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INSULATION PROPERTIES OF COMPOSITE DIELECTRIC ARRANGEMENTS

F.V. Topalis,* I.F. Gonos,* and I.A. Stathopoulos*

Abstract

This article examines the barrier effect on the dielectric strength of nonuniform electric fields stressed by impulse voltages. The electric field is a rod-plane air gap with length up to 40 cm. The barrier is a sheet of craft paper that is placed in several positions between the grounded plane and the high-voltage rod. The experimental results show that the position of the barrier substantially influences the dielectric strength of the gap. Another parameter that is also investigated is the electrode configuration. The diameter of the rod electrode and the shape of the tip affect the uniformity of the field and therefore the dielectric strength. The dependence of the breakdown voltage upon the shape of the impulse stress is also investigated. The experimental tests show that the strength of the gap decreases with the time to crest of the impulse. It becomes minimum under voltages with a time to crest of some tens of microseconds and starts increasing under slower impulses with time to crest of some hundreds of microseconds. The obtained results seem to be very useful for the design and optimization of the internal insulation of high-voltage electrical equipment.

Key Words

Air gaps, barrier effect, insulation, dielectric arrangements

1. Introduction

Insulating materials are often used in air gaps because it has been noticed that their dielectric strength increases essentially after the insertion of a barrier in their electric field [1–6]. Technically and economically speaking, the quality and the thickness of the barrier are not the most important criteria for insulation coordination. It was found that variations in the thickness of the insulating material slightly affect the mechanism of the breakdown/puncture of the barrier [7]. Noticeable changes in the breakdown voltage have been observed only when the thickness is considerably increased [1, 3]. On the other hand, the breakdown voltage is not affected even if the barrier is already punctured or, even more surprising, it has an opening [8].

* Department of Electrical and Computer Engineering, Electric Power Division, National Technical University of Athens, 9, Iroon Politehniou Street, Zografou, GR 157 80 Athens, Greece; e-mail: {topalis, igonos}@softlab.ntua.gr, stathop@power.ece.ntua.gr
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The aim of this work is to investigate the parameters that substantially affect the breakdown mechanism and the strength of the gap qualitatively and quantitatively. Rod-plane air gaps with small and medium distances are tested experimentally under impulse voltage stresses. The investigated parameters are the gap length, the diameter, and the tip radius of the high-voltage electrode, the position of the barrier, and the shape of the impulse voltage.

2. Experimental Setup

The test arrangement is a rod-plane air gap of length 10–40 cm. The rectangular plane is at the earth potential, and the high voltage is applied to the rod electrode. Five different rods (Fig. 1) are used, three of them with diameter $D = 12$ mm and the other two with $D = 16$ and 23 mm. The tip of the rod is terminated with a cone. The angle of the tip is 30°. The rod of the three electrodes with $D = 12$ mm ends to a spherical surface with radius $R = 1$, 2, and 4 mm, respectively. The tip radius of the other rods ($D = 16$ and 23 mm) is 1 mm. The material of the electrodes is brass.

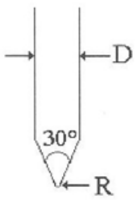

Figure 1. High-voltage rod electrode. D: diameter; R: radius of the tip.

The insulating barrier is a sheet of paper, enriched with epoxy resins, which is used for the insulation of transformer windings. It has the following technical characteristics: thickness 0.39 mm, weight 481 g/m^2, breakdown voltage in air 4.5 kV, pH in water solution 6–8, moisture 8%, nitrogen 2%, and ashes 1%. The dimensions of the barriers are always greater than the dimensions of the grounded plate, in order to avoid a flashover. The barrier is placed perpendicular to the axis of the rod-plane gap (Fig. 2) at a distance x from the high-voltage rod. The distance x is

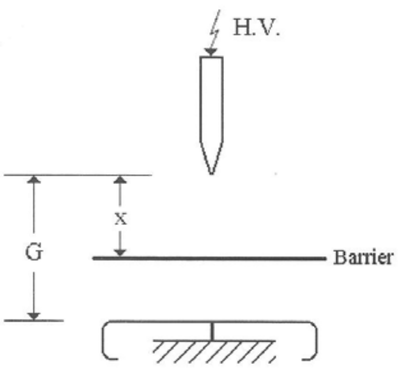

Figure 2. Rod-plane air gap with insulating barrier. G: length of the gap; x: distance between the barrier and the high-voltage rod.

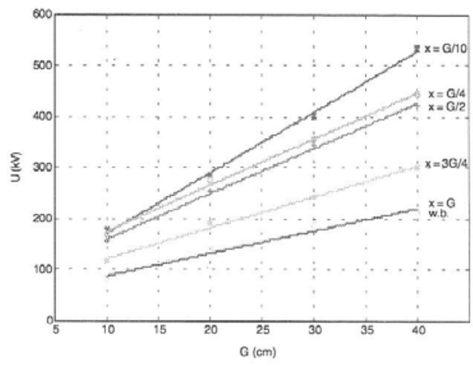

Figure 3. Effect of the position of the barrier on the dielectric strength under the standard impulse voltage $1.2/50\,\mu$s. $D = 12$ mm; $R = 1$ mm; w.b.: breakdown voltage without the barrier.

varying between 0 (barrier in touch with the high-voltage rod) and G (barrier in touch with the grounded plane), in steps of $0.25G$.

The gap is stressed by high-impulse voltages of positive polarity with time to crest T_{cr} varying in the range of 2–435 μs. Among them are the standard lightning impulse $1.2/50\,\mu$s and the standard switching impulse $250/2{,}500\,\mu$s. The test voltage is produced by an 8-stage Marx impulse voltage generator, with a charging voltage of up to 200 kV and an energy of up to 2 kWs per stage. The voltage is measured by a 1.2 MV damped capacitive divider connected, via a 20 m coaxial cable, to a digital oscilloscope and a peak voltmeter. The instruments are placed in a Faraday screened chamber.

All tests are performed in a temperature- and humidity-controlled climate chamber, completely made of insulating materials. Its volume is approximately 12 m^3 (2.4 m × 2.2 m and 2.2 m height). The absolute humidity during the experiments is between 7 and 16 g/m^3, the air pressure between 1,000 and 1,013 mbar, and the temperature almost constant at 20°C. All the measured values of the breakdown voltage are corrected, according to IEC 60, to the standard climatic conditions $T = 20°C$, $p = 760$ mmHg, and $H = 11\,g/m^3$.

The experimental procedure for the determination of the breakdown voltage is the multiple-level method as it is described in the literature and the international norms. The breakdown voltage without the barrier of each electric field configuration is measured before the insertion of the barrier and the performance of the tests. The barrier is replaced by a new one after each breakdown/puncture. A breakdown of the gap due to flashover, without puncture of the barrier, is very rare and is not taken into account.

3. Results

The dielectric strength of the gap is strongly influenced by the position of the barrier in the gap. The dependence of the breakdown voltage upon the distance x from the high-voltage electrode is shown in Fig. 3. It is obvious that the strength of the gap is not influenced if the barrier is placed on the grounded plate ($x = G$). The value of the breakdown voltage starts increasing when the barrier is moved towards the high-voltage rod. It takes its maximum at a distance $x \approx G/10$ from the rod and starts decreasing when the barrier is brought to the rod.

The increase of the dielectric strength of the gap that it is gained with the thin barrier is substantial. It should be noticed that this increase cannot be explained using only the theory of electrostatic fields. On the contrary, the breakdown process is completely changed. The insertion of the barrier in the gap changes the distribution of the electric field lines. The strong electric field stress causes Corona discharges at the neighbourhood of the high-voltage electrode that accumulate electrostatic load on the surface of the barrier facing the electrode. Simultaneously, opposite load appears on the other side of the barrier. It can be claimed that two gaps are formed, connected in series: (1) a rod-to-plane gap where the barrier is the plane, and (2) a plane-to-plane gap where the one plane is the barrier and the other is the grounded plane. The barrier is the common plane electrode in both gaps. When the voltage reaches its critical value, the first gap with the rod is bridged. The breakdown of the second gap follows instantaneously.

The accumulation of the load on the barrier is faster when the barrier is placed near the high-voltage rod where the field strength is high enough. In this case the gap is bridged at lower values of the stress voltage. Generally, the propagation of the streamer, initiated from the high-voltage rod, is impeded by the insulating barrier. Therefore, the streamer is not extended below the barrier towards the grounded plane.

The influence of the shape of the high-voltage rod is a less important parameter of the breakdown process in the gap (Fig. 4). As is expected, the breakdown voltage increases with the increase of the diameter or/and the radius of the tip of the rod because the electric field near the rod weakens.

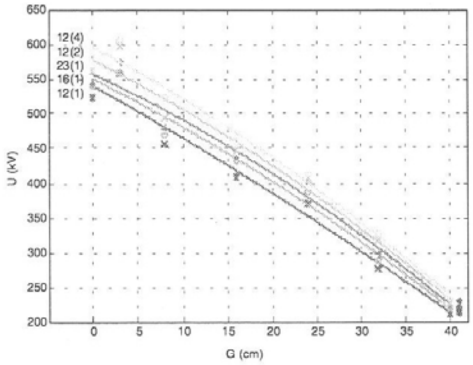

Figure 4. Effect of the shape of the rod electrode on the dielectric strength under the standard impulse voltage $1.2/50\,\mu$s. $G = 40$ cm; $D = 12$, 16, 23 mm; $R = 1$, 2, 4 mm.

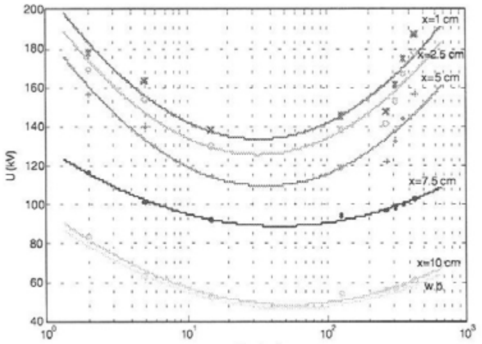

Figure 5. Breakdown voltage versus the time to crest T_{cr} of the test voltage. $G = 40$ cm; $D = 12$ mm; $R = 1$ mm; w.b.: breakdown voltage without the barrier.

Another parameter, which greatly affects the strength of the air gap, is the shape of the impulse voltage stress. The time to crest T_{cr} (time from zero to the peak of the impulse) is an important factor of the breakdown mechanism. The influence of T_{cr} of the applied voltage on the strength of the gap is demonstrated in Fig. 5. It is obvious that the breakdown voltage follows the well-known form of the U-curve, which is characteristic of the air gaps (without the barrier).

The breakdown voltage decreases (Fig. 6(a)) with the increase of T_{cr} and takes its minimum when T_{cr} is in the order of some decades of microseconds. Then ($T_{cr} > 100\,\mu$s) the value of the dielectric strength starts increasing (Fig. 6(b)), and finally ($T_{cr} > 400\,\mu$s) exceeds the one under the standard lightning impulse $1.2/50\,\mu$s.

The determined curves, one for each gap arrangement, completely describe the insulation properties of the gap and provide a useful tool for the optimization of the insulation coordination of medium- and high-voltage installations.

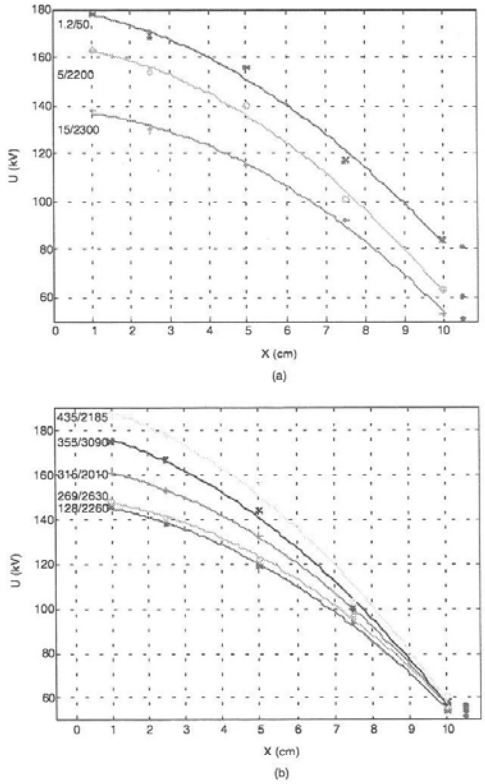

Figure 6. Effect of the shape of the impulse on the dielectric strength. $G = 10$ cm; $D = 12$ mm; $R = 1$ mm; • breakdown voltage without the barrier. (a) Test voltage: $1.2/50\,\mu$s, $5/2{,}200\,\mu$s, $15/2{,}300\,\mu$s. (b) Test voltage: $128/2{,}260\,\mu$s, $269/2{,}630\,\mu$s, $315/2{,}010\,\mu$s, $355/3{,}090\,\mu$s, $435/2{,}185\,\mu$s.

4. Conclusion

The use of insulating materials in air gaps is an efficient technique for insulation dimensioning and coordination because the increase in the withstand voltage of the gap that is attained is considerable. Generally, to attain optimum results, the best position of the barrier in the gap is at the vicinity of the high-voltage electrode. According to the experimental results of this investigation, the best position seems to be at a distance equal to 1/10 of the length of the gap. Other researchers recommend a longer distance, almost one-quarter of the gap length. It is believed that these deviations in test results are due to use of different insulating materials (thickness, insulation properties, homogeneity, etc.) and to the different experimental apparatuses and test techniques. Very interesting is the conclusion of Remde and Boecker [2], that the peak value of the applied voltage is not the only criterion for determination of the breakdown properties of the gap. The value of the surge capacitor of the impulse voltage generator, and therefore the energy of the generator, are quite critical. If the capacitor cannot give the required current, the breakdown process stops even if the voltage is high enough.

Generally, all researchers agree that the highest dielectric strength is attained when the barrier is placed near but not too close to the high-voltage electrode. The position of insulating materials near the grounded electrode is useless except if it is too thick. In this case the cost is high and the results moderate. The aim of the designer is to alter the breakdown mechanism (thin barrier near the high-voltage electrode) and not just to improve the distribution of the electric field lines with thick and sometimes expensive materials.

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Biographies

Frangiskos V. Topalis received the diploma in mechanical and electrical engineering and his Ph.D. from the National Tech nical University of Athens (NTUA) in 1979 and 1990, respectively. He is the head of the Laboratory of Photometry of NTUA, Electrical and Computer Engineering Department, where he teaches photometry and lighting. His research interests concern photometry, lighting, rational use of energy, and harmonics.

Ioannis F. Gonos received his diploma of electrical engineering in 1993 from the National Technical University of Athens. He has been a Ph.D. student since 1996 at the same university, and a Teaching Assistant at the Greek Naval Academy and the Technological Education Institute of Athens since 1996. His research interests concern grounding system, insulators, and high-voltage measurements.

Ioannis A. Stathopoulos studied in the Faculty of Electrical and Mechanical Engineering of the National Technical University of Athens (1969–1974). He earned his doctorate at the Technical University of Munich (1974–1978). He then became Teaching Assistant at the Technical University of Munich (1974–1978), Production Engineer in the company Vianox–Franke (1979–1980), Teaching Assistant at the National Technical University of Athens (1979–1983), and thereafter Lecturer (1983–1987), Assistant Professor (1987–1991), Associate Professor (1991–1995), and Professor (1995) at that university.