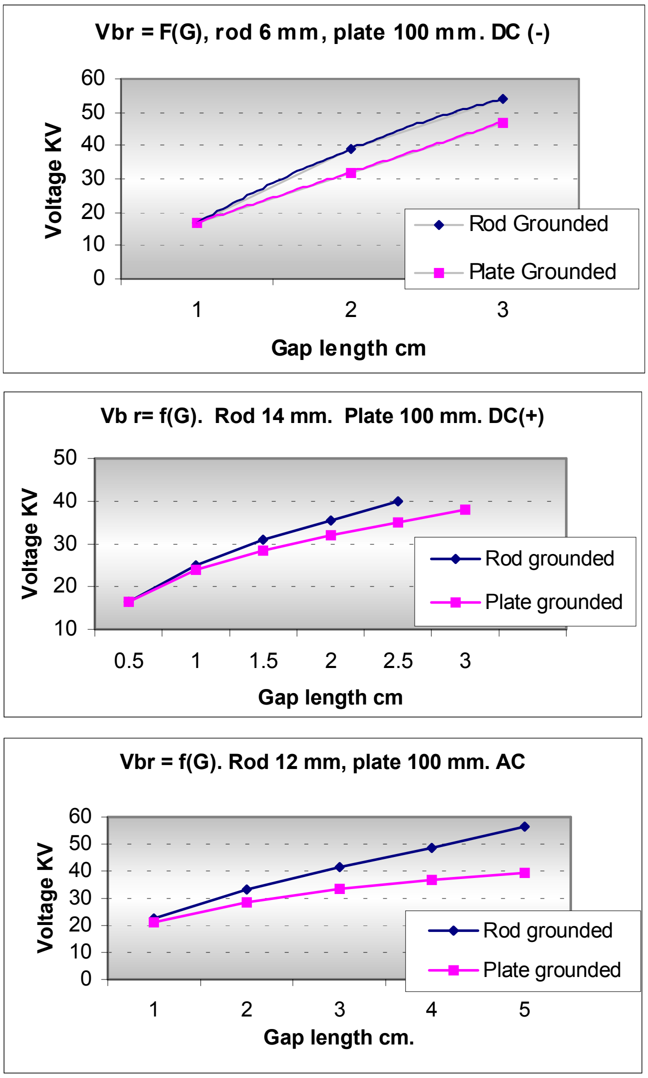


Fig 11. Breakdown voltage of rod – plate arrangements without barrier, with the rod or the plate grounded for different diameters of the rod and for AC, DC negative and DC positive applied voltage.

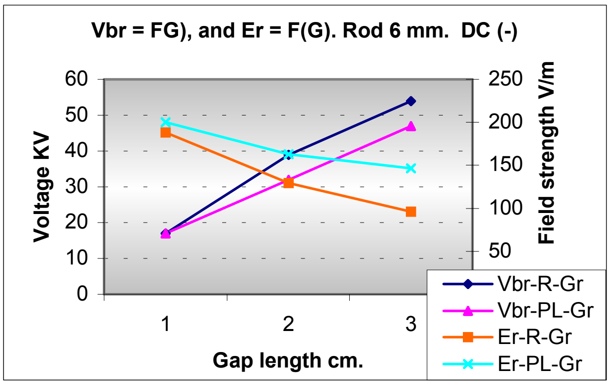
5 Connection between the breakdown voltage and the field distribution.

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, (on the rod), or the field factor, [1], [2], [3], [4].
From figs 12 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 breakdown voltage of the gap. If the maximum field strength on the rod is smaller, then the

breakdown voltage is higher. 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 breakdown voltage, and E_1 and E_2 the values of the field strength 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 form.



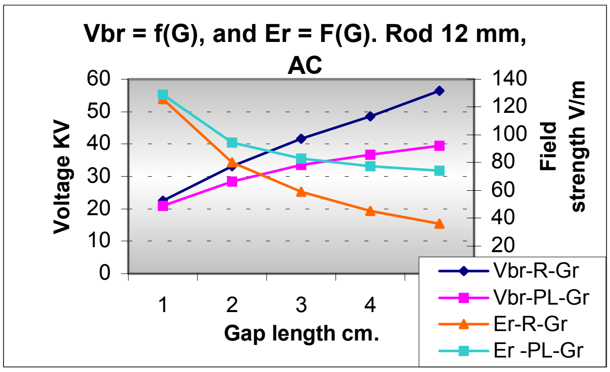
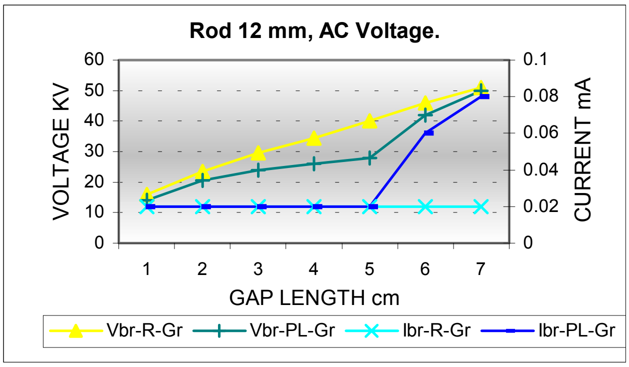


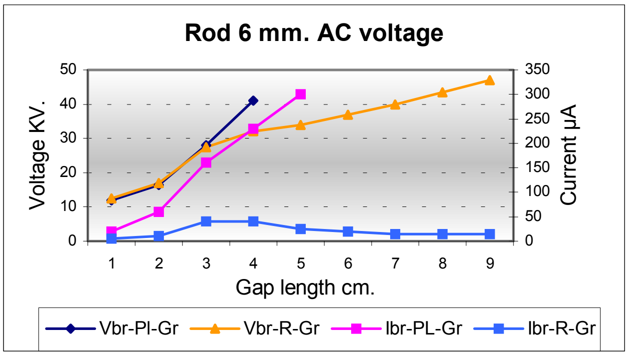
Fig 12. The breakdown voltage in comparison to the maximum value of the field strength in rod-plate air gaps, for the two different arrangements with the rod or the plate grounded.

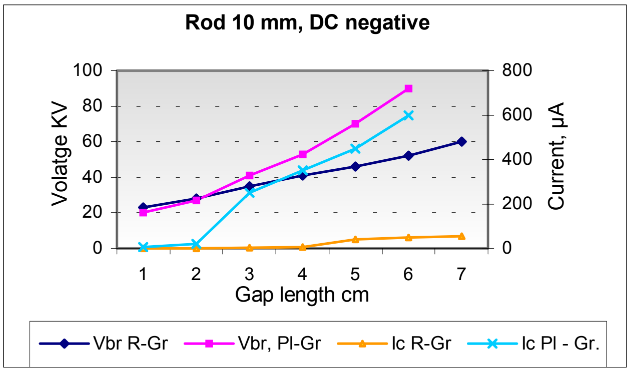
The relation between the maximum value of field strength and the breakdown voltage seems to be stronger when the gap is stressed by positive DC or AC voltage and less strong when the gap is stressed by negative DC Voltage. This is valid because with negative DC voltage the corona effects are more intensive.

6 The influence of the corona leakage current.

If the gap length becomes larger, the corona leakage current affects the distribution of the field more than the Ground Effect and the breakdown voltage increases significantly. Especially in the arrangement with the plate grounded it increases and becomes higher.







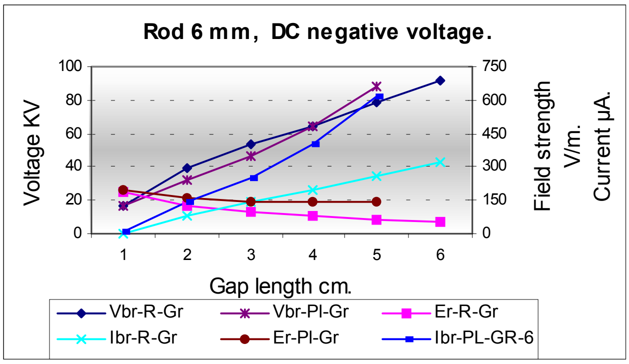


Fig 13. The breakdown voltage in connection to the corona leakage current and field strength in rod-plate air gaps for the two different arrangements with the rod and the plate grounded, and for DC and AC voltage.

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 higher.

From fig 16 it results that the breakdown voltage is much higher for the arrangement with the plate grounded, although the field strength is higher, and so is the leakage current. 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. It is obvious that 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: a) 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, b) V_{br} and V_1 are the real and the theoretical (if there was no leakage current) values of the breakdown voltage, and c) A_1 and A_2 are functions of the gap's dimensions and properties, and their units are Ω/m and Ω respectively.

In the case of rod – plate arrangements with barrier, the corona leakage current is less significant when the stressed voltage is DC or AC, and so the Ground Effect is not affected.

7 Conclusions.

1. From the study of the field analysis diagrams with the FEM we can easily conclude that the Ground effect is intense in all rod-plate arrangements, and particularly it grows stronger when the rod's diameter is decreased and the plate's diameter is increased. This means that the more inhomogeneous the electric field becomes the more intense the Ground Effect appears. 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. The difference between the two arrangements sharpens when the plate's diameter is smaller and the gap length increases.
2. From the study of the diagrams of the breakdown voltage in rod-plate arrangements in comparison with the diagrams of the maximum field strength or the field factor, it is shown that the Ground Effect influences the breakdown voltage of rod-plate air gaps strongly. The influence is significant when the breakdown voltage is smaller than the corona onset voltage of the arrangement.
3. The influence is less significant when a barrier is placed between the electrodes. The barrier is charged, disturbs the field distribution and increases the breakdown voltage.
4. When the maximum value of the field strength in the gap exceeds the corona onset field strength, then the value of the breakdown voltage is mainly influenced by the corona leakage current in the gap.
5. Attention should be given to the fact that the Ground Effect doesn't relate directly to the Polarity Effect, which only refers to the polarity of the applied voltage. The Polarity Effect though intensifies the Ground Effect.

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