The influence of the Effect of Grounding and Corona Current to the Field Strength the Corona Onset and the Breakdown Voltage of Small Air Gaps

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Abstract: In the present paper the values of the field strength at Corona onset and Breakdown in small air gaps in connection to the effect of grounding is investigated. The effect of grounding is occurred due to the fact that in air gap arrangements one electrode is usually grounded. The field distribution is analyzed with the Finite Element Method. The corona onset and the breakdown voltage are experimentally measured. The maximum value of the field strength at corona onset and breakdown are calculated for the different arrangements with one electrode grounded and with the electrodes symmetrically charged, and are compared. It is resulted that the effect of grounding influences the field distribution, the corona onset, and the breakdown voltage of small air gaps greatly. The effect is intense in the non-symmetrical rod-plate air gaps and less significant in the symmetrical ones, rod-rod and sphere-sphere. The values of the corona onset and the breakdown voltages are much higher in the arrangement with one electrode grounded, and in the rod-plate air gaps with the rod grounded. The correspondent values of the field strength are almost equal for the two different cases. In longer air gaps the corona current suspends the breakdown, the effect of grounding is vanished, and the field strength at breakdown is higher in the arrangement with the plate grounded. Relations between the field strength, the gap length and the rod's diameter, as well as between the corona current and the breakdown voltage and field strength arise. The principle of action-reaction is valid.

Key-words: - Field Strength, Field Factor, Electric Breakdown, Corona Onset, Corona Current, Finite Element Method, Grounding Effect.

1 Indroduction

The air gaps are very important insulating arrangements for high voltage applications (power lines, electrostatic filters, electrostatic painting, etc.). The mostly used air gaps, for experimental purposes mainly, are the sphere-sphere, the rod-rod (or point-point), and the rod-plate (or the point-plate) air gaps.

The most determinant factor for the dielectric behavior and especially for the dielectric strength of an air gap is the electric field distribution in the gap, 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, [1-13].

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 a different maximum value of the field strength are observed in comparison to the arrangement where both electrodes are electrically charged with opposite charges, [14-19]. The differences occur due to the asymmetry that is caused to the electric field by the grounding of one of the

electrodes and consequently the different initial conditions in the analysis.
The influence of the effect of grounding is intense in small rod-plate and rod-rod arrangements and less significant in small sphere-sphere arrangements, depending on the gap length, as well as the rod's, the plate's and the sphere's diameter.
In the rod-plate arrangements the electric field in the gap is more inhomogeneous when the plate is bigger. For a very big plate the rod-plate arrangement functions like a rod-rod arrangement of double length stressed by double voltage, and the influence of the effect of grounding decreases. This is the Mirror Effect, which's accuracy depends on the rod's and the plate's diameter, as well as the gap length.
In the papers [14-19] it was presented that the effect of grounding influences the corona onset and the breakdown voltage of the arrangement accordingly. The values of the corona onset and the breakdown voltage are higher in the arrangements with the rod grounded in rod-plate air gaps and in the arrangements with symmetrical charged electrodes in the rod-rod and sphere-sphere air gaps.
When the gap length is relatively small and the rod's diameter relatively big, there are no corona effects before breakdown. In bigger air gaps the field is more inhomogeneous, the corona effects appear in a lower voltage, and suspend the breakdown, which takes place in a higher value of voltage.
In this paper, apart from the Polarity Effect, the effect of grounding is investigated as it concerns the field's distribution, the corona onset and the breakdown voltage, as well as values of the field strength at corona onset and breakdown. The influence of the corona current to the breakdown voltage in the rod-plate arrangements is also investigated and presented.
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 axisymetric models.
The values of the corona onset and breakdown voltage, as well as the corona current are from experimental work.

2 The Investigated Arrangements

The arrangements, which have been modeled, analyzed, and experimentally studied, are typical rod-plate, rod-rod, and sphere–sphere air gap arrangements of different electrode geometries. The sphere electrode is a sphere with a relatively big diameter, the rod electrode is a cylinder long enough, with a relatively small diameter (4-14 mm) and a hemisphere tip, and the plate electrode is a disk up to 100 mm in diameter. High DC voltage of negative 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 axisymetric with a spherical boundary shield big enough in diameter at earth potential, (Figures 1, and 2).

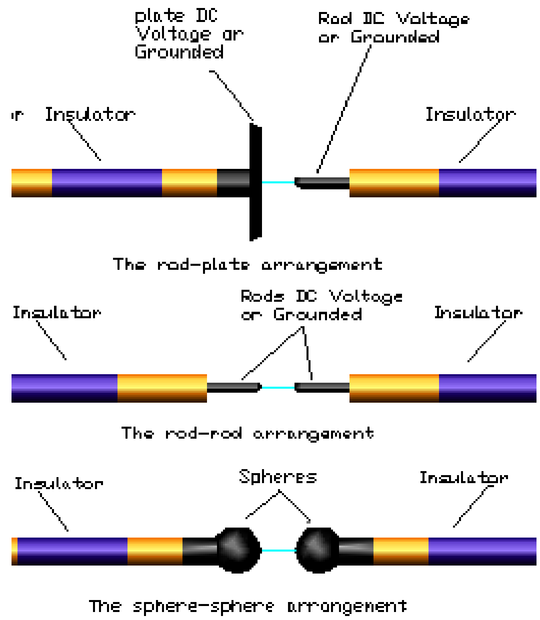


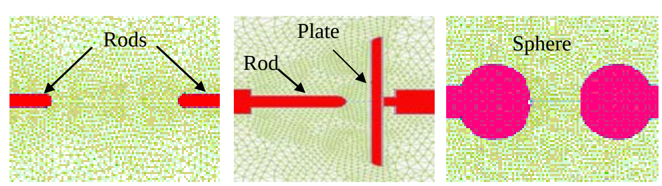
Fig. 1: The experimental arrangements. One electrode is stressed by negative polarity, whereas the other is grounded, or both electrodes are stressed symmetrically by equal and opposite voltages.

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

$$E_{av} = V/G \tag{1}$$

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:

$$n = E_{max}/E_{av} \tag{2}$$



(a) Rod-rod (b) Rod-plate (c) Sphere-sphere
Fig. 2: The simulated models with Finite Element Method

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

$$n=[(G/D+1)+\{(G/D+1)^2+8\}^{0,5}]/4, \qquad (3)$$

or n=G/2D, if G>>D,

and for a rod-plate air gap, with a very big plate, the field factor is given by equation [1], [2]:

$$\mathrm{n}=\frac{2G}{r\cdot\ln(G/r)} \quad \text{If } G>>r, \qquad (4)$$

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, D is the diameter of the sphere, and r is the radius of the rod's tip. The plate's diameter is big enough.

The polarity of the applied voltage on the stressed rod influences the field strength at Corona Onset, the influence depending on the rod's diameter and the environmental conditions, (Polarity Effect), [1-4].

3 The Simulation Results of the Effect of Grounding

From the simulation analysis it is resulted that there are big differences in the field distribution in the air gaps of the three different arrangements with the rod or the plate grounded, or with symmetrically charged electrodes. The field distribution, the maximum value of the field strength, and the field factor along the axis of the gaps are demonstrated in "figs 3, and 4".

3.1 The rod-plate air gaps

In the rod-plate air gaps the inhomogeneity has the highest grade when the plate is grounded (pl-gr), decreases when both electrodes are symmetrically charged (symm), and reaches the lowest value when the rod is grounded (r-gr), with the inhomogeniety depending on the gap length and the rod and plate's diameter (figs 3a).

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 turns much higher as the length of the gap increases, "figs 3a". Correspondent results are valid for the Field factor across the axis of the gap, "figs 4a". The effect of grounding is very intense.

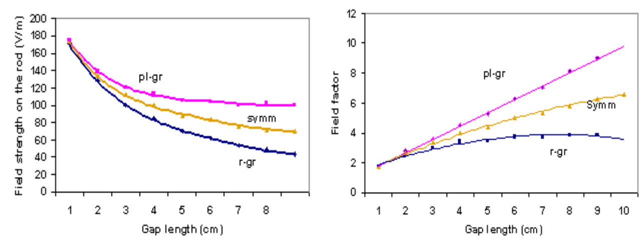
The rod's diameter is 10 mm, and the plate's diameter 100 mm. The simulation voltage is 1 V. In "fig 4" the plate grounded (pl-gr) curve is in full agreement with equation (4).

3.2 The rod-rod air gaps

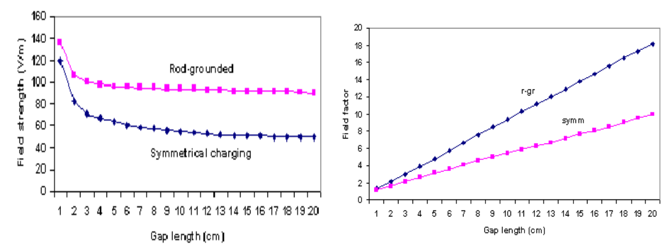
In the rod-rod air gaps the electric field is more inhomogeneous in the arrangements with one electrode grounded, (r-gr) and less in the arrangements with symmetrically charged electrodes (symm), with the inhomogeniety depending on the gap length and the rod's diameter. "figs 4b".

The maximum value of the field strength in the gap (field strength on the stressed rod), and the field factor across the axis decrease with the gap length, and they are higher in the arrangement with one rod grounded (figs 3). The rod's diameter is 10 mm; the simulation voltage is 2 V.

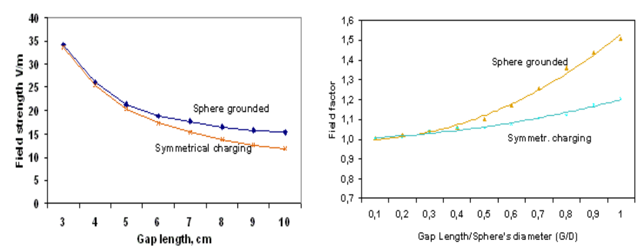
3.3 The sphere-sphere air gaps



(a) Rod-plate arrangements



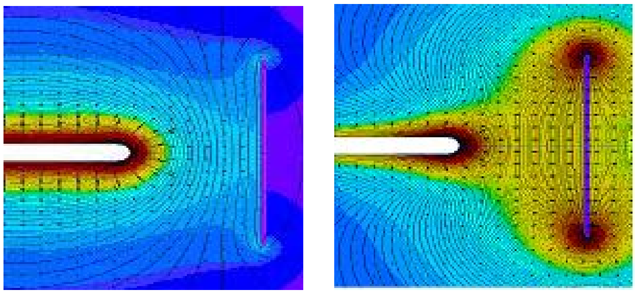
(b) Rod-rod arrangements



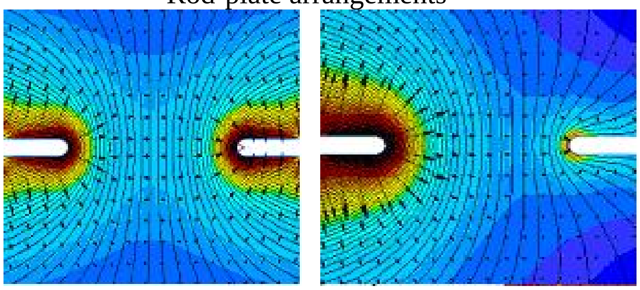
(c) The sphere-arrangements

Fig. 3: The maximum values of the field strength and the field factor for the different arrangements with the rod (r-gr), or the sphere (sph-gr), or the plate grounded (pl-gr), either with symmetrically charged electrodes (symm.).

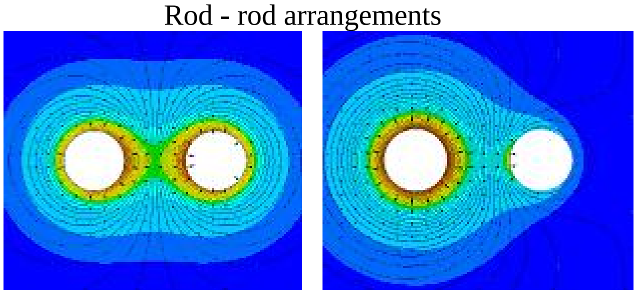
In the sphere air gaps the electric field is more inhomogeneous in the arrangements with one electrode grounded, (sph-gr) and less in the arrangements with symmetrically charged electrodes (symm), with the inhomogeniety depending on the gap length and the rod's diameter, "figs 3c".



(a) Rod grounded (r-gr) (b) Plate grounded (pl-gr)
Rod-plate arrangements



(b) Symmetrical charging (b) One rod grounded (r-gr)
Rod - rod arrangements



(c) Symmetrical charging (b) One sphere grounded
Sphere-sphere air gaps

Fig. 4: Field strength distribution in rod-plate, rod–rod and sphere-sphere air gap models for the different arrangements from simulation analysis. The effect of grounding is obvious.

The maximum value of the field strength in the gap (field strength on the stressed sphere), and the field factor decrease with the gap length, and they are higher in the arrangement with one sphere grounded “figs 3c, and 5c”.

The sphere’s diameter is 100 mm; the simulation voltage is 2 V.

In “fig 3c” the curve of symmetrically charged electrodes is in good agreement with equation (3)

In all air gap arrangements (with the rod or sphere 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) decreases with the gap length. It is higher in the arrangement with the plate grounded in rod-plate air gaps and turns much higher as the length of the gap increases, while in rod-rod, and sphere-sphere arrangements it is higher in the arrangement where one of the electrodes is grounded (figs 3).

4 The Experimental Results of the Influence of the Effect of Grounding

The grounding of one of the electrodes influences the corona onset and the breakdown voltage significantly depending on the gap length, as well as the rod’s, the plate’s, and the sphere’s diameter.

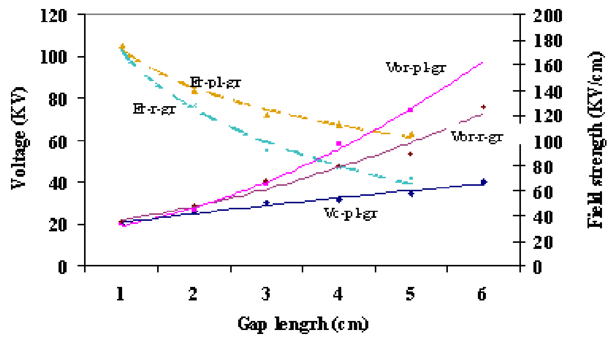
4.1 The rod-plate air gaps

It is concluded from the experiments that in small rod-plate air gaps the values of the corona onset and the breakdown voltage are higher for the arrangement with the rod grounded, in comparison to the arrangement with the plate grounded, or the one where the electrodes are symmetrically charged, and it grows much higher as the gap length increases, “fig 5a”. This is in full agreement with the results of the analysis of “figs 3a”. The rod’s diameter is 10 mm, and the plate’s diameter 100 mm. DC negative voltage is applied to the arrangements with one electrode grounded, and DC negative and positive to the symmetrical charging arrangements.

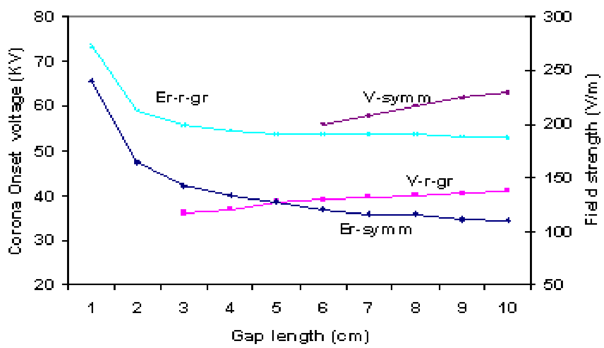
4.2 The rod-rod and sphere-sphere air gaps

In small rod-rod and sphere-sphere air gaps the values of the corona onset and the breakdown voltage are higher for the arrangement with one electrode grounded, in comparison to the arrangement where the electrodes are symmetrically charged, and it grows much higher as the gap length increases, “figs 5b and 5c”. And this is also in full agreement with the analysis results of “figs 3”. The rods’ diameter is 10 mm, and the spheres’ diameter 100 mm. DC negative voltage is applied to the arrangements with one electrode grounded, and DC negative and positive to the symmetrical charging arrangements.

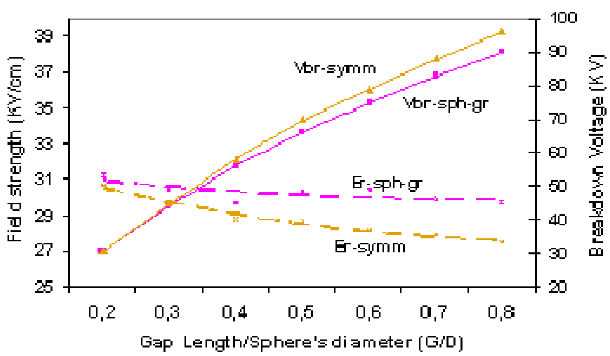
When the field is less inhomogeneous, e.g. when the rod’s or the sphere’ diameter is big enough, and the gap length is small, there are no corona effects before the breakdown. This is also valid in the small rod-plate air gaps with the rod grounded. In these cases we can compare the corona onset voltage of the plate grounded arrangement, with the breakdown voltage of the rod grounded arrangement, considering the corona onset voltage equal to the breakdown voltage.



(a) Rod-plate air gaps. The rod's diameter is 10 mm



(b) Rod-rod air gaps. The rod's diameter is 10 mm.

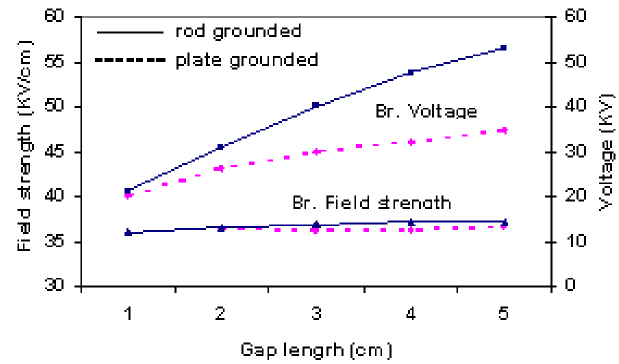


(c) The sphere-sphere air gaps. The sphere's diameter is 45 mm.

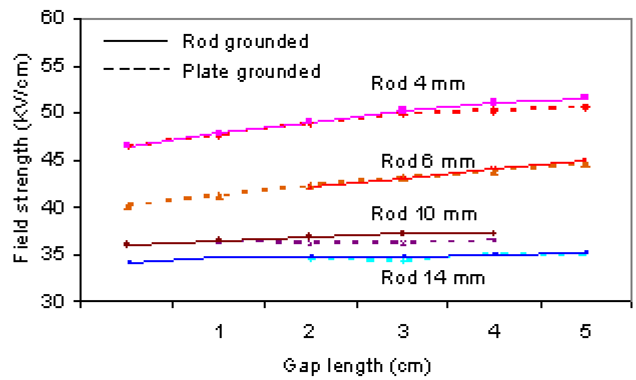
Fig. 5: The corona onset (Vc) and the breakdown (Vbr) Voltage in rod-plate, rod-rod and sphere-sphere air gaps for the different arrangements with the rod (r-gr), or the sphere (sph-gr), or the plate (pl-gr) grounded, either with symmetrical charging of the electrodes (symm), in comparison to the maximum values of the field strength (Er) in the gaps.

5 The Values of the Field Strength at Corona Onset and Breakdown

Combining the analysis with the experimental results, the maximum value of the field strength in the gap (field strength on the rod) is calculated for different arrangements, and especially for the different cases of grounding and electrode charging. The results are shown in "figs 7, 8, and 9".



(a) The rod's diameter is 10 mm



(b) The rod's diameter is 4-6-10-14 mm.

Fig. 6: The field strength at corona onset or breakdown in small rod-plate air gaps of different geometry. The plate's diameter is 100 mm, and the rod's diameter is 4, 6, 10, and 14 mm. The two different cases with the rod or the plate grounded are presented. DC negative voltage is applied.

It is resulted from "figs 6" that the values of the field strength at corona onset or breakdown do not depend on the way of grounding and charging of the electrodes, (pl-gr, or r-gr, or symm) as it was expected. They increase with the gap length, and decrease with the rod's diameter. A model equation that can describe this relation in rod-plate air gaps is:

$$E = 29 + (2 \cdot G + 33)/r \quad \text{(KV/cm)}, \qquad (5)$$

where G is the gap length in cm and r is the rod's radius in mm.

Equivalent curves for rod-rod air gaps are shown in "fig 8". The results show that the values of the corona onset field strength for the two different cases, with one of the rods grounded or with symmetrically charging of the electrodes, are relatively close, as it is expected. The small differences are due to measuring errors.

In "fig 7" the graphs the values of the field strength at breakdown from model equation (5) are very close to the results from analysis and experiments. The plate's diameter is 100 mm, and the applied voltage is DC negative.

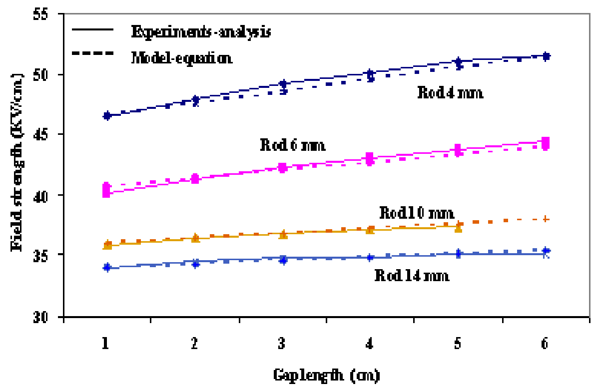


Fig. 7: The Breakdown field strength in small rod-plate air gaps of different geometry. With continuous lines the values from experiments and analysis, and with dashed lines from model equation (5).

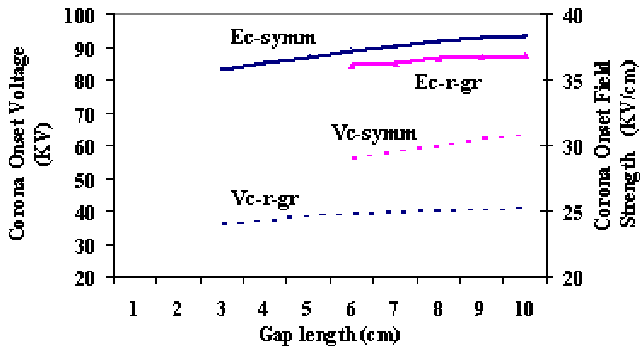


Fig. 8: The field strength at corona Onset and Breakdown (Ec and Ebr), and the Corona Onset and Breakdown Voltage (Vc, Vbr) of small rod-rod air gaps, in comparison. The applied voltage is DC negative in the rod grounded arrangements (r-gr), or DC negative and positive in symmetrical charging (Symm).

6 The Influence of the Corona Current to the Breakdown

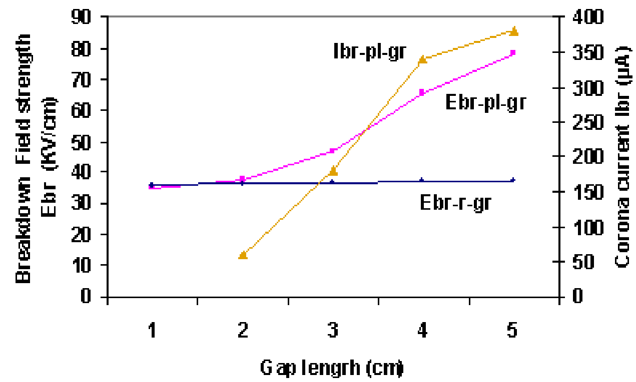
The influence of the effect of grounding to the breakdown voltage is most significant and clearer when the value of the breakdown voltage appears before the corona effects. This is valid when the gap length is relatively small, and the field is less inhomogeneous.

When the gap length is long enough, the field is more inhomogeneous, the corona effects are intense, and the influence of the corona current suppresses the effect of grounding. Thus the breakdown voltage appears to be higher in the arrangement with the plate grounded, "figs 9". Consequently the values of the field strength at breakdown are higher in the arrangement with the plate grounded.

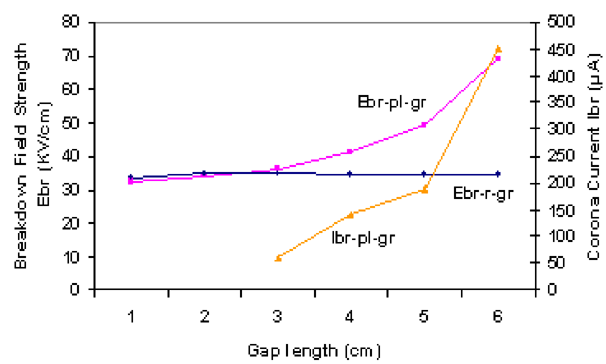
In the curves of "figs 9" the breakdown voltage in the arrangement with the plate grounded is below the breakdown voltage of the rod grounded arrangements, at small gap length, and crosses over at bigger lengths.

The corona current causes an increase of the breakdown voltage. If it can be accepted that the breakdown voltage is inversely proportional to the maximum value of the field strength, it is resulted that the corona current causes a decrease of the value of field strength on the rod. The bigger the corona current is, the lower the value of the field strength on the rod becomes.

Correspondent diagrams for the rod-rod arrangements are shown in "fig 10".



(a) The rod's diameter is 10 mm



(b) The rod's diameter is 14 mm

Fig. 9: The breakdown field strength for rod-plate air gaps for the two different arrangements with the rod (Ebr-r-gr) and plate (Ebr-pl-gr) grounded, and the corona current (Ibr-pl-gr) for the arrangement with the plate grounded. In the arrangement with the rod grounded there is no corona current before the breakdown. The applied voltage is DC negative.

Relations between the value of the breakdown voltage and field strength, and the corona current appear.

The model equations that can describe these relations are:

$$\Delta E_{br} = A \cdot \Delta I \qquad (6)$$

$$\Delta V_{br} = B \cdot \Delta I \qquad (7)$$

where ΔE is the theoretical field strength differences, ΔVbr the breakdown voltage differences, ΔI is the corona current differences between the two different arrangements (pl-gr

and r-gr), and A and B are parametric functions, their values depending on the gap's geometry and properties, with units Ω/m and Ω respectively.
The following model equation (8) gives a relation between the values of the field strength at breakdown, the values of the field strength at corona onset, and the corona current at breakdown for a rod-plate air gap with the plate grounded:

$$E_{br} = E_C - (0.1 \cdot G/r) \cdot I_C \qquad (8)$$

where E_{br}, and E_c are the values of the field strength at breakdown and corona onset on the rod in KV/cm, G the gap length in cm, and r the rod's radius in mm.
In "fig 11" the connection between the field strength and the corona current is shown for a rod-plate arrangement. It is resulted that the influence of the corona current to the field strength (and hence to the field distribution) is greater when the field is more inhomogeneous (bigger gap length, smaller rod's diameter). The graphs from model equation (8) are very close to the results from analysis and experiments. The rod's diameter is 10 mm, and the applied voltage DC negative.

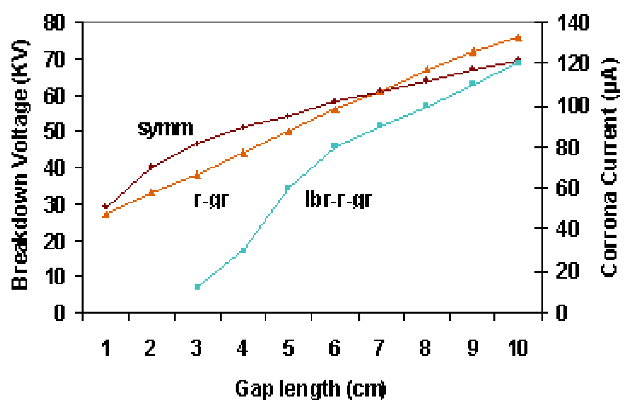


Fig. 11: The breakdown voltage and the corona current of rod-rod air gaps for the two different arrangements with one rod grounded (r-gr) or with symmetrical charging of the electrodes (symm). In the arrangement with symmetrical charging the corona current is negligible.

The law of action-reaction (3rd law of Newton) seems to be valid. We can define the following statement: "The inhomogeneity of the field produces the Corona Effects, and the Corona Current tending to oppose to the reason that causes it, tries to make the field less inhomogeneous, decreasing the maximum value of the field strength".

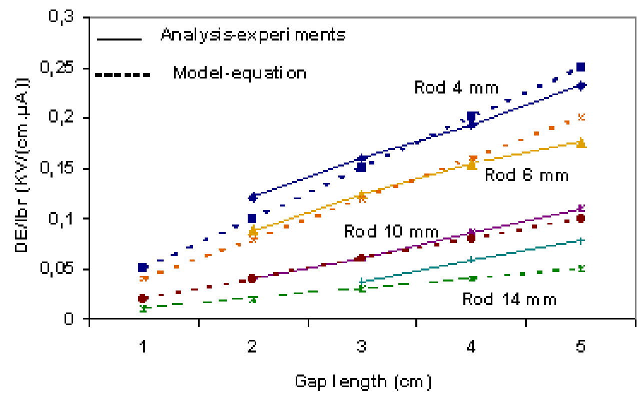


Fig. 11. The breakdown field strength for rod-plate air gaps for the two different arrangements with the rod and plate grounded. Comparison between analysis-experimental results and values from model equation (8)

6 Conclusions

The effect of grounding influences the field distribution in rod-plate air gaps, with the influence depending strongly on the gap length as well as the rod's diameter, and the plate's diameter. The maximum value of the field strength is higher in the arrangement with the plate grounded. The effect of grounding influences the rod-rod and the sphere-sphere arrangements accordingly, the field strength being higher in the arrangements with one electrode grounded.
The effect of grounding influences the corona onset and the breakdown voltage of small rod-plate air gaps. In small air gaps with the rod grounded, the corona onset and the breakdown voltage are higher, in comparison to the arrangement with symmetrical charging of the electrodes, or with the plate grounded. The influence to the rod-rod and sphere-sphere air gaps is smaller.
The values of the field strength at corona onset and breakdown for the different cases of grounding of small air gaps are very close, as it was expected. The values increase with the gap length, and decrease with the rod's diameter.
A relation between the values of the field strength at corona onset or breakdown, the gap length and the rod's diameter, and a model equation is formulated.
In longer rod-plate air gaps with smaller rod's diameter, the field is more inhomogeneous, the corona effects appear in a lower voltage, and suspend the breakdown, which takes place in a higher voltage and correspondent field strength in the arrangement with the plate grounded, and hence the effect of grounding vanishes.
A relation between the breakdown field strength and the corona current, and a model equation arises. The principle of action-reaction (Newton's third law) is valid. "The corona current reacts against the action of the

inhomogeneity 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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