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Experimental investigation along with simulation analysis of small rod–plate air gaps with or without a Barrier. The Ground Effect.

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Abstract: The rod – plate air gaps are of great importance in High Voltage applications. The rod – plate air gap with the plate grounded has been investigated enough, while a study of the case with the rod grounded is missed. In the present paper both arrangements of a rod – plate air gap 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, when 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 electrodes and the arrangement of the gap, and especially by the grounded electrode (Ground Effect). A dielectric plate, called barrier, placed between the electrodes, is electrically charged when the stressed voltage is higher than the corona onset voltage on the rod. The maximum value of the voltage on the barrier is equal, less or greater than the rod voltage depending on the position of the barrier, the grounded electrode, and the polarity of the voltage. The charged barrier influences the distribution of the field and the breakdown voltage, vindicating a special relation between them. The simulation and experimental results are compared.

Key Words: Barrier Effect, Simulation, Air Gaps, Breakdown Voltages, Field Strength.

1 Introduction

The study of the field strength distribution in electric fields, and especially in non-uniform electric fields, like the fields in rod – plate air gaps, is of great importance in high voltages, because the most determinant factors of the dielelectric strength of the insulating materials is the field strength distribution inside the mass of the materials, when stressed by high voltages, as well as the corona leakage current through the air in the gap [17].

The experimental measurement of the field strength in small air gaps stressed by High Voltages is a very difficult process and not quite accurate. The insertion of a measuring arrangement (e.g. a probe), especially near the stressed electrode, is not an easy process and it affects the distribution of the field, influencing the results. The analysis of the proper models of the air gap electric fields using Laplace's and Poisson's equations for general 2 or 3-dimensional fields with a theoretical - mathematical way is more accurate but it is time consuming and in some cases it leads to difficulties. The most convenient way is to use numerical procedures.

This paper investigates the Modelling and Analysis of the electric field distribution in rod plate air gaps at breakdown, under different geometries and arrangements of the gaps, using the Finite Element Method, in relation to experimental results. The influence on the electric field distribution, caused by the insertion of a dielectric insulated plate, called barrier, between the electrodes in a non-uniform electric field arrangement is also analysed and presented. The simulation results are compared with relative experimental or theoretical results of referent research works.

2 Theoretical background.

Software Quick field developed by Terra Analysis has been used in the present paper. 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:

$$\boldsymbol{E} = -\nabla \boldsymbol{U} \qquad (1)$$

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

or

$$\nabla^2 \boldsymbol{U} = -\rho/\varepsilon, \qquad (3)$$

where ρ is the space charge density in C/m^3, ε is the dielectric constant of the medium, U is voltage, and $\boldsymbol{D=\varepsilon E}$, is the dielectric displacement.

The electric charge density, and total Electric charge in a particular surface S, or volume included in surface S, is calculated by the equations:

$$q = \Delta D_n, \quad and \quad Q=\int_s D_n ds \qquad (4)$$

The boundary conditions and especially the mesh density used for the analysis are of great importance for accurate results. Space charges have not been taken into account at present work.

3 The simulated models.

The models that have been studied experimentally and analyzed with Finite Element Analysis are typical rod - plate air gap arrangements of different geometries. The rod electrode is a cylinder long enough, with a small diameter, and a hemisphere tip. The plate electrode is a disk plate, with a relatively big diameter. 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, with very small thickness (less than 1 mm), located at a distance ***L*** from the stressed electrode.

All the analyzed models are axisymetric with a spherical boundary surface. The radius of the boundary sphere is large enough (at least 10 times the arrangement dimensions) in order to eliminate errors. The boundary Dirichlet condition is V=0. [15], [16], [18].

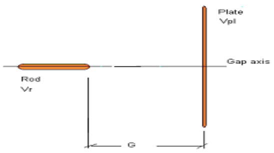


Fig 1. Rod - plate air gap.

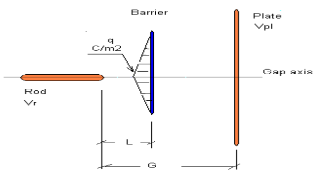


Fig 2. Rod - plate air gap with barrier

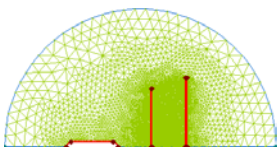


Fig 3. Rod - plate air gap with barrier. Picture from QF analysis

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

$$Eav = V/G \qquad (V/m) \qquad (5)$$

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 the equation:

$$n= Emax/Eav \qquad (6)$$

For a rod – plate gap it is given by the equation:

$$n=2*G/(r*\ln(4G/r)), \quad \text{if } G>>r \qquad (7)$$

where G is the gap length, Emax and Eav the maximum and the average values of the field strength, and r is the radius of the tip of the rod. [1], [2]

3.1 Models of air gaps without barrier

Rod – plate arrangements, with different grounded electrode, different dimensions of the plate and the rod, different length of the gap and no barrier between the electrodes have been modeled and analyzed. The maximum value of the field strength and the field factor of the gap are demonstrated in figs 4,5,6, and 7. The values of the breakdown voltages are measurement data from experimental work.

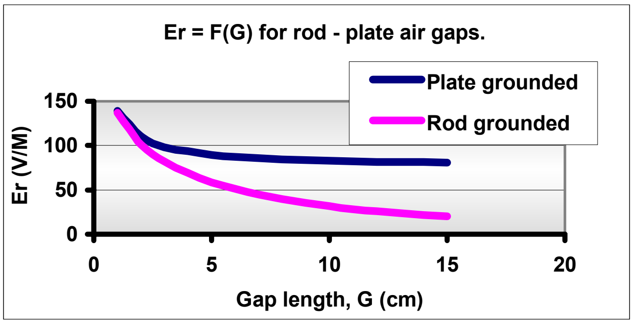


Fig 4. Rod plate air gap. Maximum value of field strength on the rod for the 2 different arrangements with the rod and the plate grounded. The applied voltage is 1 V. The plate's diameter is 100 mm, and the rod's diameter is 10 mm.

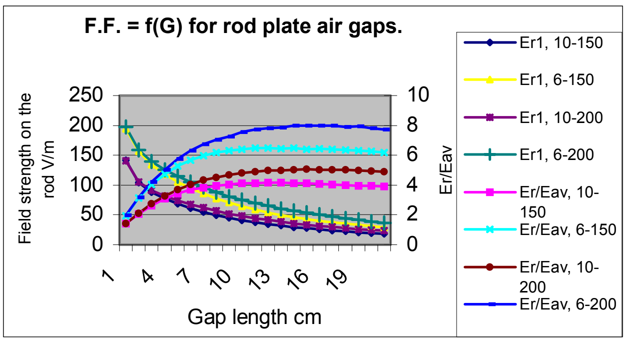
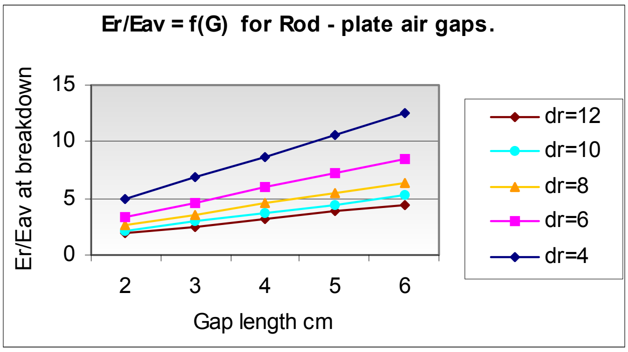
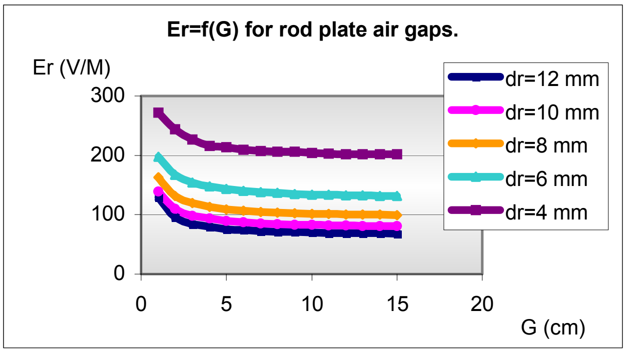


Fig 5. Rod - plate air gap, with the rod grounded. The maximum value of field strength and the field factor along the axis of the gap for different values of the rod's diameter, the plate's diameter and the gap length is shown. The applied Voltage is 1 V.



(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 Field strength on the rod and the field factor along the axis of the gap for different values of the rod's diameter (dr) and the gap length is shown. The plate diameter is 100 mm. The applied Voltage is 1 V

The comparison between the two different cases of arrangement with the rod or the plate grounded, (figures 4, 5, 6 and 7) results that there are big differences between the two different arrangements. 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 much higher and tends to get a steady value for each value of the rod diameter when the gap is longer than 80% of the plates diameter.

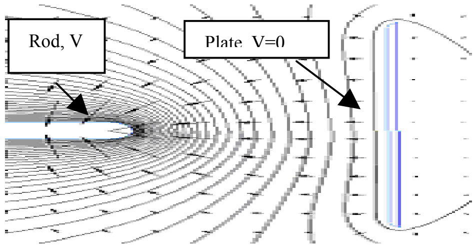
It is also resulted that the Field factor (Er/Eav) increases with the gap length. In the rod grounded arrangement it is lower and tends to get a steady value for each value of the rod's diameter when the gap length is longer than 80% of the plate's diameter. The equation that can describe the above results it is an exponential equation of the type **Er/Eav=f(G,dr).e^f(G,dr)** **(8)**, at least for the first part of the graphs.

The graphs in fig 5a are in complete agreement with relative graphs according to equation (7):

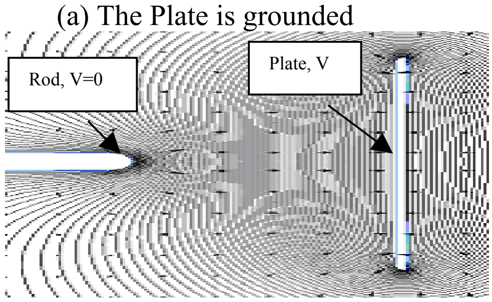
$$n=2*G/(r*\ln(4*G/r)).$$

The values of the field strength on the rod, and the field factor increase with increasing gap length and plate's diameter.

In the rod-plate air gap with grounded rod the field is less inhomogeneous. Since the inhomogeneity of the field is one of the basic reasons for the breakdown voltage to have different values for arrangements with the same gap length, we can say that there is a **Ground Effect for the rod-plate air gaps, similar to the polarity effect. The Ground Effect affects the dielectric strength of the air gap greatly** (fig 7**).**



(a) The Plate is grounded



(b) The rod is grounded

Fig 7. Field strength distribution in a rod – plate air gap model.

3.2 Models of air gaps with Barriers.

The electrical insulation of power apparatus is generally made of composite dielectrics. A basic composite insulation arrangement is that of a rod-plate arrangement with a dielectric plate, called barrier, placed between a stressed electrode and a grounded one. The influence of the Barrier to the distribution of the electric field and thus to the discharge and the breakdown voltage of the gap is called Barrier Effect. [3], [4],[5],[6],[7].

The dielectric barrier, when placed between the electrodes 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. [3],[4],[5],[6],[15],[16],[18].

When a rod – plate air gap with a barrier is stressed by voltage and the value of the field strength on the rod is higher than the corona onset field strength, corona space charges drift through the air to the

barrier and accumulate on the surface facing the rod electrode (fig 8). 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 and the position of the barrier in the gap. This is called Barrier Effect.
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.

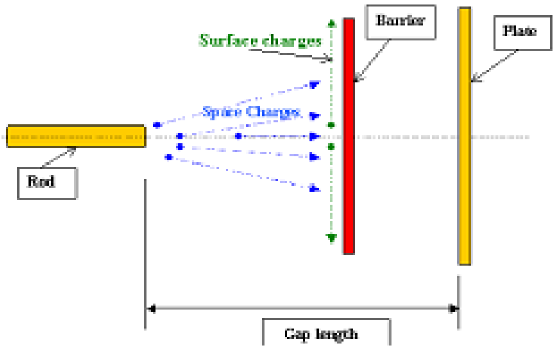
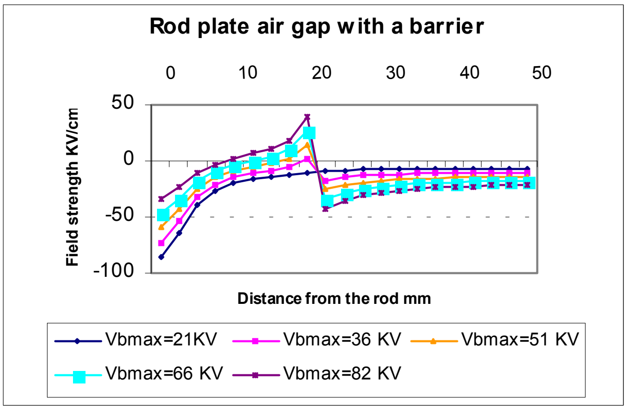
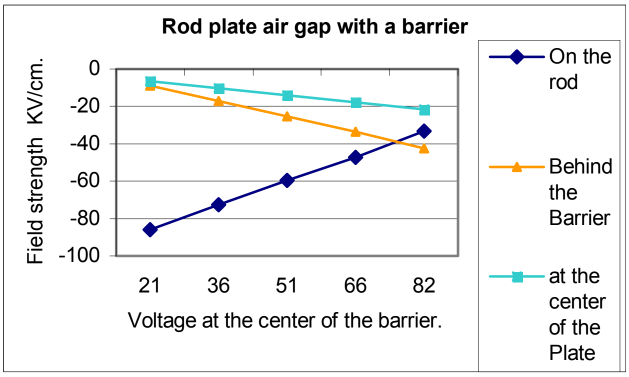


Fig 8. Rod–plate air gap stressed by high voltage. Electric charge is accumulated and distributed on the barrier.

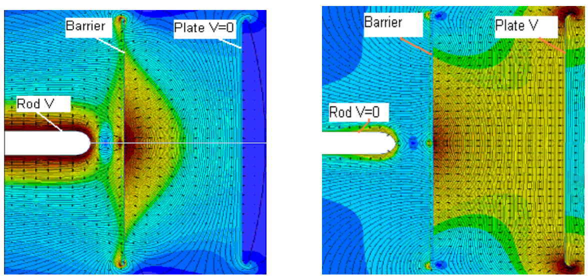
The field strength distribution along the axis of the gap for different values of the voltage of the barrier and different positions of the barrier in the gap is shown in fig 9, and 11. The two different cases of the arrangements with the rod grounded or the plate grounded have been investigated.
It follows from figure 9 that 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.
The field strength on the barrier and the average field strength of the whole gap increase significantly. The average field strength in the part, which is between the barrier and the plate, increases as the charged barrier moves towards the plate (fig 10).
It is concluded from the analysis (fig 11) that while the maximum values of the field strength in the part between the barrier and the plate are near the expected values for the breakdown (near 30 KV/cm) [6],[7], the values of the voltage at the center of the barrier is 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, [3], [4], [5], [6], [7],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 figs 10, 11 from analysis with the QF, 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.



(a)Field strength distribution along the axis.

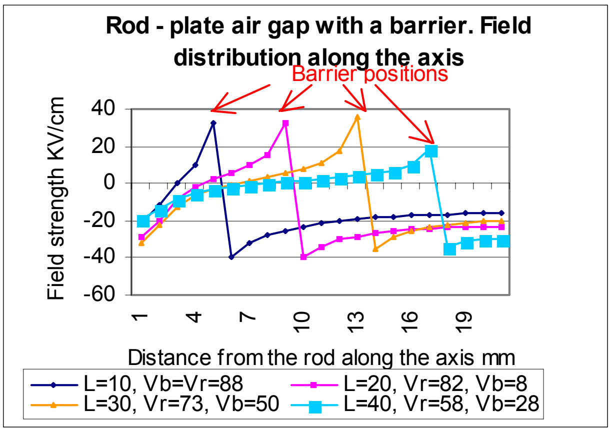


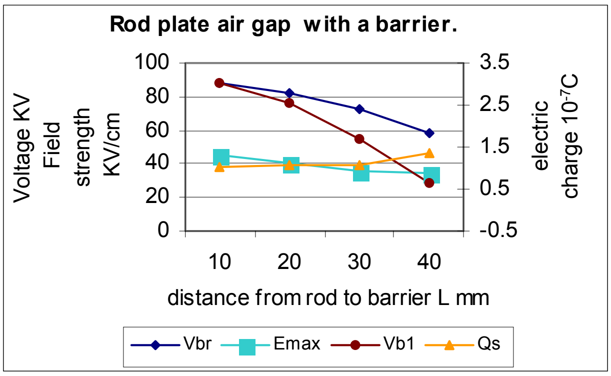
(b) Field strength at specific points along the axis.
Fig 9. Rod - plate air gap with a barrier at L=20 mm from the rod. The plate is grounded and the barrier is charged with different values of voltage Vb linearly decreasing from the center to radial direction. The Applied voltage is DC negative voltage. The breakdown voltage is 82 KV.



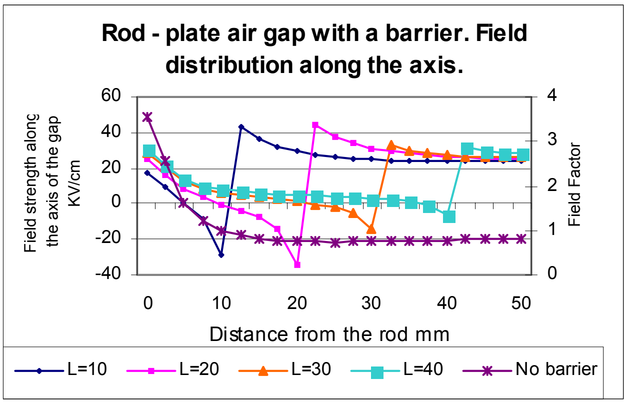
The plate is grounded. The rod is grounded

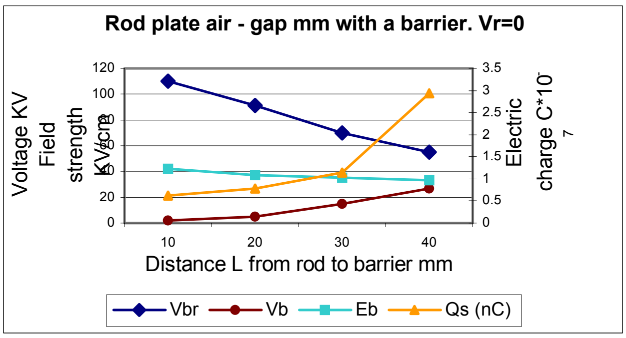
Fig 10. The field strength distribution in a rod plate air gap with a charged barrier from QF analysis.





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





(b) The Rod is grounded, Vr=0

Fig 11. Rod plate air gap 50 mm long with a charged barrier at different positions. The breakdown voltage (Vbr), the field strength on the rod (Er) and behind the barrier (Eb), and the electric charge on the barrier (Qs) are shown. The applied voltage is negative DC voltage.

The field strength on the barrier, at fig 11, has a typical value near 30 KV/cm, which is the expected value of the breakdown for the part of the gap between the barrier and the plate.

From figure 9 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. Practically the space charge and the electric leakage current through the air of the gap limit its value. It is easy to understand that the field strength on the barrier's surface, facing the rod, cannot exceed the zero value.

The distribution of the field strength in the rod plate air gap with a barrier, and especially in the part between the barrier and the plate, at breakdown, has been investigated for the special case in which the barrier is charged but the rod has no voltage.

The analysis results are shown in fig 12 in comparison with the results for the case with the rod normally stressed. It is resulted that the field distribution in the part between the barrier and the plate depends slightly on the rod voltage when the barrier is charged. Especially the field strength distribution along the axis from the barrier to the plate suffers no change when the voltage of the rod changes. This leads to the conclusion that the dielectric strength of a rod plate arrangement with a barrier depends mainly on the behavior of the part between the barrier and the plate, reinforcing the point of view that the behavior of the air gap depends mainly on the behavior of the part between the barrier and the plate.

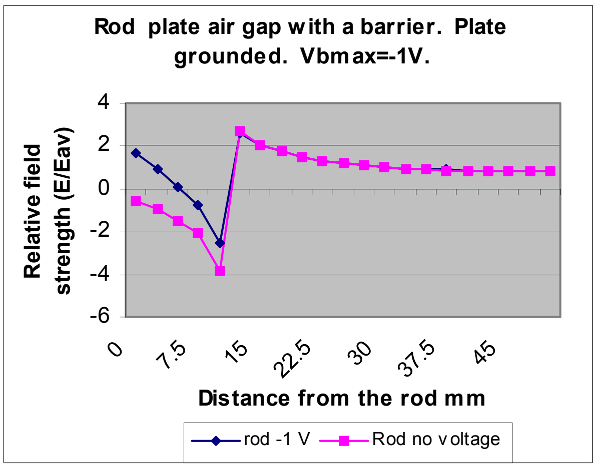
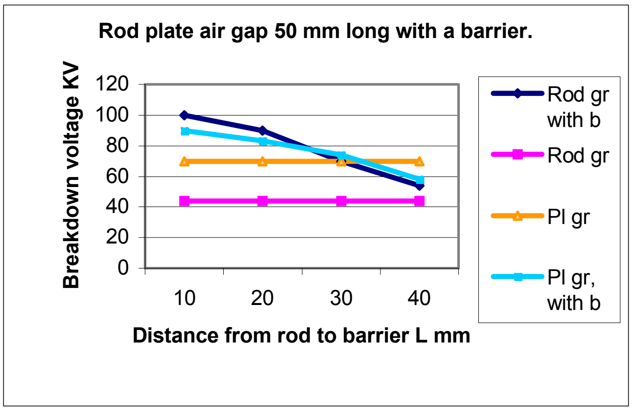


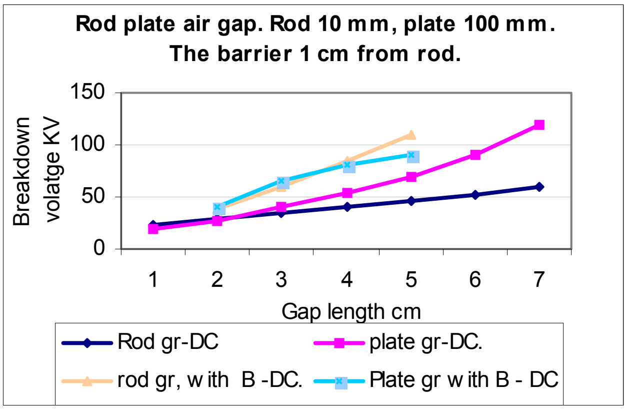
Fig 12. Rod plate air gap with a charged barrier at a distance of 10 mm from the rod and no voltage on the rod. The field strength along the axis of the gap in comparison with the case where the rod is normally stressed. The plate is grounded.

4 The breakdown voltage of the rod plate air gaps with or without barrier.

The breakdown voltage of rod plate arrangements with or without a barrier has been investigated and the results are shown in fig 12. It is obvious from this fig that the values of the breakdown voltage are very different for the two different cases with the plate and the rod grounded. The **Ground effect** is valid for the breakdown voltages of both arrangements. It strongly influences the arrangements without barrier, while it has less influence to the arrangements with a barrier. The insertion of the barrier influences the arrangement more when the rod is grounded, increasing significantly the breakdown voltage.



(a) Breakdown voltage as a function of the position of the barrier in a rod plate air gap of 50 mm long, with or without a barrier.



(b) Breakdown voltage as a function of the gap length, when the barrier is located at a distance of 10 mm from the rod.

Figure 13. Rod plate air gap, with a barrier at distance L from the rod. Rod 10 mm. Rod diameter 10 mm, plate diameter 100 mm. The applied voltage is negative DC voltage.

It also follows from figure 13 that the values of the breakdown voltage of the arrangement decrease as the barrier is closer to the plate. This statement is well known for the air gaps with the plate grounded. [3],[4] [5], [6], [7], [8], [9], [10], [11], [12], [15], [16], [18].

The breakdown voltage of a plain rod – plate arrangement with the plate grounded is lower, than for the arrangement with the rod grounded, when the gap length is less than 2 cm. 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 plate grounded is higher (fig 4). In the air gaps with bigger than 2 cm length the breakdown voltage is higher for the arrangement with the plate grounded because of the corona leakage current [17].

5 Conclusions

According to the simulation analysis made in this paper with the Finite Element Method for the models of rod plate air gaps with or without dielectric barrier, and in connection to the experimental results for the values of the breakdown voltage, the following conclusions have arisen:

1. The distribution of the electric field in a rod – plate air gap and the value of breakdown voltage is strongly affected by the geometry (shape and dimensions) of the electrodes, as well as the grounded electrode.
2. It is very important to point out that there are significant differences of the field distribution and the values of the breakdown voltage between the two different arrangements, the one with the plate grounded and the other with the rod grounded. In both arrangements, the field factor along the axis increases with the gap length, but in a different way. We can call this phenomenon the **Ground Effect** of a rod plate air gap**.**
3. The maximum value of the field strength on the rod is much higher in the arrangement with the plate grounded.
4. When a dielectric plate, called Barrier, is placed between the electrodes, at high voltages it is charged with corona space charges, thus influencing the distribution of the field. The charge is linearly distributed on the barrier, and the value of the voltage at the centre of the barrier is very close to the value of the rod's voltage when the barrier is near the rod. The field becomes less inhomogeneous and the average field strength as well as the breakdown voltage for the whole gap increases significantly.
5. The breakdown voltage of a rod plate arrangement without barrier depends mainly on the electrode chosen to be grounded (Ground Effect). The basic

reason is the electric field distribution and the leakage current due to the corona space charges. In small air gap arrangements, in which the breakdown voltage is lower than the corona onset voltage, there is no significant leakage current. In these cases the breakdown voltage of the arrangement with the plate grounded is lower than of the arrangement with the rod grounded.

6. The breakdown voltage of a rod plate arrangement with a barrier depends mainly on the position of the barrier in the gap and the maximum value of the field strength at the part between the barrier and the plate. The influence of the Ground Effect is less significant than in the plain gaps.

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References:

[1] E. Kuffel, W.S. Zaengl, J. Kuffel. (2000) *High Voltage Engineering. Fundamentals*. Newnes Oxford.

[2] Khalifa, M. (1990) *High-Voltage Engineering, Theory and Practice*. Marcel Dekker inc., New York

[3] Marx E ., *Der Durchschlag der Luft im Unhomogenen elektrischen Felde bei verschiedenen, Spannungsarten* . ETZ, vol. 33, pp. 1161-1165.

[4] Marx E (1930), *Der elektrische Durchshlag von Luft im unhomogenen Feid* . Arch. f. El., vol. 24, pp. 61f.

[5] Roser, H. (1932), *Schirme zur Erhohung der Durchschlagapannung in Luft* . ETZ, vol. 17, pp. 411-412.

[6] Hidaka K., and Kouno, T., A (1982), *Method for measuring field in space charge by means of Pockel's device*. J. Electrostatics vol. 11 pp. 195-211

[7] Hidaka, K., Chiba, M., and Kouno, T. (1988), *Barrier effect on electrical breakdown in air*. IX International Conference on Gas Discharges and their Applications, Venice, pp. 479-482

[8] Topalis, F. V., and Stathopulos, I. A. (1991), *Barrier effect in small and medium air gaps*. VII International Symposium on High Voltage engineering, Dresden, pp. 157-160

[9] Topalis, F. V., and Stathopulos, I. A . (1992), *Barrier effect on electrical breakdown in non-uniform small and medium air gaps.* VI International Conference on Dielectric Measurements and Applications Manchester

[10] Li Ming, Mats Leijon and Tord Bengtsson. (1994) *Barrier effects in air gaps under DC voltage.* 7th International Symposium on Gaseous dielectrics Knoxville, USA

[11] F.V Topalis , and I. F. Gonos and I. A Stathopoulos (1999), *Insulation properties of composite dielectric arrangements*. Proceedings of the LASTED International Conference Power and Energy Systems. Las Vegas Nevada-USA

[12] Li Ming, Mats Leijon and Tord Bengtsson. (1995) *Factors influencing barrier effects in air gaps*. Ninth International Symposium On High Voltage Engineering. Graz, Austria.

[13] S M Lebedev, D P Agoris, I Vitellas and Yu P Pokholkov (2000). *The role of polarization in the breakdown of an air gap with barrier*. J. of Phys. D: Appl. Phys. 34 (2001)

[14] F.V Topalis , and I. F. Gonos and I. A Stathopoulos (2002) *Insulation properties of composite dielectric arrangements*. International Journal of :Power and Energy Systems, Vol 22, No. 3.

[15] A. Maglaras. *Numerical analysis of electric field in air gaps, related to the Barrier Effect*.. 1st IC-SCCE Athens, 2004.

[16] A. Maglaras. L. Maglaras. *Modeling and analysis of electric field distribution in air gaps, stressed by breakdown voltages*. WSEAS MMACTEE Athens 2004.

[17]A. Maglaras. L. Maglaras. *Numerical Modeling and Analysis of electric field distribution in rod – plate air gaps, with or without barrier, stressed by breakdown* voltages. 1st IC-EpsMsO, Athens, 6-9 July, 2005.

[18] A. maglaras, J. Andritsos, G. Soyltis, L. Maglaras. *New methods in experimental work along with simulation modeling and analysis in the laboratories of the Electrical Engineering Department of the T.E.I of Larissa*. WSEAS – International Conference on engineering Education, Athens 8-10 July 2005