Effect of surface condition and isolation mode on the efficiency of a barrier inserted in non-uniform electric field under AC voltage

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Abstract– The aim of this paper is the study of the effect of surface condition and isolation on the effectiveness of a screen inserted in a non-uniform field electrode system under AC voltage. The tests were conducted essentially on clean and dry glass barriers and on barriers contaminated with uniform and non-uniform pollution. The results show that : (i) in dry clean atmosphere, the optimisation of the system efficacy is dependent not only on the choice of the isolation mode and the screen position in the electrode gap, but also on the ratio of the screen and grounded electrode's diameters. In this case, the discharge leading to the air gap breakdown is of streamer type, (ii) The diminution in efficacy of a system with polluted screen compared to that with a clean dry screen is 14% maximum, (iii) In humid, polluted atmosphere, the screen has minimal efficacy for a surface conductivity equal to the pollution severity of a lightly-polluted site, regardless of the pollution distribution on its surface. In this case, the screen behaves practically like a conducting barrier and the air gap breakdown is caused by a leader type discharge. If an insulation level for such a system must be maintained, measures to remove pollution on the screen must be implemented and (iv) The efficacy of a system with floating glass-screen is approximately nine times higher than that of a system with directly grounded screen. In addition, the use of the base side isolated from ground as a second screen increases significantly the efficacy of the system.

Key words *–Point-plane system, glass barrier, screen isolation mode, uniform and non-uniform pollution, pollution severity, surface discharge, streamer discharge, leader discharge*

I. INTRODUCTION

The scope of application of insulation screens is very wide and touches many industrial fields, namely, gas circuit breakers, high-voltage switches, bushings, transformers and especially medium voltage electricity substations [1, 2, 3]. The results of many theoretical and experimental work have shown that the insertion of a clean and dry screen in the air gap between live parts and grounded parts of some equipment at reduced size, can improve the efficacy of such equipment by lengthening the isolation distance between them [4, 5, 6, 7, 8].

However, a polluted and humid atmosphere often produces very conductive electrolyte layers on the surface of these screens. This results in a change of potential distribution in the air gap of these systems. This can lead, in certain pollution conditions, to a very significant decrease in their dielectric strength [9]. To the author's best knowledge, this parameter was the subject of only very few investigations [10, 11, 12]. This paper reports the results of an experimental investigation on the influence of the surface condition and isolation of an insulating screen on the performance of a non-uniform field electrode system under AC voltage.

II. EXPERIMENTAL TECHNIQUE

The experimental model consists of a sharp rod electrode under high-voltage, a square flat barrier and a grounded circular plane (Fig.1). The high-voltage electrode consists of a cylindrical bronze rod 10 mm in diameter and 250 mm in length. It is terminated by a conical tip having an angle of 60° and radius of curvature of 1.1 mm. The Earth electrode consists of a steel disc 10 mm thick and with variable diameter, on which a cylindrical steel rod 20 mm in diameter and 150 mm in length is fixed (Fig.1a).

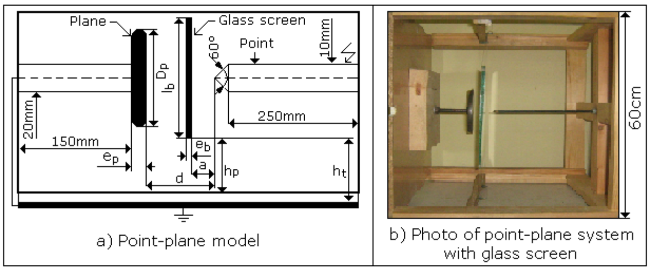

Fig.1. Construction and dimensions of Experimental model
(a) point-plane model (b) photo of the point-plane system with glass screen

The main electrodes are attached to two opposite sides of a cubic wood support of 60 cm side (Fig.1b). The air gap between these two electrodes is fixed at 5 cm. The insulating barriers are made of 6 mm thick glass, square and have different widths (10 cm, 20 cm, 30 cm and 40 cm). These screens have 5 mm-diameter holes drilled in their corners such that a circle circumscribed in the square and passing by the centres of these holes has a diameter equal to the side of the barrier (l_b). These screens are isolated from ground to a height h_t. They were fixed to the wood support cube through twelve nylon wires connecting each of the holes to the HV and ground faces of the support and to wooden sliding guides on the framework (Fig.1). These guides are used for moving the barriers horizontally. The support base is placed on a metallised wooden table, grounded and located 1 m above ground. The model can be positioned so that the axis of the electrode system is either parallel or perpendicular to the ground. A circular aluminium screen 3mm- thick and with variable diameter (20, 30 and 40 cm), was used as an extremely polluted barrier for reference.

The withstand voltage measurement and visualization of the air gap disruption phenomenon were conducted using equipment depicted in Figure 2. The circuit consists of a transformer (Tr) having a maximum secondary voltage of 135 kV and a control unit (SG) for automatic or manual speed ramp control. The test voltage is read directly on the digital peak voltmeter (V) at the low-voltage arm of a capacitive divider (C1, C2). A current-limiting resistance (Ra) is connected in series with test object.

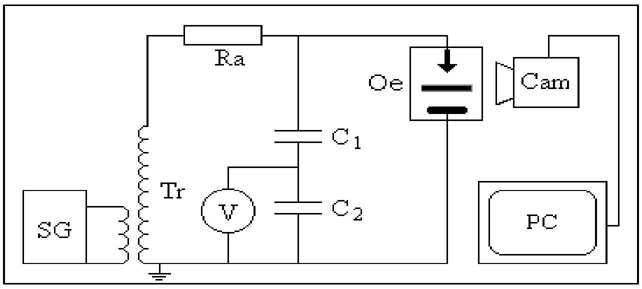

Fig.2. Schematic diagram of the measurement and visualisation circuit (SG: Transformer control unit, Tr: HV transformer, Cam: camescope, PC: personal computer, Oe: test object

The visualization system consists of a camcorder (Cam) for registering the different phases of the discharge in the air gap during each test and a PC for direct observation and analysis. Among the three most common methods of artificial pollution (saline fog, solid and liquid layers), the liquid layer method was chosen. The pollution consists of a mixture of distilled or tap water, 40 g of kaolin per litre for thickening the layer and sodium chloride the proportion of which is determined according to the desired volume conductivity in the solution.

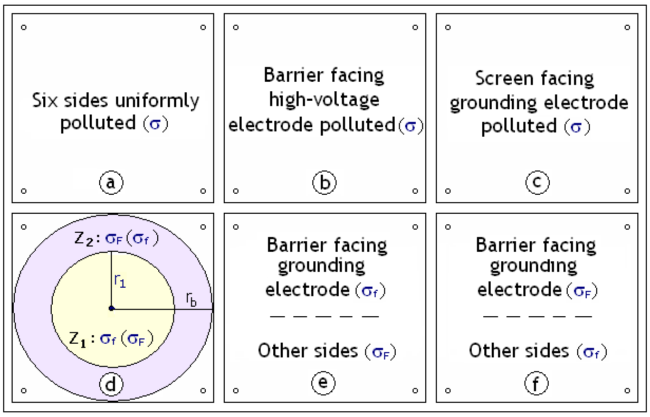

Fig.3. Pollution distribution variants on the screens (Z_1 (σ_f); Z_2 (σ_F): zones with high and low σ_s, r_1; r_b: radius of Z_1 and the screen, r_2 (Z_2) = $r_b - r_1$)

Two different modes of distribution of pollution on the surface of the insulating barrier were tested, namely uniform and non-uniform pollutant deposition distributions (Fig.3).

The barrier is said to be uniformly polluted when a polluting deposit of any electrical conductivity is applied uniformly on all six sides according to Variant 3a (Fig.3a). The pollution layer is applied using a sponge, on which a constant pollutant quantity of 2ml is injected by means of a syringe after thoroughly mixing it to keep it homogenous throughout our tests. Five pollution distribution variants have been exploited in this paper (Fig. 3b, c, d, e, f):

- In Variant 3b, the surface of the barrier facing the high-voltage electrode is polluted; the others are kept clean and dry,
- In Variant 3c the surface of the screen facing the grounding electrode is polluted, the others are kept clean and dry;
- In Variant 3d, the surface of the barrier facing the high-voltage electrode is subdivided into two circular variable areas and differently polluted Z_1, Z_2 (f, F), the other sides are kept clean and dry,
- Variant 3e is characterized by the fact that the surface of the screen next to the Earth electrode is slightly polluted and variable, and the other surfaces are contaminated with conductivity equal to 14µS F,
- Variant 3e is exactly the inverse of Variant 3e.

The system is energised immediately after the application of pollution on the barrier to avoid natural drying. Before each new test, the barrier is cleaned and rinsed with water, then dried. For each value of volume conductivity of the solution, the measurement of surface conductivity of the contaminated insulating barrier is performed using a mobile-probe conductivity meter [13]. A uniform surface coating, forming a single pollution layer of thickness e, is carried out using Variant 3a. The barrier is then left to dry for 24 hours. The surface conductivity is then measured on 25 sectors spread over the entire polluted, dried screen surface. The conductivity value is obtained by taking the arithmetic average of the surface conductivities of the selected sectors. The intervals of values of volume and surface conductivities used in this study are respectively (0.05-60) mS/cm and (1.5-50) µS. This choice is justified by the fact that these values must be representative of those encountered in actual conditions on site [13].

In each case, 25 disruptive tests were carried out. The breakdown is obtained by increasing the applied voltage at ramp a speed of to 4kV/cm until the air gap breaks down. This speed is chosen to avoid drying of the pollution layer during breakdown of the air gap. The value of the breakdown voltage is the average of all those obtained on the same series of measurement.

III. RESULS AND DISCUSSIONS

1. Surface condition and screen's degree of pollution

The efficacy (ξ_b) of the system with dry, clean screen as a function of the grounded-electrode diameter (D_p) is illustrated in figure 4. The result shows a maximum regardless of the width and position of the screen. Its value increases with the size of the screen. This optimum is characterized by a relationship between the screen width and the diameter of the grounded plane of the form:

$$l_b \approx 2D_p \qquad (1)$$

This expression remains valid also in the case where the diameter of the plan is fixed and the screen width is variable. Beyond this maximum, the efficacy of the system decreases. This decrease can be explained not only by the decrease in the potential difference between the barrier and the plan due to increase in the capacitance of air gap between the screen and ground electrode, but also by the absence of the discharge from the plane edge and the reduction of the discharge channel emanating from the point electrode.

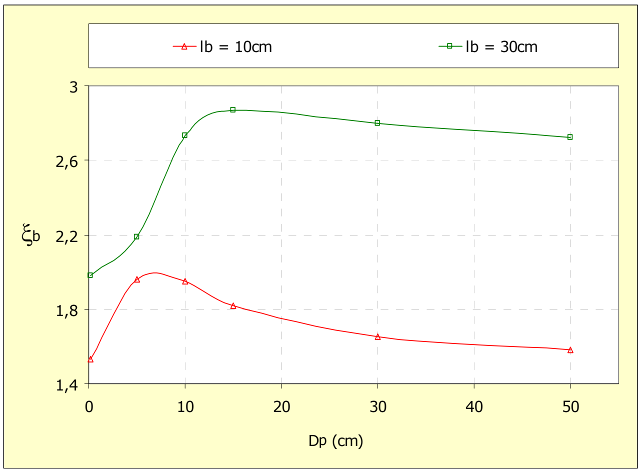

Fig. 4. $\xi_b = \hat{U}_{ab}/\hat{U}_{sb} = f\,(D_p)$ (a/d = 0%, e_b = 6mm, d = 5cm)

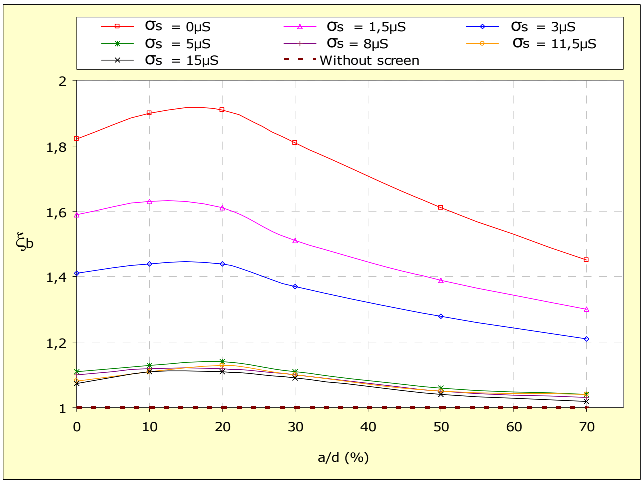

Fig.5. $\xi_b = f(a/d, \sigma_s)$ for uniformly polluted screen (l_b=10cm D_p=15cm)

Figure 5 provides a comparison between a system without screen, with a clean, dry screen where the barrier is uniformly polluted and wetted according to Variant 3a. The resulting curves are similar in shape to those of the same barrier with a dry clean surface, but with considerably smaller breakdown voltage values. This decrease can be explained by a rise in the contaminated barrier surface conductivity with a more conducting discharge path. It is noted, that beyond a limit value of conductivity equal to 5µS, all curves of $\xi_b = f(a/d)$ are practically the same (Fig.5).

For $D_p<l_b/2$, the visualization of the discharge shows the presence of surface discharges on both sides facing the electrodes in the case of a clean or contaminated barrier with conductivity below 5µS (Fig.6a).

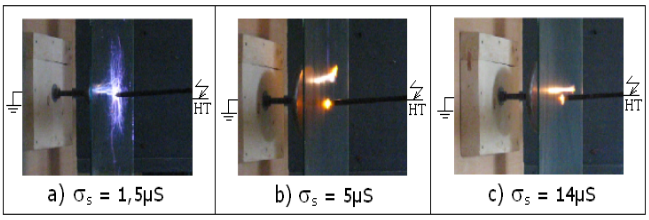

Fig.6. Effect of degree of pollution on discharge propagation over screen surfaces (a/d = 0%)

However, for $\sigma_s \geq 5\mu S$, no surface discharge was observed (Figs.6b-and-c), as if the points of impact on both sides of the screen were connected superficially and electrically by a conductor. In this case, the screen is almost equivalent to a conductive barrier. Figure 7 shows the comparison of the curves of $\xi_b = f(\sigma_s)$ where the screen is contaminated following variants given in Figs. 3(a, b and c).

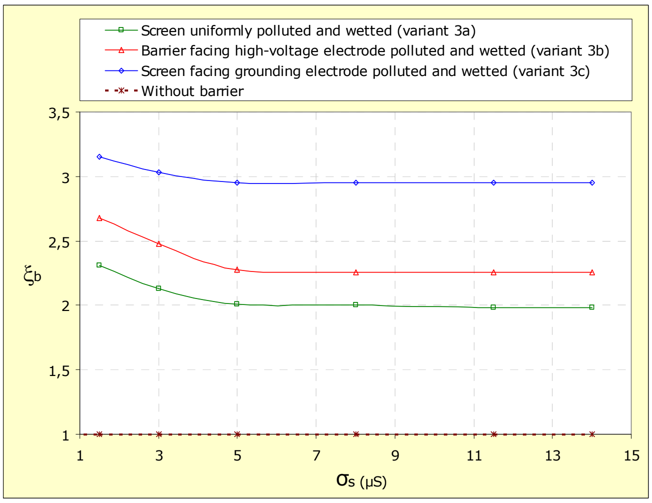

Fig.7. $\xi_b = f(\sigma_s)$ for distribution Variants 3(a, b and c) (l_b = 40cm)

The result is that regardless of the variant, the efficacy of the system decreases with increase of the barrier surface conductivity and becomes constant beyond a limit value identical to that obtained previously. Figure 7 also shows that the minimum efficacy of the system corresponds to that where the barrier is completely polluted. However, the system's dielectric strength is higher when the polluted surface of the barrier is facing the grounded electrode. The difference in the system efficacy between Variants 3b and 3c can be explained by the fact that when the high-voltage side of the barrier is polluted, the space charge generated by the discharge emanating from the HV electrode are uniformly distributed, resulting in a higher screen to ground electrode capacitance, compared with the case when this same face is clean and dry. A high capacitance therefore produces a lower dielectric strength.

Figure 8 provides the characteristic of the system's efficacy when the screen is contaminated according to Variant 3d. The efficacy of the system decreases with the diameter (D_F) of the heavily polluted area regardless of the position of the heavily and lightly polluted layers with reference to the high-voltage electrode. The extreme values of the system's efficacy are equal to those obtained when the same side of the screen is completely contaminated with surface conductivity 1.5 and 14µS respectively. They are also higher than the minimum values acquired in the case of Variant 3.

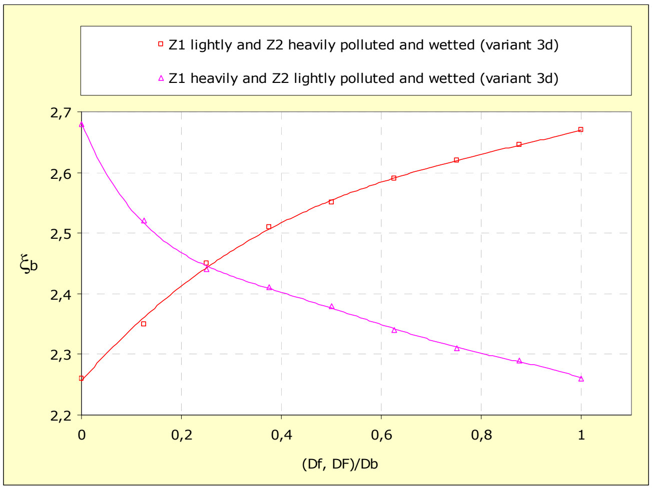

Fig.8. ξ_b = f (D_f/D_b ou D_F/D_b) for a distribution according to Variant 3d (l_b = 40cm, σ_f = 1,5µS, σ_F = 14µS)

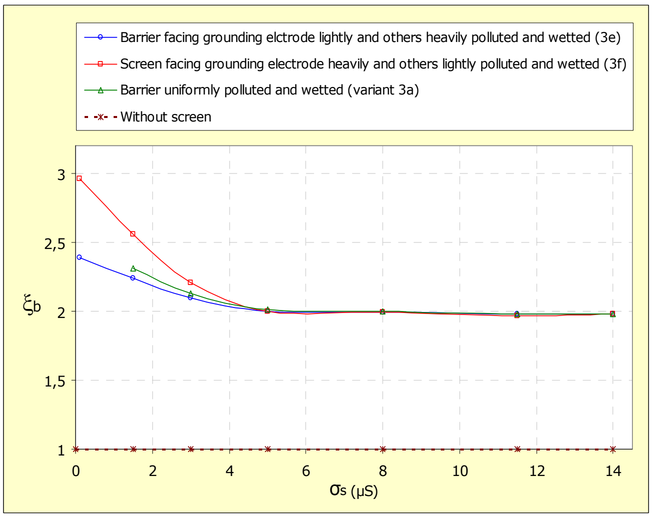

Fig.9. ξ_b = f(σ_s) for a distribution according to Variants 3a, e et f (l_b = 40cm, 0µS ≤ σ_f ≤ 14µS et σ_F = 14µS)

Figure 9 gives the characteristics ξ_b = f(σ_f) of the system in the case where the screen is contaminated following the distribution of pollution variants presented in Figure 3(e-and-f).) The result is that for σf <5µS and σF = 14µS, the curve obtained with Variant 3e show values lower than those obtained with Variant 3a. This is evident since the voltage drop on the polluted faces with σ_F = 14µS is almost zero because of the absence of the discharge on the surface. Therefore, any other variant of type 3e satisfying conditions: σ_f <5µS and σ_F≥5µS, will give values smaller than those resulting from Variant 3a. In this interval, a uniformly unpolluted screen system presents the lowest possible efficacy.

For σ_f ≥5µS, the minimum efficiency curves, obtained according to the three variants 3 (a, e and f), are practically the same. This can be easily justified by the fact that the screen is considered in these cases as being like a conductor. Therefore barrier cleaning measures are mandatory if a level of isolation required for this system must be respected in this case.

To see the effect of the degree of screens' pollution wetting on the efficacy of the systems studied, two extreme cases were experienced for a given surface conductivity value, (i) barriers were polluted then left dry for at least twenty-four hours, (ii) they have been polluted and moistened just before the voltage application. The tests were conducted on a screen of 25cm width and a system where the axis of the main electrodes is in a vertical position. The measurement results are summarized in figure 10. There is a 14% reduction in the system's efficacy for a screen polluted and dried compared to that of a clean screen while the reduction is 57% for a polluted and wetted screen. For σ_s≥5µS, the efficacy of the latter is practically similar to that of a conducting barrier. In addition, it is noted that the system with dry pollutant deposited on the surface facing the high-voltage electrode has a higher dielectric strength than when the pollution is deposited on both sides of the screen or on the side facing the grounded electrode. This can be explained by the fact that the dry pollution deposit has not only less insulation properties than clean glass but also contains small protuberances thereby disturbing the quasi uniform field between the barrier and the plane, and significant decreasing the system's efficacy.

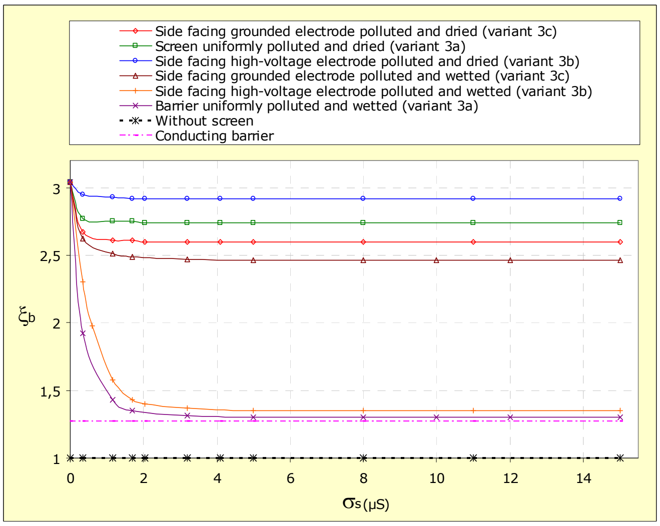

Fig.10. Effect of the degree of pollution humidification on the efficacy of a point-plane electrode system with axis in vertical position (l_b = 25cm)

2. Mode of screen isolation with reference to ground

Figure 11 shows the effect of the nature and the isolation of the base of the support containing the system with a clean screen on its efficacy. When the base is conducting and directly connected to ground, the efficacy of the system increases with the screen's isolation distance until a limit value beyond which it becomes constant. Indeed the isolation capacitance from the barrier edge to this conducting screen depends primarily on the distance separating them.

Below this value limit, the partial path with the highest dielectric strength corresponds to that which connects the barrier to the plane and the most likely disruption of the system is that of the air interval between the high-voltage electrode and the centre of screen 1, the flashover of the surface between the centre and the edge of barrier 1 and finally the failure of the air gap between the edge of screen 1 and grounded screen 2. Beyond this value, the opposite of what has been observed previously occurs. The isolation of the base from the earth produces a very small increase in the system's efficacy regardless of its position with reference to the edge of the screen. However, the replacement of this conducting screen by an insulating one leads to a 17% increase in the system's efficacy regardless of the distance separating it from the grounded electrode (Fig.11). Therefore the use of an insulating base, isolated from ground is technically favourable.

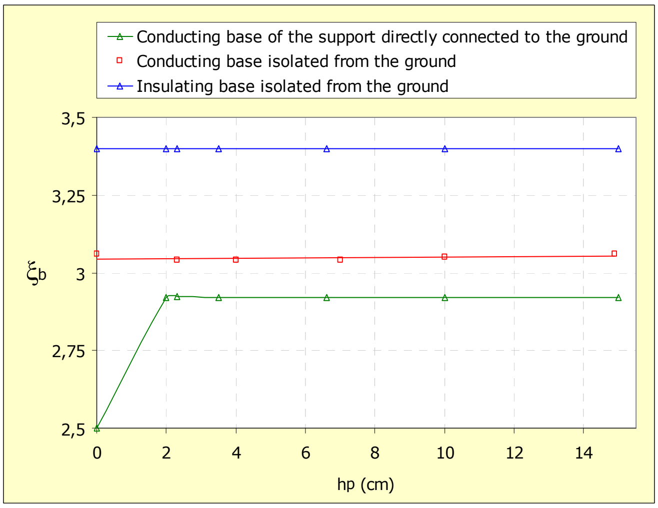

Fig.11. System's efficacy as a function of isolating distance of a clean screen, with reference to the support base (l_b=30cm, a/d=10%)

Figure 12 highlights the effect of an isolating resistance between the screen and the grounded electrode on its efficacy. The result is two limit values of resistance; the smallest ($R \leq 0.12x10^6\Omega$) corresponds to the conductive barrier directly connected to ground. In this case, the breakdown of the system's air gap is reduced to that between the high-voltage electrode and the conducting screen. The resultant efficacy of the system has a minimum value (0.25) and it is far less than that without the screen. The higher limit of resistance ($R\geq10^8\Omega$) corresponds to the case where the conductive barrier is isolated by the air gap between its bottom edge and the ground as well as the interval separating it from the grounded plane. In this case its efficacy is about nine times larger than previously.

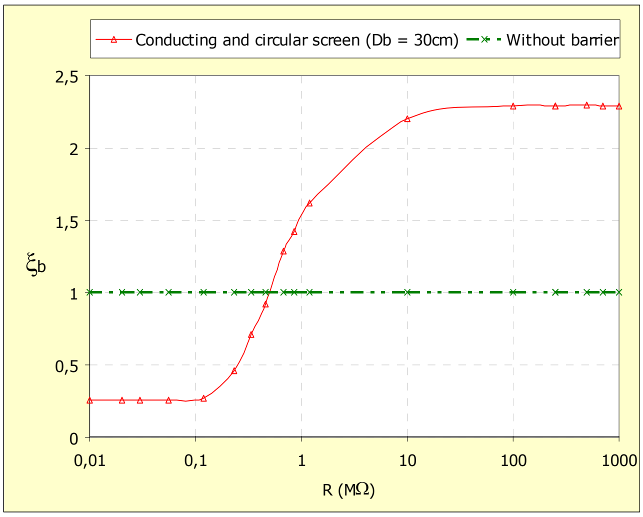

Fig. 12 Air gap disruptive voltage as a function of isolating resistance of a conducting screen (l_b = 30cm, a/d = 10%)

3. Characteristic of the system's disruptive discharge

Figure 13 shows the variation of the disruptive voltage of the air gap with the barrier width. The latter was connected directly to the ground to eliminate the discharge of interception emanating from the plane.

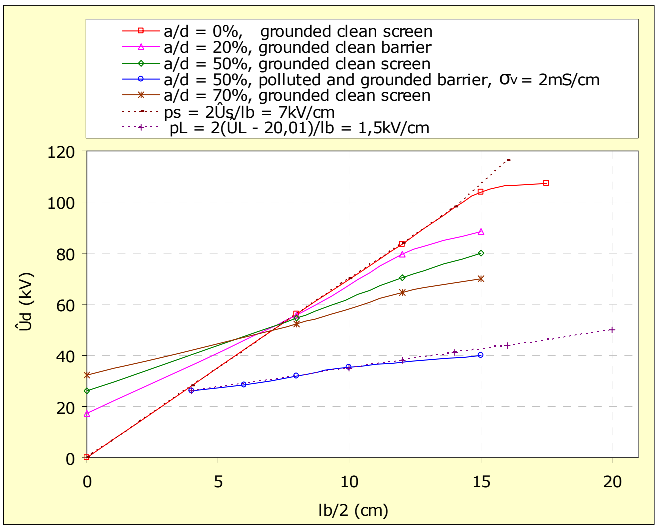

Fig.13. $\hat{U}_d = f(l_b)$ for the point-plane system with grounded screen

The characteristics $\hat{U}_d = f(l_b)$ are similar in shape to those established by Lemke [14]. The slope of the curve decreases from 7kV/cm to 3kV/cm in the case of a clean dry screen. When the barrier is covered with a pollutant deposit with a volume conductivity of 2mS/cm, the slope is of the order of 1.5 kV/cm. This simply means that the discharge emanating from the high-voltage electrode is of streamer type in the case of a clean barrier, and is of type leader when it is covered with a pollution deposit of conductivity equal to the above value. This can be justified by the agreement between these values and those given in the literature [14, 15].

IV. CONCLUSION

The analysis of the effect of the surface condition and isolation of a floating screen in an air gap of a point-plane electrode system on its efficacy has led to the following conclusions:

- Insertion of an insulating barrier slows down the development of the discharge by streamers due to the elongation of inter-electrode distance by a very resistive path equal to the width of the screen. The efficacy of the system is optimised by a careful choice of an insulating screen with clean dry surface and isolated from ground. Its width must be approximately twice the diameter of the grounded plane, and should be placed close to the high-voltage electrode;
- When the barrier is polluted, a minimum dielectric strength is reached when the contaminated face of the screen is covered by a pollution deposit corresponding to a light class pollution level, regardless of the mode of its distribution on its surface. In this case, the polluted screen behaves almost like a conductive barrier and the breakdown of the system's air gap is caused by a discharge of type leader. Therefore cleaning measures become mandatory if a minimum level of isolation is required.
- The efficacy of a system having an isolated glass screen is approximately nine times higher than when the screen is directly connected to ground. In addition, the use of the system's support base as a second insulating screen isolated from ground contributes to the increase in its efficacy.

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