Optimisation of the dielectric strength of a non-uniform air gap under AC voltage by insertion of multiple barriers

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Abstract: The aim of this article is a contribution to the optimisation of the dielectric strength a rod-rod air gap in which a suitable number of insulating barriers is inserted. The study is carried out under AC voltage in a clean or polluted atmosphere. The influence of important parameters such as the number of barriers, their position in relation to the rod electrodes, their width, the distribution and the degree of pollution on the system performance is highlighted. The results show that in a clean, dry atmosphere, a system with two barriers is about two times more efficient than that with a single barrier. Beyond this number, the effectiveness of the system remains virtually constant. However, starting from a light pollution level, which is of the order of 5µS, the effectiveness of the system with two barriers approximates the minimum value obtained by a single barrier tested under the same conditions of pollution. In this worst case, this minimum is equal to that resulting from the breakdown of the air gap between the edges of the two barriers, less the surface discharge voltages on the polluted sides of the barriers facing the electrodes. In this case, remedial actions become mandatory if an optimal level of isolation of the system must be maintained.

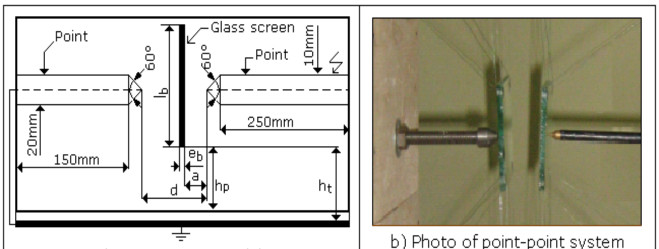
Key words: rod-barrier-rod configuration, uniform and non-uniform pollution, barriers, insulating and conductive barrier efficiency, streamer and leader discharge.

I. INTRODUCTION

The scope of application of insulating barriers is very large and key in many industrial areas, namely, gas circuit breakers, switches, bushings, transformers and substations. When it is necessary to reduce the size of such equipment, the distance of isolation between their energised and grounded parts may be reduced. To prevent short circuits between these two parts, barriers can be inserted in the air gap to achieve isolation distances greater than those obtained without barriers. Moreover, in exceptional circumstances, electrical discharges can develop and lead to the disruption of the system's air gap even in the presence of an insulating barrier. In the case of clean, dry atmosphere, many theoretical and experimental works were performed on some geometric and electrical barrier parameters to improve the performance of some equipment or electrical installations containing such systems [1-7]. However the use of multiple barriers, for a possible optimization of performance of the system, especially in polluted and humid atmosphere where it can undergo a fall starting from a very low degree of barrier pollution [1, 2, 6, 7], has been the subject of very few investigations [3]. This work reports an experimental investigation into the AC dielectric strength of an air gap with multiple inserted barriers under clean and/or contaminated atmosphere.

II. EXPERIMENTALE TECHNIQUE

The experimental model, illustrated in Figure 1, is composed of two rods and a plane square barrier.



a) Point - point model

b) Photo of point-point system with 2 glass screen

Fig. 1. Experimental model

The high-voltage electrode is made up of a cylindrical bronze rod of 10mm diameter and 250mm length, finished by a bronze conical point having an angle of 60° and 1.06mm radius of curvature. The grounded electrode is a steel rod 20 mm in diameter and 150mm length. At its end a steel conical point having an angle of 60° and 0.57mm of radius of curvature is fixed. The two electrodes are fixed on two opposite faces of a cubic wooden framework of 60cm side. Horizontal displacements of the barriers are ensured by two wooden guides. These are fixed on the cubic support, which is placed 1m above ground, on a metallised wooden table. The barriers are made of glass, have a square form of 6mm thickness and different widths (10cm, 20cm, 30cm). The size of the barrier in this case is characterized by the width "l_b". Its height of insulation from ground is h_t (Fig.1a). Isolation and paralleling of the various barriers was achieved by means of a nylon wire attached to the wooden support (Fig.1b). The characterization of the performance of the system with barriers and the visualization of the electric phenomenon evolving in the air gap was carried out according to the electrical diagram illustrated in Figure 2. The circuit for measuring the system's breakdown voltage is composed of a 135kV transformer Tr with automatic or manual ramp speed control, a peak voltmeter V, a protection resistance R and a capacitive voltage divider C1/C2 to which the test object is connected. The circuit of visualization consists of a Camwood camescope for registering various phases of the electric discharge developing in air gap and a PC for observation and analysis.

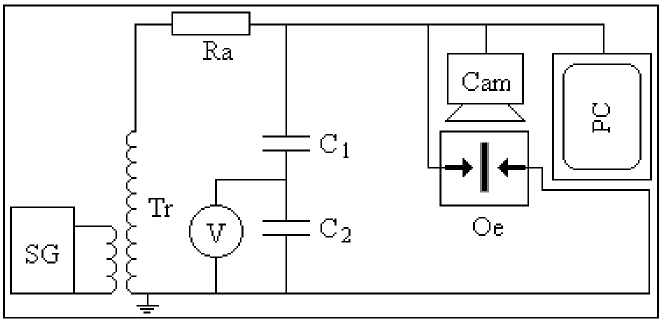


Fig. 2. Measurement and visualisation circuit
SG: Transformer control unit; Tr : HV Transformer; Cam: Digital Camescope; PC: computer; Oe: test object

The polluting solution is made up of distilled water or tap water mixture according to desired volume conductivity, 40g of kaolin per litre and sodium chloride the proportion of which is given according to the desired volume conductivity of the solution. The measurement of the surface conductivity of the contaminated insulating barrier is made by means of the mobile probe conductivity meter [8]. Two modes of distribution of pollution on the surface of the insulating barrier, namely uniform (all faces) and not uniform (only one face) of polluting deposits, were used. The application of the pollution layer on the barrier is carried out using a sponge maintained always clean and on which is deposited, with the means of a syringe, a quantity of constant pollution of 2 ml after thorough mixing. The energisation of the system is carried out immediately after the application of the pollution of the barrier to avoid natural drying. Before each new test, the barrier is cleaned and rinsed with water then dried using paper tissue. For each degree of severity of pollution, 25 breakdown tests were carried out. The value selected of breakdown voltage is the arithmetic mean of the breakdown voltages of the same series of measurement. For an inter-electrode distance d=5cm, we determined, initially, the width, the number and the position of the clean barriers corresponding to a maximum breakdown voltage, then the effect of the degree of pollution of these barriers taken in this position on the air gap breakdown was studied.

III. RESULTS AND DISCUSSIONS

A..Dry clean insulating barrier

A1. Single barrier

A clean barrier is obtained by washing and rinsing with distilled water and then drying with paper tissue. The system efficacy is defined as the ratio of the breakdown voltage of the air gap with barriers and the breakdown voltage without barriers. The system efficacy as a function of barrier width (l_b) and its position with reference to the high-voltage electrode (a/d) is illustrated in Figure 3. The results show that the dielectric strength of the air gap with barrier is by far higher than that without barrier, regardless of the barrier width.

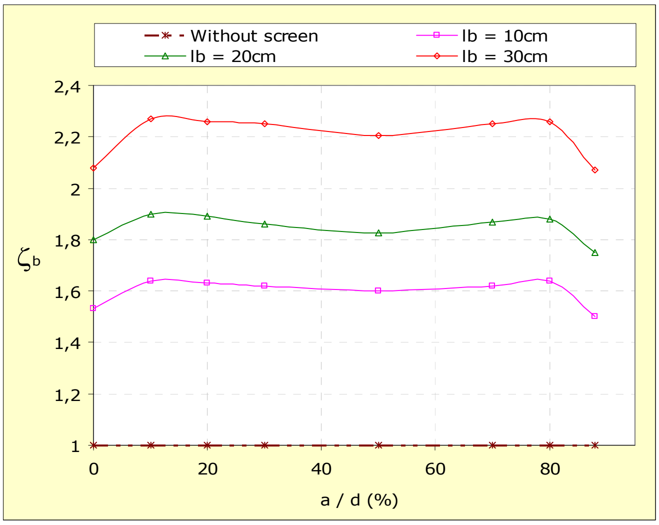


Fig.3. Efficacy of a system with clean barrier as a function of barrier position with reference to the high-voltage electrode (a/d) and its width (l_b)

It is noticed that the efficacy of the barrier in the rod-barrier-rod system is maximum closer to the electrode high voltage electrode (a/d = 10 - 20%) or ground electrode (a/d = 70 - 90%). It can also be seen that the system efficacy increases with the width of the insulating barrier. These results are in very good conformity with those obtained in the case of a system with hard paper and/or PVC barrier of 100cm width, of thickness varying between 1 and 15mm, inserted in an interval of air equal to 15cm under AC voltage [9].
From the visualization of the of the electric discharge, we observed that the increase in the breakdown voltage of the system is especially related to the lengthening of the very resistive path, followed respectively by the positive and negative streamers on the HV and grounded sides of the barrier. Indeed, the air gap disruptive channel is governed by two positive and negative streamer discharges resulting respectively from the high-voltage rod and the grounded rod, propagating in opposite directions, initially in the air, then slipping on the two large opposite faces of the barrier. The junction of these two discharges frequently occurs on the edges or ground face of the barrier. Thus the positive streamers are faster and longer than the negative ones. These various ways are highlighted by the various phases summarized in Figure 4.

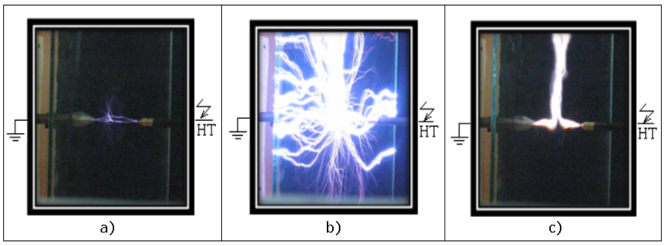


Fig.4. Discharge development phases up to breakdown of rod-clean dry barrier-rod–(a: inception, b: propagation and discharge ramifications, c: disruption)

A.2. Two barriers

The system efficacy of a system with two barriers of same variable width, where one is put in contact with the high-voltage rod and the other at a distance a_{bb} from the first is shown in Figure 5.

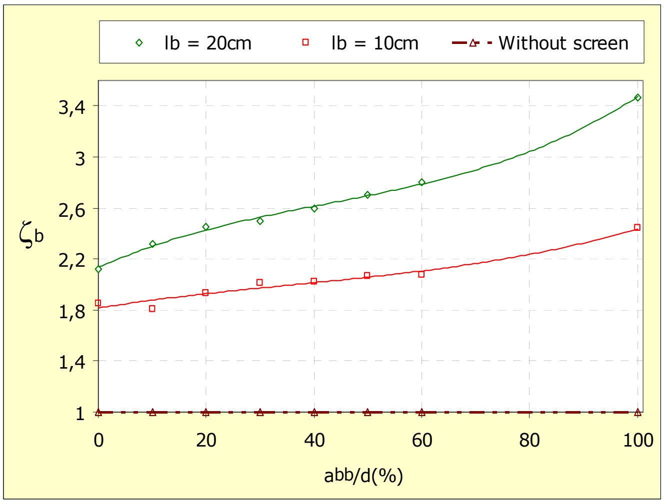


Fig.5. Efficacy of a system with two dry-clean barriers with one in contact with the HV electrode, as a function of their separating distance and their width.

The results show that the efficacy of such a system increases with the width of the barrier. Its maximum value is reached when the second barrier is in contact with the grounded electrode. It's value is 2.4 for a barrier width of 10cm, value of 3.5 for a barrier width of 20cm. Similar results were obtained for the case where the two barriers, positioned initially in the middle of the inter-electrode interval, then displaced in opposite directions towards the electrodes. From the comparison of Figures 3 and 5, the system efficacy with two barriers of 20cm width is practically twice that of the same system with only one barrier of same dimensions. The rise in the system efficacy with two barriers can be explained by the uniform electric field between the two barriers of different polarities and the system is composed of three intervals of air: 2 rod-plane and 1 plane-plane in series. The air gap breakdown is always governed by two electric discharges of streamer type of opposite polarity being propagated one towards the other. The first evolves from the high-voltage rod electrode to the middle of the surface of the barrier located opposite, then tot the edge of the same barrier and from the edge to that of the second barrier. The negative streamers, slower and shorter in size, leave the grounded electrode and progress towards the centre of the surface of the barrier and then move towards its edge. The point where the two discharges meet frequently occurs on the barrier located in the vicinity of the grounded electrode.

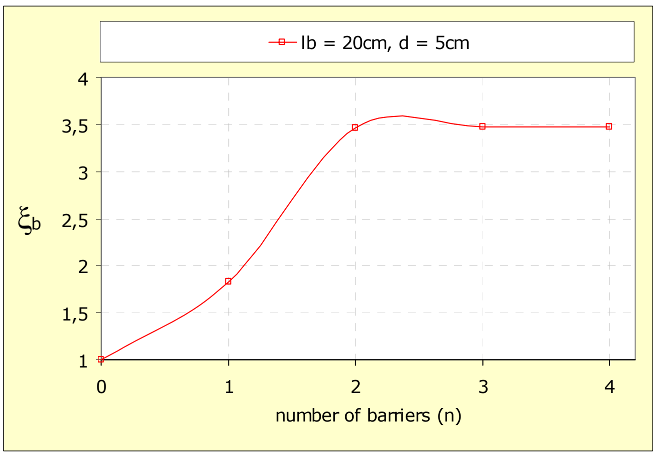


Fig.6. System efficacy as a function of the number of barriers (l_b =20cm, d = 5cm)

Figure 6 shows the variation of the system efficacy with the number of parallel barriers of the same dimensions. The efficacy increases as the number of barriers increases up to 2 and then remains practically constant.

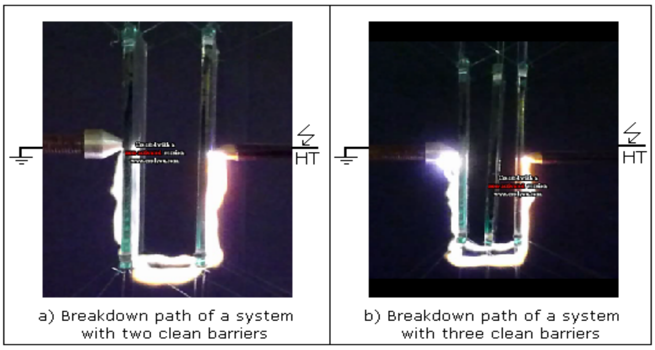


Fig.7. Effect of number of barriers on the discharge path

According to the visualization of the electric discharge, the path followed by the discharge in the case of two barriers (Fig.7a) is practically the similar to that where the number of barriers is higher than 2 (Fig7b).

B. *Polluted insulating barrier*

B.1. *Single barrier*

The effect of the pollution severity on the dielectrics strength of the air gap was was studied for a barrier of width varying between 10 and 30cm and a level of pollution varying from 0 with 8µS. The results of measured breakdown voltage for different of pollution distribution and the degrees of pollution are shown in Figures 8, 9 and 10.

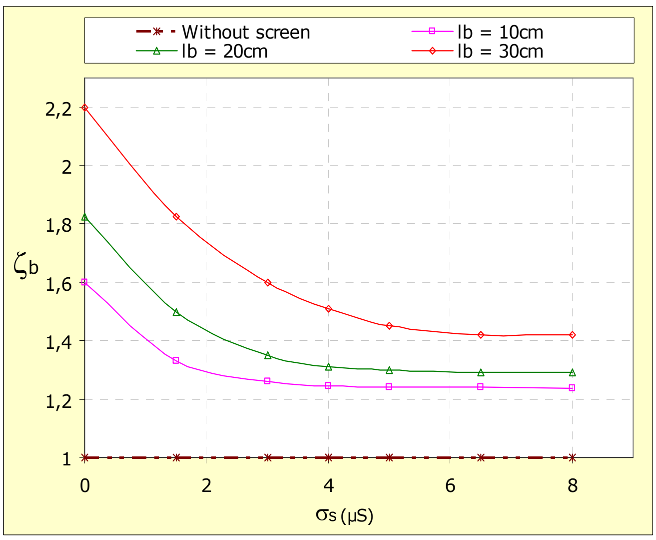


Fig. 8. Efficacy of a sytem with polluted barrier (a/d = 50%) as a function of surface conductivity and barrier width.

Figure 8 shows that the efficacy of the system with a uniformly polluted barrier very quickly decreases with the surface conductivity to a limiting value which depends on the barrier width and beyond which it remains constant whatever the degree of severity of pollution. This limit corresponds to the discharges emanating of the electrodes and progressing towards each other in inter-electrode space without slipping over the two faces of the barrier. It is to be stressed that this minimal value with contaminated barrier remains always higher than that obtained in absence of barrier

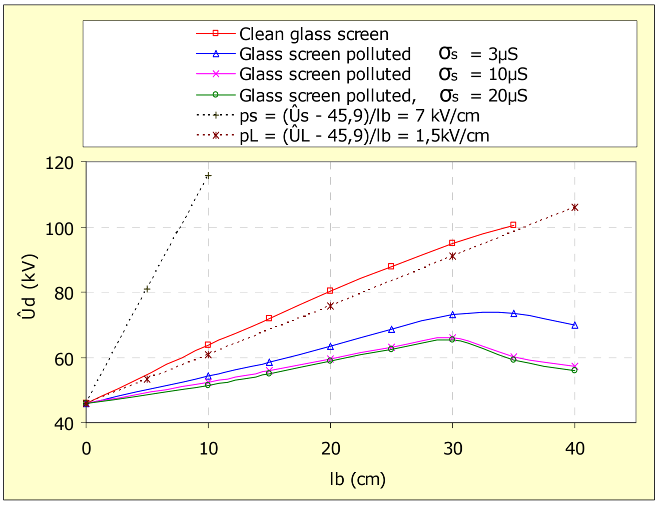


Fig. 9. Breakdown voltage of air gap with barrier as a function of barrier width for different degrees of surface pollution

Figure 9 shows the variations of the breakdown voltage of the electrode-barrier system with the width of the barrier and for different barrier surface conditions. It is found that the shapes of the curves resulting from the air gap breakdown are similar to those established by Lemke in long air intervals [10, 11]. Indeed, the Ûd=f(d) characteristic presents two distinct zones; the first zone (streamers zone) is characterized by a slope equal to 4.5kV/cm and the second zone (leader zone) has a voltage gradient of about 1kV/cm. These values were confirmed by other researchers who found gradient intervals respectively between 4.5 and 7kV/cm for positive streamers and between 10 and 15kV/cm for negative streamers. Concerning the linear voltages corresponding to positive discharges of leader type, they vary between 1.5 and 0.5kV/cm [12, 13].

When the barrier is clean and dry, the gradient of the characteristic $\hat{U}_d = f(l_b)$ is closer to that where the discharge is of type leader (p_L). This means that the discharge resulting from the HV rod would be of type leader and that emanating from the grounded rod of the streamers type (p_S). On the other hand, when the screen is contaminated, the linear voltage is much lower than 1.5kV/cm, indicating that the two discharges are of leader type, assuming that the gradient of the curve for a negative leader is of the same order of of magnitude as that established in positive polarity [11].

Figure 10 compares the efficacy of the system for two modes of pollution distribution: uniform pollution and pollution only on the surface facing the HV electrode. It can be seen that the system has lower dielectric strength if the barrier is completely and uniformly contaminated. This difference increases with the increase in the degree of pollution and can be explained by the variation in resistance of the discharge path on the surface of the clean barrier opposite the grounded electrode compared to the case where it is contaminated with a variable conductivity.

The visualization of the discharge for a uniformly polluted barrier with surface conductivity lower than 5µS, shows that the disruption of the system is governed by two discharges being propagated one towards the other while slipping on the two faces of the floating screen (Fig. 11). On the other hand when the degree of pollution is equal to or higher than 5µS, the surface discharges on its two faces do not occur (Fig. 12) and the strongly contaminated screen behaves like a conducting barrier.

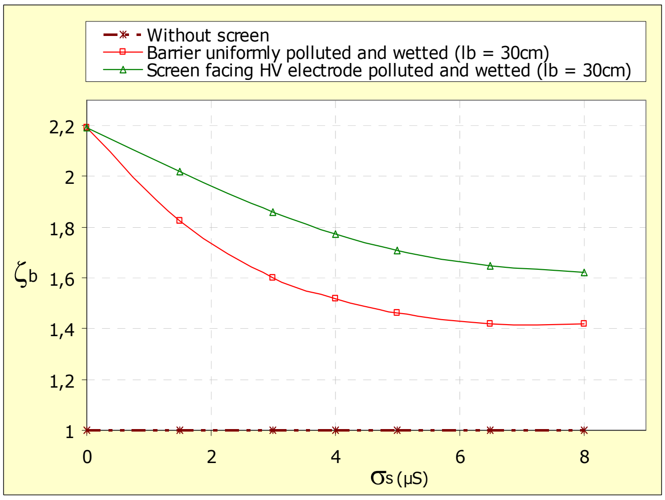


Fig. 10. Efficacy of a sytem with one barrier as a function of mode of pollution distribution and degree of pollution (a/d=50%)

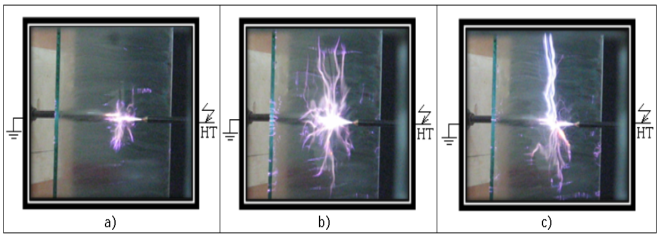


Fig. 11. Discharge development phases for a uniformly polluted barrier with surface conductivity lower than 5µS (a: discharge inception, b: propagation and ramifications of discharges, c: breakdown of the air gap

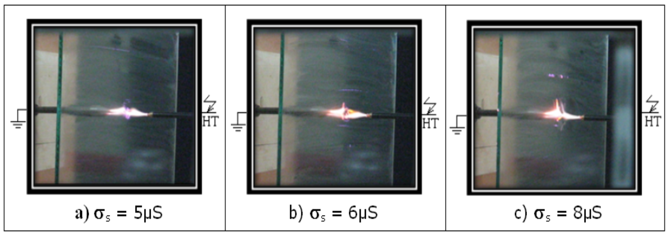


Fig. 12. Disruption of the air interval for a uniformly polluted screen with surface conductivity equal to or higher than 5 µS.

B.2. Two barriers

The influence of the degree of pollution on the system efficacy for two barriers was carried out with the barriers uniformly polluted and put in contact with the two electrodes. The variation of the system's efficacy with surface conductivity is shown in Figure 13. The variation is the same whatever the number of barriers. Figure 13 also shows that the system efficacy with two barriers of equal width of 20cm and of surface conductivity higher or equal to 5µS falls sharply to a minimal value corresponding to that of a single screen tested under the same conditions of pollution. This minimal value is equal to that resulting from the disruption of the air interval between the edges of the two barriers, therefore decreased by the surface discharge voltages on the polluted faces of the barriers facing the electrodes. In this case, cleaning measures are essential if an optimal level of insulation equivalent to that of a clean dry atmosphere is to be maintained.

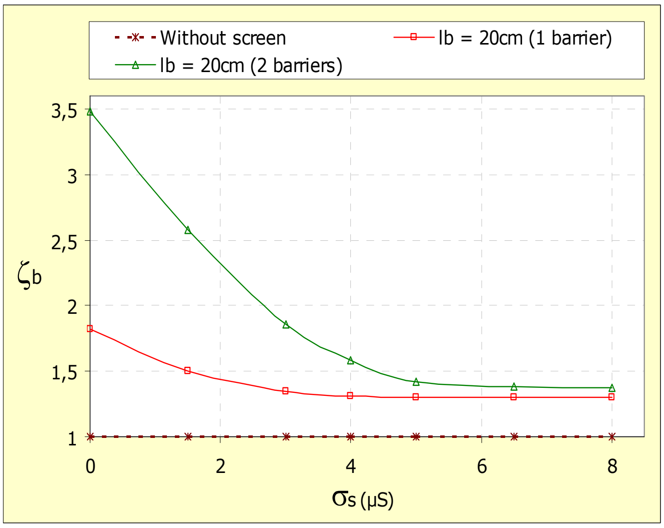


Fig. 13. Efficacy of a system with two uniformly polluted barriers (a_{bb}=5cm) as a function of surface conductivity and barrier width

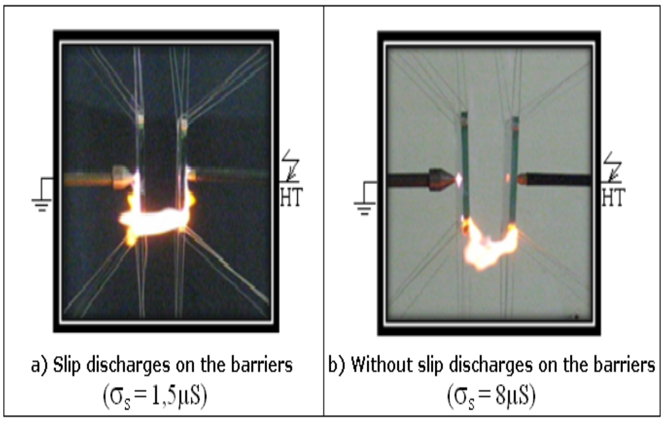


Fig.14. Effect of degree of pollution on the breakdown path of the air interval of a system with two barriers (a: σ_s = 1,5μS, b: σ_s = 8μS)

Figure 14 shows the discharge path in the case of two barriers slightly (σ_s=1.5μS) and strongly (σ_s=8μS) conducting. Like a single barrier, the breakdown of the air gap with two barriers is governed by the development in opposite directions of two discharges whose junction generally takes place in the vicinity of the edge of the screen in contact with the grounded rod. It can be said from Figure 14a that, whatever the mode of distribution of pollution on the two barriers, the breakdown of the air interval is governed by discharges in the space between the two screens after propagating over the barrier surfaces of the two barriers as long as their polluted surface conductivity is lower than 5μS. For higher surface conductivities, the rupture of the system is equivalent only to the breakdown of the air interval between the edges of the two barriers (Fig.14b), i.e., without slip discharges on the barriers' strongly polluted faces facing the electrodes, regarded as conducting surfaces (Fig.14b).

IV. CONCLUSION

The effect of the number of insulating barriers on the efficacy of a system of rod-rod electrodes led to the following significant results:

- The efficacy of a system increases with the number of inserted barriers up to two barriers. Beyond this number, the system efficacy remains almost constant. It results from the visualization of the electric phenomenon that the discharge path is independent on the number of added barriers.
- The dielectric strength of a system with two clean and dry barriers in contact with the electrodes is approximately twice than that of the same system with only one barrier under the same conditions. In this case, the breakdown of the air gap is governed by discharges in the air interval between the two barriers following positive and negative streamers propagating on the respective faces of the two barriers facing the electrodes.
- When the surface conductivity of the two uniformly contaminated barriers is about 5μS, the system efficacy decrease quickly towards the minimal value of the same system with only one barrier tested under the same conditions of pollution. This diminution of performance, identical to that resulting from leader discharge in the air interval between the barriers' edges, can be explained by the cancellation of the two surface discharges voltages on the polluted faces of the barriers facing the electrodes. Cleaning measures are essential if the maintenance of the optimal efficacy of the system obtained in the case of a clean dry atmosphere must be respected.

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