The influence of the Corona Current to the Ground and the Polarity Effect of small air gaps

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Abstract: The Corona Current in air gaps influences the values of the breakdown voltage of the air gaps greatly. This happens because the corona current changes the field distribution in the gap making it less inhomogeneous. Thus the value of the breakdown voltage increases and becomes bigger as the value of the corona current increases. A major result of this phenomenon is the appearance of the Polarity Effect. The Polarity Effect is a phenomenon occurring due to the alteration of the polarity of the applied voltage to the gaps. When the applied voltage is negative the value of the breakdown voltage is bigger and this happens because the corona current is considerably higher. A second important result of the Corona Current Effect is the inversion of the Ground Effect. The Ground Effect is the phenomenon that occurs due to the different way the gap is grounded and influences the distribution of the field in the gap, the corona onset voltage, as well as the breakdown voltage in small gaps. In longer air gaps, the Corona Effects become very intense and the influence of the Ground Effect to the breakdown voltage is overlapped. 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 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, [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] - [15].

In less homogenous electric fields like the small air gaps with relatively big diameters of the electrodes, the corona effects do not appear before the 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, [16[, [17].

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. 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 specific electrode is grounded [15]-[19].

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 [15]-[19]. 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 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.

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

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:

$$\mathrm{E} = -\nabla V \qquad (1)$$

$$\nabla \mathrm{D} = -\rho \qquad (2)$$

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

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].

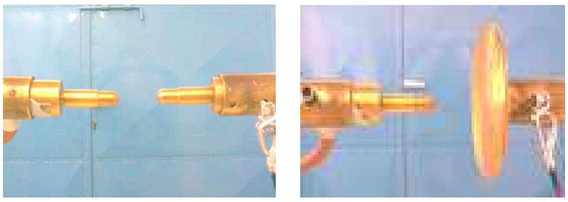
The electric charge density, and the total electric charge on a particular surface S, or in the volume included in surface S, is calculated by equations [1], [2].

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

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

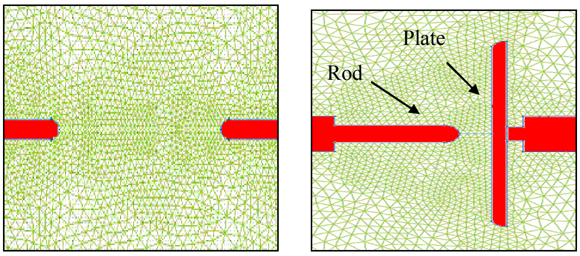
2. The investigated arrangements.

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 is applied to one electrode while the other is at earth potential (grounded). Models with symmetrical charging of the electrodes (Symm) have also been analyzed and investigated. All the analyzed models are axisymetric, with a spherical boundary shield big enough in diameter, "figs 1, 2 and 3".



(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

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 and the Breakdown voltage of the gaps.

3.1 The influence to the field distribution

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.

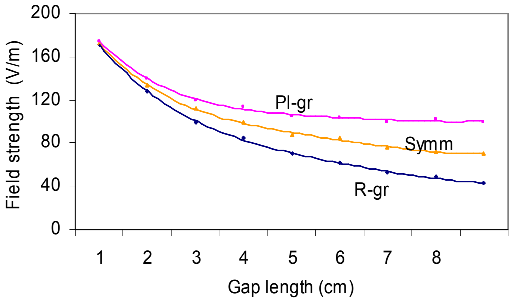


Fig. 3: Maximum values of the field strength on the rod, in rod - plate air gaps, from simulation analysis.

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.) are 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.

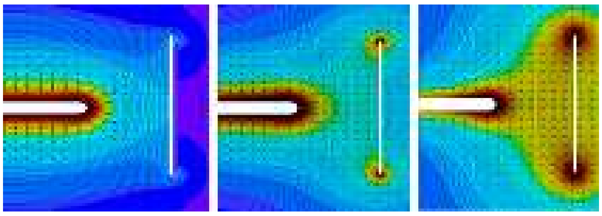


Plate grounded Symmetrical ch. Rod grounded

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

When the plate's diameter becomes very big the Ground Effect decreases. In this case the rod-plate arrangement functions like a rod-rod arrangement of double length, stressed by double voltage symmetrically, (Mirror Effect).

3.2 The influence to the Corona Onset 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.

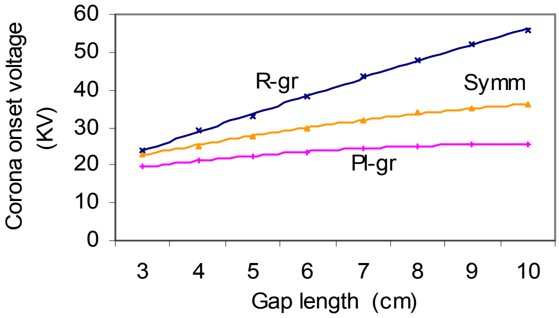


Fig. 5: The influence of the Ground effect to the Corona Onset Voltage of rod-plate air gaps, in function with the gap length, for DC voltage.

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. 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, or with symmetrically charged electrodes is comparatively lower, and grows lower as the gap length increases, “fig 5”.

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:

$V_{c\text{-}r\text{-}gr} / V_{c\text{-}pl\text{-}gr} = A*(E_{r\text{-}pl\text{-}gr} / E_{r\text{-}r\text{-}gr})$, where $A \leq 1$ (8)

Correspondent relations are valid for the rod-rod arrangements.

3.3 The influence to the breakdown voltage

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 or lightning Impulse voltage. This is in full agreement with the results of the analysis, “fig 3”.

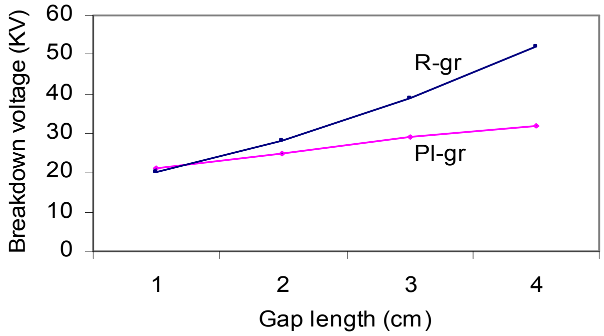


Fig. 6: The influence of the Ground Effect to the Breakdown Voltage of small rod-plate air gaps, in function with the gap length, stressed by DC voltage.

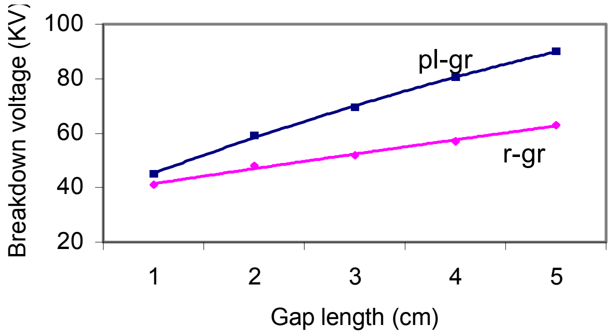


Fig. 7: The influence of the Ground Effect to the Breakdown Voltage of small rod-plate air gaps, stressed by Impulse voltage 1.2/50 μs.

The influence is most significant and clearer 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.

From “fig 8” it is resulted that the calculated maximum values of the field strength at corona onset for the two different arrangements with the plate or the rod grounded are very close. The values of the field strength at Corona Onset depend on the rod’s diameter and the gap length. So they depend on the inhomogeneity of the field, but they don’t depend on the way the gap is grounded, as it is expected.

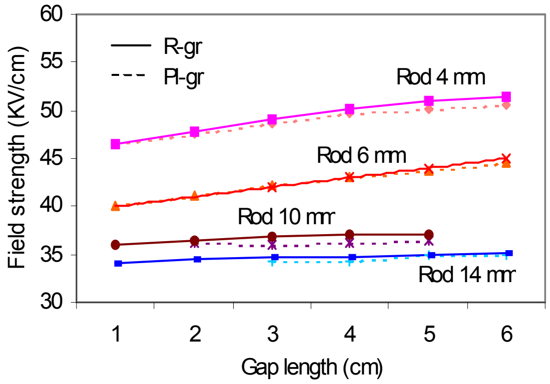
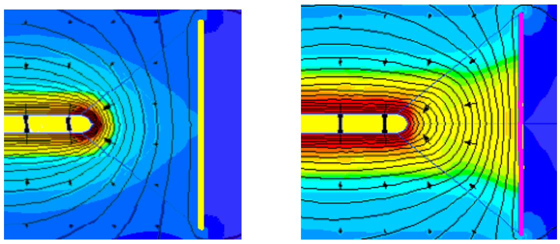


Fig. 8: The corona onset field strength for rod-plate air gaps with a plate’s diameter of 100 mm and a rod’s diameter of 4, 6, 10 and 14 mm.

4 The influence of the Corona Current to the Ground Effect

In longer air gaps, where the corona effects appear before the 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.

Fig. 9: Field strength distribution in a rod-plate air gap model with or without corona charges from simulation analysis.

The analyzed model in “fig 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 Current 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, “fig 10”.

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”.

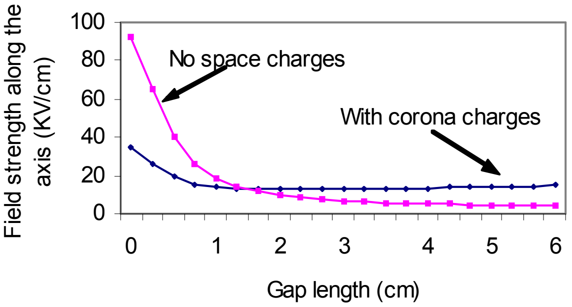


Fig. 10: The influence of the corona space charges to the field strength values along the axis of a rod-plate air gap model.

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. 11”.

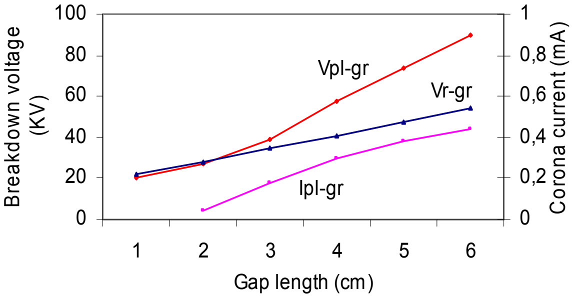


Fig. 11: The inversion of the Ground Effect by the Corona current. The applied voltage is negative DC.

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 “figs 11 and 12”.

The influence of the corona effects is stronger when the rod is stressed by DC negative voltage or when its diameter is very small, because in these cases the corona current is a lot higher, “figs 11 and 12”.

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 the equation (9).

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

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).

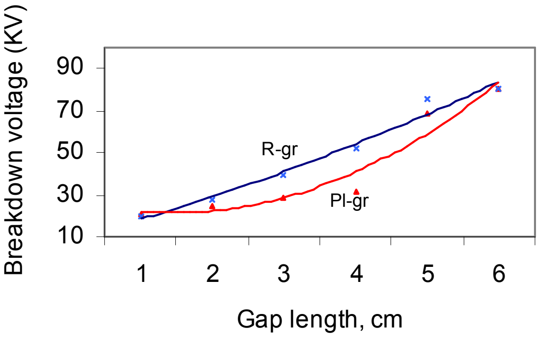


Fig. 12: The influence of the corona current to the Ground Effect. Positive DC voltage is applied.

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, “fig. 12”. This is the well-known Polarity Effect.

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

$$V_{br-} - V_{br+} = A\left(I_{br-} - I_{br+}\right) \qquad (10)$$

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 “fig 12” the parameter A=ΔV/ΔI seems to be linear in function to the gap length.

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 “fig 7”. 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.

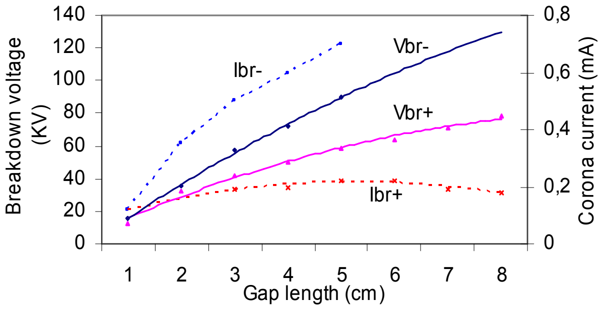


Fig. 13: The influence of the Corona current to the breakdown voltage of rod-plate air gaps.

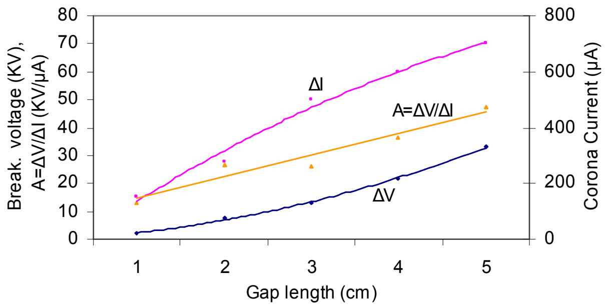


Fig. 14: The connection between the Breakdown voltage and the Corona Current of rod-plate air gaps

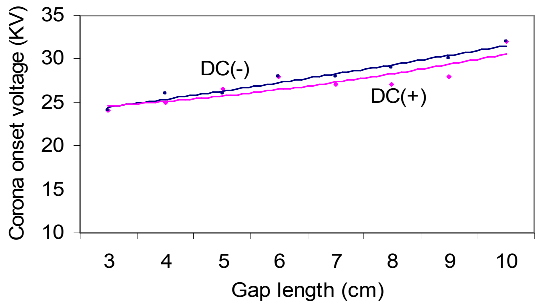


Fig. 15: The Polarity Effect to the Corona onset of rod-rod air gaps. The rod’s diameter is 4 mm.

Correspondent to equations “(9) and (10)” come out for the values of the field strength at corona onset and breakdown accordingly.

The polarity Effect also influences the corona onset voltage of air gaps, but the influence is very small, “fig 15”.

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 small rod-plate arrangements the field is less inhomogeneous when the rod is grounded, and hence the values of the Corona Onset or the Breakdown voltage are higher.
3) When the field is less inhomogeneous there are no corona effects before the breakdown.
4) A relation between the maximum value of the field strength on the rod and the corona onset or the breakdown voltage appears.
5) The corona onset or the breakdown field strength for the different cases of grounding of small air gaps are very close, although the correspondent values of corona onset or breakdown voltage are much different due to the Ground Effect.
6) In longer rod-plate air gaps with smaller rod’s diameter, the field is more inhomogeneous and the corona current influences the field distribution and hence the breakdown. The breakdown voltage is higher when the Corona Current is higher, and so the Ground Effect may be overlapped.
7) The Polarity Effect, as far as the breakdown voltage is concerned, is clearly connected to the Corona Current through the gap.
8) A relation between the breakdown voltage and the corona current arises. 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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