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Control and Optimization of the Corona Effects and Breakdown of Small Rod-plate Air Gaps Stressed by dc and Impulse Voltages

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***Abstract*— In the present paper methods of controlling Corona and breakdown in small rod-plate air gaps are investigated. Combining experimental and simulation-theoretical work, it is resulted that when the rod's diameter is bigger, the gap length larger and the rod is grounded the field is less inhomogeneous. Therefore the value of the dc breakdown voltage without Corona is higher. If Corona occurs then the values of the Corona onset voltage are higher, and the corona effects are not intense. The Corona effects, lead to a rise of the value of the dc breakdown voltage especially when the rod is negatively charged. Moreover an insulated thin barrier, when positioned near the rod increases the breakdown dc voltage to a maximum value, and minimizes the Corona effects. Especially for gaps stressed by impulse voltage the Corona effects, appearing with the form of electric current pulses, are influenced by the same factors with a different way. The values of the breakdown voltage in contrast to what happens with dc voltage are higher when the Corona effects are weaker, depending on the influence of the field's inhomogenity (geometry and effect of grounding). It is also resulted that a resistor connected in series with the gap decreases its maximum charging voltage and increases the value of the breakdown voltage.**

Keywords— Corona; Breakdown; simulation; impulse; capacitance

I. Introduction

Air gaps are the most conventional insulating arrangements and thus are considered as one of the most important parameters for the design and dimensioning of insulating arrangements. In designing nearly every electrical arrangement, air gaps are essential components that arise necessarily in constructions, and especially in high voltages (switches, gaps between power lines, or power lines and earth, gaps between electrical and electronic components in most devices, etc.).

The mostly studied air gaps are the sphere-sphere, rod-rod and especially the rod-plate or point-plate air gaps mainly when the plate is grounded, because these gaps feature the least dielectric strength and the most intense Corona effects.

The basic effects which are referred as the dielectric behavior of an air gap are the Corona effects (electric charges in the gap) and the breakdown voltage [1-2]. The basic magnitudes which describe the dielectric behavior of an air gap are the Corona onset voltage, the Corona current in the form of current pulses and the Breakdown Voltage, [1-4].

The most known effects which influence the values of the above mentioned magnitudes are, the polarity effect, [1-2], and the barrier effect (composite insulation), [7]. Other lately investigated phenomena which have great influence on the dielectric behavior of the air gaps are the ground effect, that is the influence of the different electrode chosen to be grounded on the field distribution of a gap [8-9], and the Corona current effect, that is the influence of the Corona effects on the dc breakdown voltage of an air gap.

The polarity effect and its influence to the breakdown voltage have also been studied from many researchers involving arrangements with a grounded plate. The corona current effect combined with the polarity effect and ground effect has recently been an object of study mainly for arrangements stressed by dc voltage [9].

Air gaps with the rod grounded stressed by impulse voltages have not been investigated yet. In such arrangements the electric field in the gap is less inhomogeneous and the voltage needed for the Corona pulses to occur is higher and consequently the breakdown voltage is also higher, [10]. In the present paper the combined influence of the ground and the barrier effect on Corona and breakdown in rod-plate arrangements stressed by dc voltage, as well as the influence of

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the ground in combination to the Corona effects on arrangements stressed by lightning impulse voltage are investigated. The corona effects, which occur in air gaps before breakdown, when stressed by dc or low frequency ac voltages postpone the breakdown mechanism [8], while with impulse voltages they lead to breakdown [1].

The basic magnitude which influences the dielectric behavior of the air gaps is the field strength, and especially the maximum value of the field strength in the gap

$$E_{\max} = n \cdot E_{av} \ , \qquad (1)$$

where $E_{av} = V/G$, V (V) is the applied voltage, G (cm) is the gap length, and n is the field factor of the gap. For a rod-plate air gap, with a very big plate, and r_r the rod's diameter the field factor is given by equation [1, 2]:

$$\mathrm{n} = \frac{2G}{r_r \cdot \ln(G/r_r)} \ , \quad \text{if } G \gg r_r, \qquad (2)$$

The equations that calculate the values of the dc corona onset field strength on the tip of a rod are taken from bibliography, such as the empirical equation:

$$\mathrm{E_c} = 22{,}4 \cdot \left[1 + \frac{1}{\sqrt[3]{\mathrm{r}}}\right] \text{(kV/cm) for dc voltage,} \qquad (3)$$

where E_c (kV/cm) is the corona onset field strength on the tip of a rod with radius r (cm), that is located separately in the area, far from the grounded environment. It is understandable that the above equations cannot be fully implemented on inter – electrode air gaps, like the rod – plate gaps.

The Corona effect is one of the major factors that influence the operation of various installations and high voltage devices. Conductors and insulators, for example, experience intense Corona effects and in general partial discharges. This phenomenon leads to energy and electric charge losses, disturbance in wireless communications and ozone production. Thus it is very crucial to design common high voltage electric circuits and devices free from Corona effects, or partial discharges, when installed and activated with operating voltage. The optimization towards that direction is very important.

On the other hand many modern applications (electrostatic filters, electrostatic painting, electrostatic sound boxes, etc) rely on the existence and control of Corona effects in order to operate and function. In these cases the optimization towards the direction of controlling the Corona effects is of major importance.

The Corona effects and the breakdown of air gaps have been experimentally investigated by many researchers for the most commonly used arrangements where the gap is formed between two electrodes one of which is grounded and the other is stressed by high voltage. Especially in rod – plate air gaps the used so far technique of the experimental work concerns arrangements where the plate electrode is grounded (pl-gr) and voltage is applied to the electrode of the rod [1-7].

Several methods for controlling the corona effects have been proposed, [7]. In the present paper a new method is investigated through experimental work, mathematical analysis and by simulation, based on the results given from the influence of grounding (ground effect) in connection to the barrier effect and the polarity effect. A resistor connected in series with an air gap leads to a new method of controlling the impulse breakdown voltage and an experimental method of measuring the capacitance of an air gap arrangement.

II. The Procedure Followed

Experimental work has been carried out for air gap arrangements stressed by dc voltage. The arrangements, which have been modeled, analyzed, and experimentally studied, are typical rod-plate air gap arrangements of different electrode geometry, and gap length. The rod electrode is a hemispherical capped long cylinder with a relatively small diameter (4 or10 mm), and the plate electrode is a disk of 100 mm in diameter, both made of brass. High dc or lightning impulse voltage of negative or positive polarity is applied to one electrode while the other is at earth potential (grounded). An oscillator HAMEG HMO1022 has been used to record the values of the measured voltages.

The influence of the surrounding is minimized, by keeping relatively big distances between the models and the boundary shielding, as well as between the experimental arrangements and the grounded elements of the laboratory.

Mathematical models (Fig. 1) of the experimental arrangements have been designed, and the equation of initial conditions concerning the analysis of the electric field in the gaps, or the electric circuit, in connection to the ground, the polarity and the barrier effect has been formulated and analyzed. Appropriate models have been designed and simulation analysis has been held, with the use of special software (Fig. 2).

III. Theory of Field Analysis

Equations describing the initial conditions of rod plate air gaps without barrier and for the different arrangements with the plate or the rod grounded (Fig. 1a) are linear, presented in [8] and are described from basic equations (4), (5) and (10), (11).

In rod-plate air gaps with a barrier, the linearity of equations is not valid since the results depend on the position and the charging of the barrier. The surface of the barrier is charged through small partial discharges that occur in the gap. Thus there is a voltage developed on the surface of the barrier, resulting to the influence of the occurring electric field distribution in the gap. The latter is influenced differently in a rod-plate gap according to the electrode chosen to be grounded and its dielectric behavior is greatly affected.

a) For the arrangements in which the plate's voltage is V_{pl}, the barriers voltage varies linearly, the center of the barrier having voltage V_{bo}, the barriers edge V_{b1}, while the rod and the boundary shield are grounded the following equations are valid:

$$V(x,y) = 0, \ if \ (x,y) \in R_1 \cup \Gamma \qquad (4)$$

$$V(x,y) = 1, \ if \ (x,y) \in P \qquad (5)$$

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$$V(x,y)=V_{b0}+|y|\cdot K_1,\ if\ (x,y)\in S \tag{6}$$

$$V_{pl}\geq V_{b0}\geq 0 \tag{7}$$

$$V(x,y)=V_{b0}+|y|\cdot K_1,\ if\ (x,y)\in S \tag{8}$$

and when the barrier is near the rod

$$V_{pl}\geq V_{b0}\geq 0 \tag{9}$$

b) For the arrangements in which the plate is grounded and the rod is stressed the following equations are valid:

$$V(x,y)=0,\ if\ (x,y)\in P\cup\Gamma, \tag{10}$$

$$V(x,y)=1,\ if\ (x,y)\in R_1\ , \tag{11}$$

and $V_{b0}\leq 1$ (when the barrier is near the rod), (12)

where:

$$\Gamma=(x,y)\in\Re^2 : x^2+y^2=R^2 \tag{13}$$

$$R_1=\begin{Bmatrix}(x,y)\in\Re^2 : -r_r\leq y\leq r_r, \\ -a+r_r-G/2-\sqrt{r_r^2-y^2}\leq x\leq -r_r-G/2+\sqrt{r_r^2-y^2}\end{Bmatrix}, \tag{14}$$

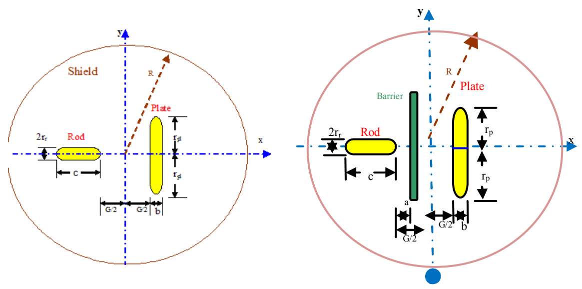
$$P=\begin{Bmatrix}(x,y)\in\Re^2 : \frac{G}{2}\leq x\leq\frac{G}{2}+b, \\ -r_p+\frac{b}{2}+\sqrt{\left(\frac{b}{2}\right)^2-\left(x-\frac{G}{2}-\frac{b}{2}\right)^2}\leq y\leq r_p-\frac{b}{2}-\sqrt{\left(\frac{b}{2}\right)^2-\left(x-\frac{G}{2}-\frac{b}{2}\right)^2}\end{Bmatrix}, \tag{15}$$

$$S=\begin{Bmatrix}(x,y)\in\Re^2 : x=-\frac{G}{2}+a, \\ -r_b\leq y\leq r_b\end{Bmatrix}, \tag{16}$$

$$K=\frac{V_{b0}-V_{b1}}{V_{b0}\cdot r_b}\qquad 0\leq V_{b0}\leq V\qquad K_1=\frac{V_{b1}-V_{b0}}{V_{b0}\cdot r_b} \tag{17}$$

a is the distance between the rod and the barrier and r_b the radius of the barrier (the plate and the barrier are in the form of a disc). Radius R is very big (Fig. 1).

It is resulted from comparison of equations (5), (6) and (10), (11) that there are significant differences between the arrangements with the rod or the plate grounded (ground effect), and are expected to lead to different dielectric behavior for the two arrangements



(a) Without barrier (b) With a barrier

Fig. 1 Theoretical models of rod-plate air gaps.

IV. SIMULATION RESULTS

The simulation analysis with the Finite Element Method and the use of special software has shown a significant influence of the effect of grounding and barrier on the field distribution in rod-plate air gaps. The differences between the arrangements, with the rod or the plate grounded, with the existence of a barrier between the electrodes are presented in [10], (Fig. 2).

The barrier effect is well known to influence the breakdown voltage of the air gaps [7]. When Corona occurs, the charge accumulated on the surface of the barrier becomes a wall that opposes to the furthermore movement of the corona charges leading to minimization of the corona current in the gap, and eventually the distribution of the field in the gap is changed. The electric field becomes less inhomogeneous thus influencing the dielectric behavior of the gap. The models that were analyzed in the present paper were similar to the experimental models. The results of the distribution of electric field strength in the gap are shown in Fig. 2 for a rod-plate gap with a grounded plate or grounded rod and a barrier placed perpendicular to the axis of the gap, for a specific value of the voltage at the center of the barrier. It is clearly shown that the voltage on the barrier's surface influences the field distribution in the gap and hence their dielectric behavior. The latter is influenced as well from the electrode chosen to be grounded (ground effect), (Fig. 2).

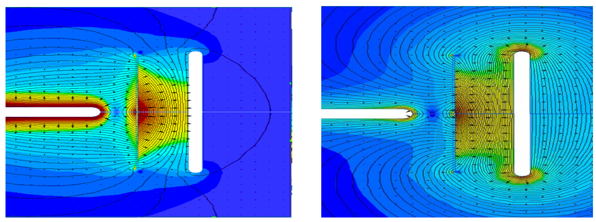


Plate-grounded (pl-gr) Rod-grounded (r-gr)

Fig. 2 The field strength distribution in a rod-plate gap with a barrier in comparison for the two different arrangements with the rod or the plate grounded. With blue color are the points with the minimum field strength, and with brown - red color points with the maximum field strength.

V. THE EXPERIMENTAL RESULTS

A. *Air Gaps Stressed by dc Voltages*

The results for the rod-plate air gaps without barrier are presented in [8, 9]. It has been resulted that the minimum values of the Corona onset voltage and maximum values of the Corona current and breakdown voltage occur in air gaps with a thinner negative rod when the plate is grounded (pl-gr), (Fig. 3).

It is well known that the barrier effect influences the value of the breakdown voltage of air gaps [5-9]. It is resulted from the experimental work of the present research project that the barrier effect, in connection to the ground effect, influences greatly the values of the Corona onset and breakdown voltage and the Corona current as well, as it is shown in Figs. 4 and 5, in comparison to the values of the gaps without barrier (WB). It is obvious that the Breakdown voltage maximizes when the barrier is placed near the grounded rod. The Corona onset voltage is lower in the gaps with the barrier near the grounded electrode (rod or plate), but in the same time the Corona current is very lower and becomes negligible when the barrier is in specific positions, (Fig. 4). All the above results are also

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influenced by the geometry of the gap (gap length and electrodes dimensions).

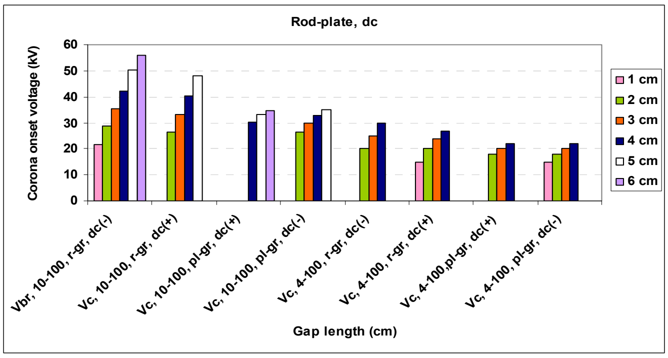
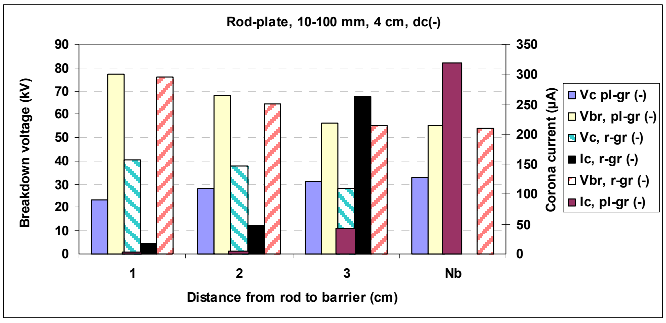
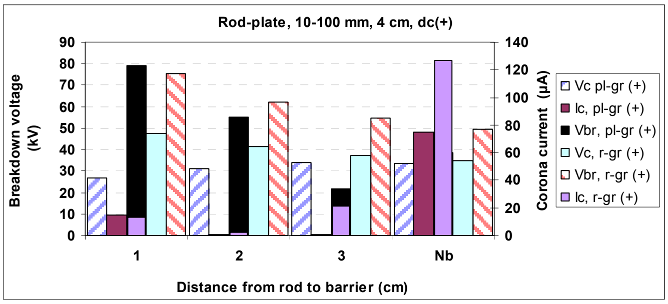


Fig. 3 The Corona onset and the breakdown voltage of rod-plate air gaps of different geometry stressed by dc voltage.



(a) Negative polarity



(a) Positive polarity

Fig. 4 The values of the Corona onset and breakdown voltage, and the Corona current before breakdown for rod-plate air gaps 10-100 mm, 4 cm long, with a barrier in 3 different positions, in comparison to air gaps without barrier (Nb). DC voltage applied.

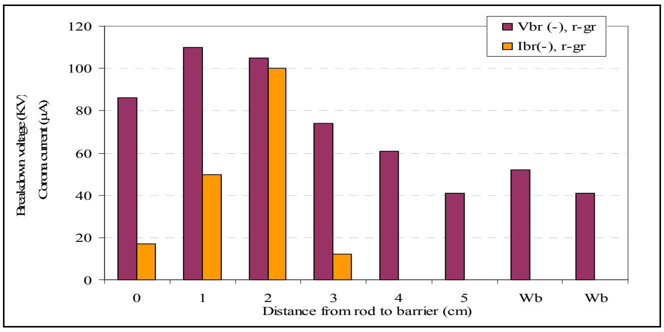


Fig. 5 The values of the breakdown voltage and the Corona current of rod-plate air gaps, 10-100 mm, 5 cm long, with a barrier in 6 different positions , in comparison to air gaps without barrier (Wb). DC(-) voltage applied.

B. *Air gaps without barrier stressed by impulse voltages*

Experimental tests on rod-plate air gaps stressed by impulse voltage have been fulfilled with the experimental set up as schematically illustrated in Fig. 6. This arrangement has been built up to measure the applied to the air gap impulse voltage, and the value of the voltage V_{R4} across the resistor R_4, as well as the Corona pulses and the breakdown voltage occurring in the gap. The Corona current through the gap can be easily calculated from equation $Ic=V_{R4}/R_4$. The results shown in Fig. 7 establish the influence of the ground effect, as well as the polarity effect on the breakdown voltage of the gap. The influence is much different when the gaps are stressed by dc voltage. The Corona effects are minimized and the breakdown voltage maximized when the rod is grounded with positive voltage applied on the plate. Anyway the value of the impulse breakdown voltage is proportionally higher than the value of the dc breakdown voltage.

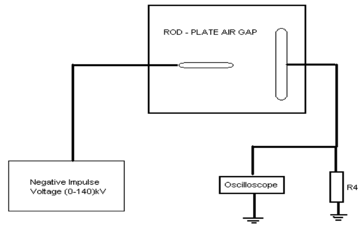


Fig. 6 The experimental arrangement schematically.

Impulse voltages are produced by impulse generators. The schematic diagram of the impulse generator used in the present paper is shown in Fig. 8. In the used model C_1=100 nF, C_2=1.2 nF, R_1=677 Ohms, and R_2=350 Ohms, while the value of the air gap capacitance (C_{gap}) is a few pF and the value of the ground resistance (R_g) is less than an ohm (Fig. 8, with R_4=0). The maximum value of the output voltage of an impulse generator with negligible ground resistance applied on the air gap is usually a little smaller than the voltage of the C_1 capacitor.

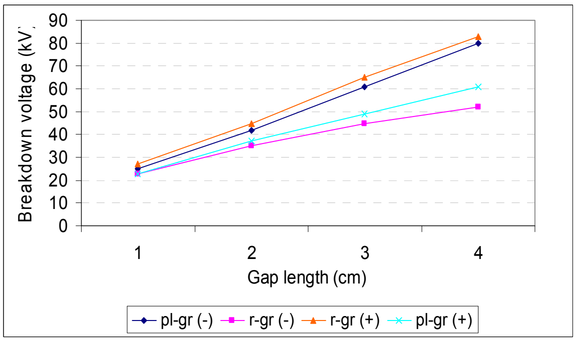


Fig. 7 The values of the breakdown lightning impulse voltage (V50%) of 10-100 mm air gaps stressed by impulse voltage 1.2/50 μs in combination with the ground effect and the polarity effect. Pl-gr and r-gr is the plate-grounded and rod-grounded arrangement respectively.

In an air gap arrangement the capacitance is very small and when it is connected to the generator and resistor R_4 is very small (Fig. 8), the charging time of the capacitance of the air gap arrangement is negligible compared to the rise time of the impulse voltage (1.2 μs) and the maximum voltage value of the

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fully charged gap (Vgap) is the same as the maximum value of the generators impulse voltage.

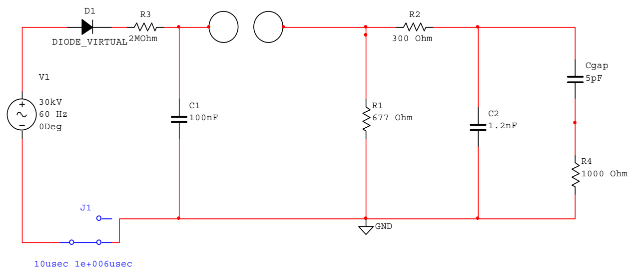
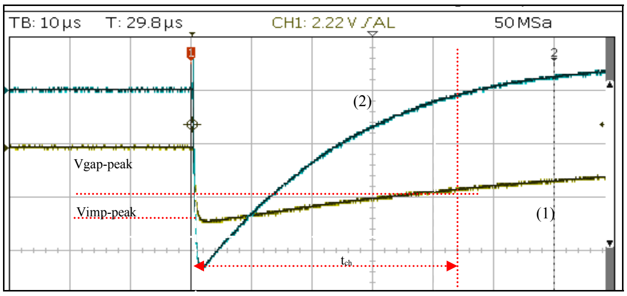
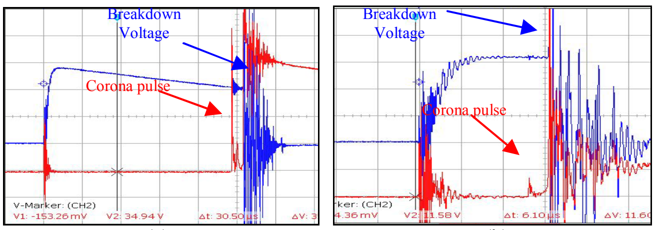


Fig. 8 The schematic diagram of the experimental arrangement. C_{gap} is the capacitance of the air gap arrangement.



20 kV/div, 10 µs/div, (1) and (2) are the graphs of the impulse applied voltage (V_{C2}) and the voltage across R_4 respectively

Fig. 9 Oscillogram showing the decrease of the maximum voltage of the fully charged rod-plate air gap when the R_4=100 kOhms. Charging time of the gap arrangement is 47 µs, the maximum value of the impulse applied voltage is 30 kV (1), while maximum value of the fully charged gap is 16 kV (2).



(a) (b)

Fig. 10 Oscillograms showing the breakdown positive impulse voltage and the Corona pulse occurred before breakdown for the 10-100 mm rod-plate air gaps, with a length of 3 cm. R_4=120 ohms. (a) In the plate grounded gap the corona pulse is large and the breakdown voltage lower: 20 kV/div, 0.8 A/div, 5µs/div. (b) In the rod grounded gap, the corona pulse is small and the breakdown voltage higher: 20 kV/div, 0.8 A/div, 1µs/div

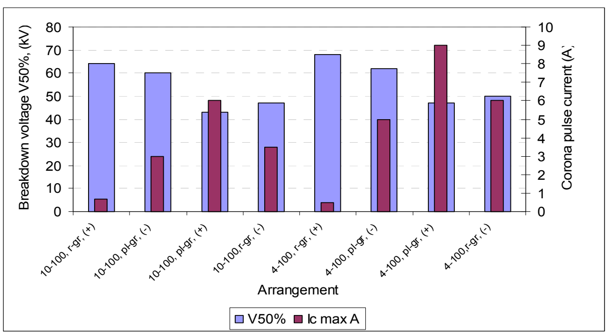


Fig. 11 The values of the breakdown voltage of rod-plate 10-100 mm air gaps, 3 cm long, stressed by impulse voltage 1.2/50 µs of both polarities, in comparison to the peak values of the Corona pulses occurred before breakdown.

On the contrary when the value of the resistor R_4 is high the charging time may become much bigger than the rise time of the applied impulse voltage and so the final voltage of the fully charged gap (V_{gap}) may be significantly lower than the maximum value of the applied impulse voltage, (Fig. 9). As expected the lower value of the gap voltage decreases the likelihood of Corona effects or breakdown to occur subsequently after (Figs. 10 and 11), [12].

VI. Simulation Analysis

P-Spice software has been used for simulation analysis. An equivalent model used for the analysis is shown in Fig. 12.

As the applied voltage is a rapidly changing pulse of short duration, the air gaps capacitance presents a high capacitive reactance. Thus in the analysis model used, a need to add a resistor R_5 in series with the gap emerged, simulating with a high precision the reactance of the capacitance of the gap. The value of the capacitance of the gap (C_{gap}) was defined as well. The addition of the above resistor R_5 in combination with the appropriate each time value of the capacitance, gave the curves for voltage V_{R4} as shown in Fig. 13 (b), which match the relative curves of the oscillograms, for a rod-plate, 10-100 mm, 4 cm long air gap, (Fig 13a).

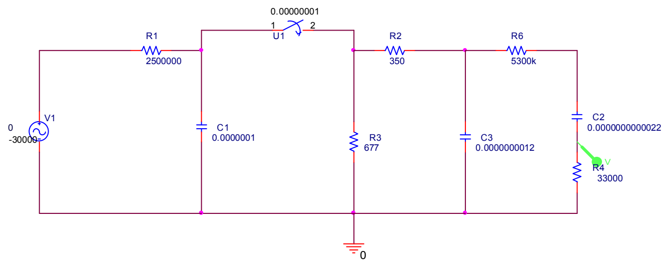
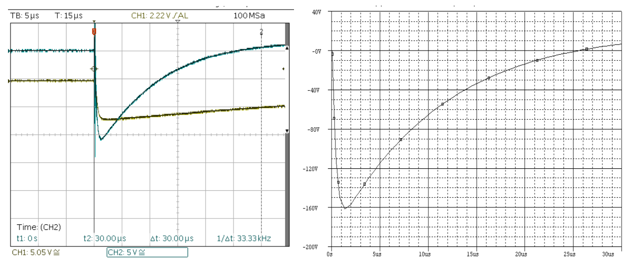


Fig. 12 Equivalent model for the simulation analysis, with R_4= 33 kOhms, R_5=5,3 Mohms and C_{gap}=2,2 pF

It is resulted that for the circuit of Fig. 12, with R_4=33 kOhms and in order for the curves obtained from simulation to match the ones taken from experimental work (Fig. 13) the capacitance of the air gap arrangement should be set to 2.2 pF, and the resistor R_5 to 5.3 MOhms, [12].



(a) (b)

Fig. 13 Oscillograms with R_4=33 kOhms in series with air gap. (a) From experimental arrangements 50 V/div, 5 µs/div, (b) from simulation analysis of the circuit of Fig. 12, with R_5=5.3 Momhs, and Cgap=2.2 pF.

Mathematical investigation of the experimental results (the TRC data of the oscilloscope) with the use of Matlab reveals the values of the capacitance of the air gap arrangement (Cgap) and the resistor R_5 as well. For a rod-plate air gap of 4 cm length, with electrode diameters of 10 mm and 100 mm respectively and with the use of a resistor R_4=33 kOhms, a value of 2.19 pF was resulted for C_{gap} and a value of 5.249 MOhms for resistor R_5. These values are very close to the ones calculated from simulation analysis and thus it can be concluded that the method used for the calculation of the capacitance is correct and can be implemented on any insulating arrangement. Furthermore the value of the resistor R_5 is very close to the value of the reactance X_c of the capacitance of the gap corresponding to the frequency of the maximum voltage range of the Furrier analysis, (Fig. 14), or to a period two times the charging time (t_{ch}) of the voltage across R_4, (Fig. 9).

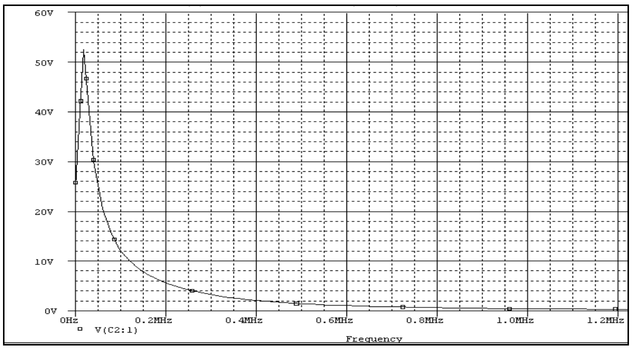


Fig. 14 Oscillogram of Fourier analysis of the model of figure 12. The Frequency with maximum range is about 15 kHz

VII. CONCLUSION

The dielectric behavior of an air gap stressed by dc voltage is characterized by less intense Corona effects when the electrode with the smaller dimensions is grounded (ground effect) and positively charged (polarity effect) in comparison to the other electrode. The insertion of an insulating paper sheet in a proper position between the electrodes maximizes the breakdown voltage (barrier effect) and minimizes the corona effects.

When the gap is stressed by lightning impulse voltage the breakdown voltage is proportionally higher, and the influence of the ground and the polarity effect is obvious but with much different results.

Connecting a resistor in series with the gap the voltage of the fully charged gap decreases and hence the breakdown voltage increases and the Corona pulses are less intense. The experimental and simulation results reveal a method of calculating the capacitance of any insulating arrangement.

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