Streamer Propagation in Rod-Plane Air Gaps with a Dielectric Barrier

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Abstract—High-voltage design optimization requires a fundamental understanding of electrical breakdown mechanisms under different stress situations. The impulse withstand voltage is normally used as dimensioning criterion for medium voltage air-insulated systems as flashover mechanisms in air are rapid. Prediction of withstand voltage relies on streamer inception and propagation models that are not always sufficiently accurate. Positive impulse voltage experiments were performed on a rod-plane gap with a dielectric barrier at different positions parallel to the ground plane. Streamers initiate from the rod tip and propagate in the field direction. Charge deposited on the dielectric surface changes the field situation and can result in a higher inception voltage. The streamer propagation was recorded with a fast ICCD camera. Finite element method field simulations of the background field were used to evaluate the effect of a barrier surface potential on the streamer inception voltage. Streamers reach the ground electrode without initiating electrical breakdown. The discharge activity from the rod was reduced by deposited charge on the barrier.

I. INTRODUCTION

Space is a limiting factor in high voltage engineering, resulting in an incentive to minimize equipment size. The breakdown strength of the insulating medium restricts designers of gas insulated systems. Sulphur hexafluoride gas (SF_6) is often used as insulating medium because of its good dielectric properties, but alternatives are sought since SF_6 is a very potent greenhouse gas. The withstand voltage of air is roughly a third of the corresponding value for SF_6 and is therefore normally not used when space is limited. Dielectric barriers can, however, significantly improve the breakdown strength of air [1]. The size and position of such barriers must be chosen carefully. For instance, it has been observed that small barriers close to the live electrode can reduce the withstand voltage relative to that of the corresponding barrier-less gap [2]. Estimation of the withstand strength of such hybrid gas-solid insulation systems require better knowledge of the interaction between gas discharges and dielectrics. An important aspect is the field distortion that can arise when charge is deposited on dielectric surfaces. This work aims to further explore the characteristics of electrical discharges in an inhomogeneous air gap with a dielectric barrier. Standard positive lightning impulse voltages ($1.2/50\,\mu s$) are used since they are usually dimensioning for gas insulation systems in the medium voltage (MV) range.

II. BREAKDOWN IN AIR

A. Streamer inception

In atmospheric air with gap distances larger than a few mm, the prediction of breakdown is based on the streamer inception criterion

$$\int_{\Gamma} \alpha_{\text{eff}} dx = \ln(N_c) \tag{1}$$

where $\alpha_{\text{eff}}(E)$ is the field-dependent effective ionization coefficient, and N_c is the critical number of electrons in the electron avalanche needed to create a self-propagating streamer head. For atmospheric air MV applications in strongly inhomogeneous fields, $\ln(N_c) \approx 18.4$ should be used [3]. Finding the correct streamer path Γ is not straightforward in complex geometries. A common approximation is to assume that it starts in the high field region and follows a field line along which $\alpha_{\text{eff}} > 0$. The integration path is typically a few mm and ends when the background field reaches a critical value E_c such that $\alpha_{\text{eff}}(E_c) = 0$. $\alpha_{\text{eff}}(E_c)$ can be estimated with empirically determined fit functions [4]. E_c is the field strength at which the probability of ionization is equal to that of recombination, typically around $2.5\,kV/mm$ for atmospheric air [3], [5].

B. Streamer propagation

A sufficiently high voltage must be applied if streamers are to reach the ground electrode d mm away. For a strongly inhomogeneous field distribution E in a gap where $5\,cm < d < 2\,m$, the prediction of streamer propagation distance is based on the assumption of a constant field strength E_{st} in the streamer channel. The propagation distance d_S is estimated with the equal area rule $E_{st} \cdot d_S \approx \int_0^{d_S} E(x)dx$ along a field line. The impulse voltage level leading to breakdown in air is approximately [3]

$$U_W = U_0 + d \cdot E_{st} \tag{2}$$

where $E_{st} \approx 0.54\,kV/mm$ is the internal field strength along the positive streamer behind its front. $U_0 \approx 20 - 30$ kV is equivalent to the streamer head potential needed to generate a breakdown [6].
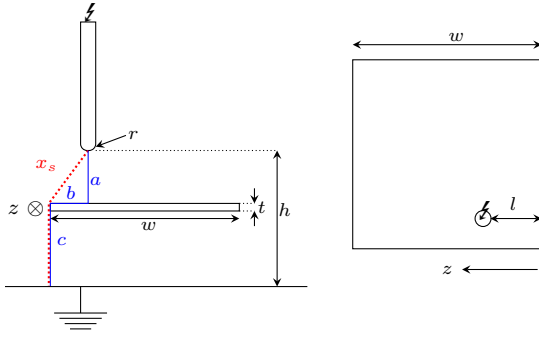
Fig. 1. Rod-plane gap with insulating barrier.

Fig. 2. Experimental set-up.

C. Barrier effect

The withstand voltage of an air gap can be increased by introducing an insulating barrier between the electrodes. This can be understood in terms of an elongated path for air discharges, as a longer distance d in (2) results in a higher withstand voltage U_W. The shortest path to the ground electrode in Fig. 1 is $x_s = \sqrt{a^2 + b^2} + c$, whereas in a barrier-less gap the distance would only be $a + c$.

Furthermore, streamers deposit charge on the dielectric surface, reducing the field between the rod and barrier while increasing it between the barrier and ground. With a large and sufficiently charged barrier, the field between its surface and ground will be weakly inhomogeneous. The withstand voltage $U_W(c)$ of the gap between barrier and ground is then governed by streamer inception, not propagation. Assuming that the barrier is charged to a potential equal to that of the streamers reaching the barrier, the impulse level necessary for breakdown becomes [2]

$$U_W = U_W(c) + a \cdot E_{st}. \tag{3}$$

Small barriers close to the electrode can result in poor withstand voltages [2]. This could be caused by high tangential background field strengths that can support streamer propagation along the entire surface or edge effects [2], [7].

III. EXPERIMENTAL

A. Experimental set-up

A $1.2\,\mathrm{MV}$ Marx impulse generator was used to generate lightning voltages over a rod-plane gap with a dielectric barrier, see Fig. 2. An Imacon 468 camera with an 85 mm f/1.8 Nikkor lens in a Faraday cage at a distance of $\sim$1 m from the live electrode was used to capture the discharge activity. An optical beam splitter in the camera divided incoming light into 8 paths, each with an intensified charge-coupling device (ICCD). The exposure time of each frame is controlled by a digital circuit, giving a minimum possible time resolution of 10 ns. The images were timed to the impulse voltage using a digital delay generator. The applied voltage and camera trigger monitor pulse were measured with an oscilloscope.
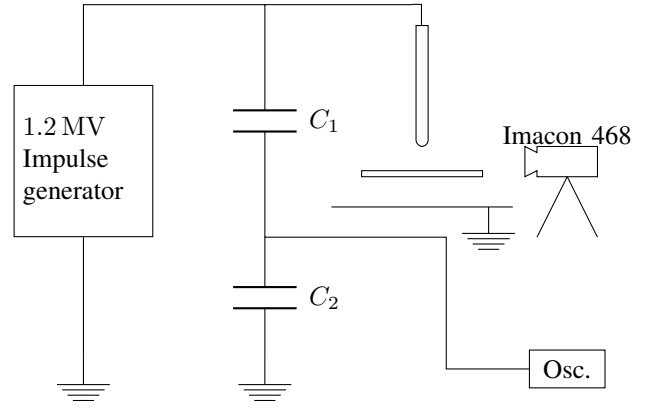
B. Experimental procedures

Positive lightning impulses were applied to a rod-plane gap with a $600\,\mathrm{mm} \times 600\,\mathrm{mm} \times 5\,\mathrm{mm}$ polycarbonate barrier over a $1\,\mathrm{m} \times 1\,\mathrm{m}$ ground plane. An electrode with a hemisphere rod-tip radius $r = 3.5\,\mathrm{mm}$ was placed centrally above to the ground plane at a height $h = 60\,\mathrm{mm}$. To achieve better imaging conditions, the electrode was shifted towards the camera so that l in Fig. 1 was $\sim$170 mm. The overhang b was varied between $40\,\mathrm{mm}$ and $0\,\mathrm{mm}$ by moving the barrier transverse to the camera axis z. The distance a from the barrier surface to the rod tip was kept constant at $20\,\mathrm{mm}$. The ratios w/b and l/b were chosen relatively large to ensure that streamer propagation would occur inside the frame and transverse to the camera axis z.

All sides of the barrier were cleaned with isopropanol between each impulse to remove deposited charge. A hand-held electrostatic voltmeter was used to verify that the surface potential was less than $500\,\mathrm{V}$. The temperature, pressure and relative air humidity were logged.

C. Image processing

Calibration pictures with no voltage stress on the gap were taken after each successful streamer image sequence to adjust for differences in the ICCD light sensitivity. This calibration picture sequence was later subtracted from the streamer image sequence, resulting in more uniform background light. As the discharges were very faint, it was also necessary to enhance the image brightness and contrast. These parameters were adjusted to the same values for all images in order to normalise the evaluation of discharge intensity.

D. Simulations

3D electrostatic simulations of the background field were made using COMSOL Multiphysics. Charge deposited was simulated with an electric potential on the barrier surface and side. This potential was approximated using (3) to the potential of streamers that have reached the barrier $U_W - a \cdot E_{st}$. The streamer inception criterion (1) was computed along field lines from the rod tip to ground.
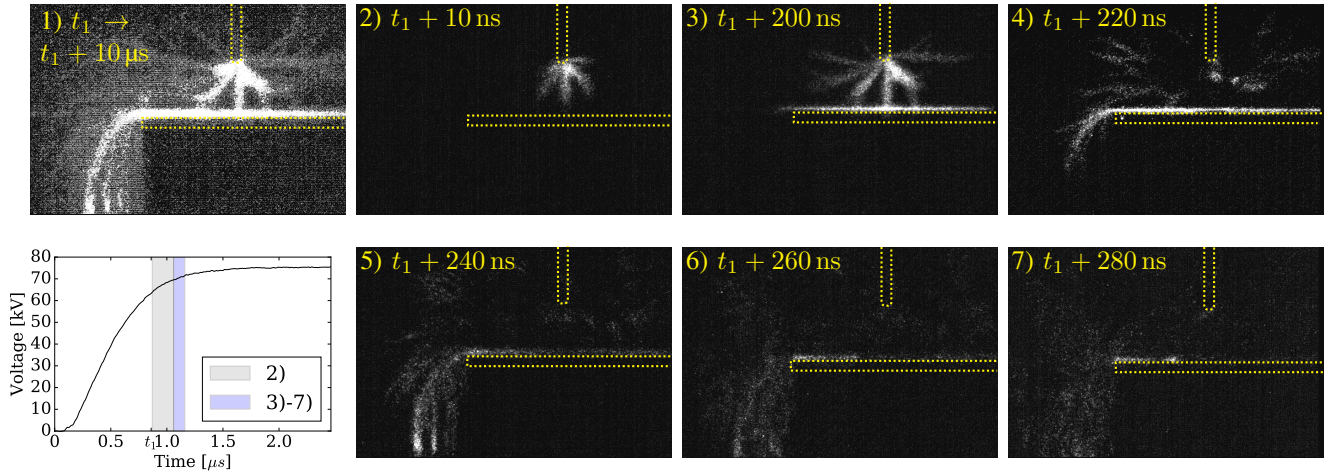
(a) Barrier overhang b = 40 mm with applied lightning impulse voltage U = 75.37 kV. Rel. air humidity 35 %, temp. 22 °C, air pressure 100.8 kPa.
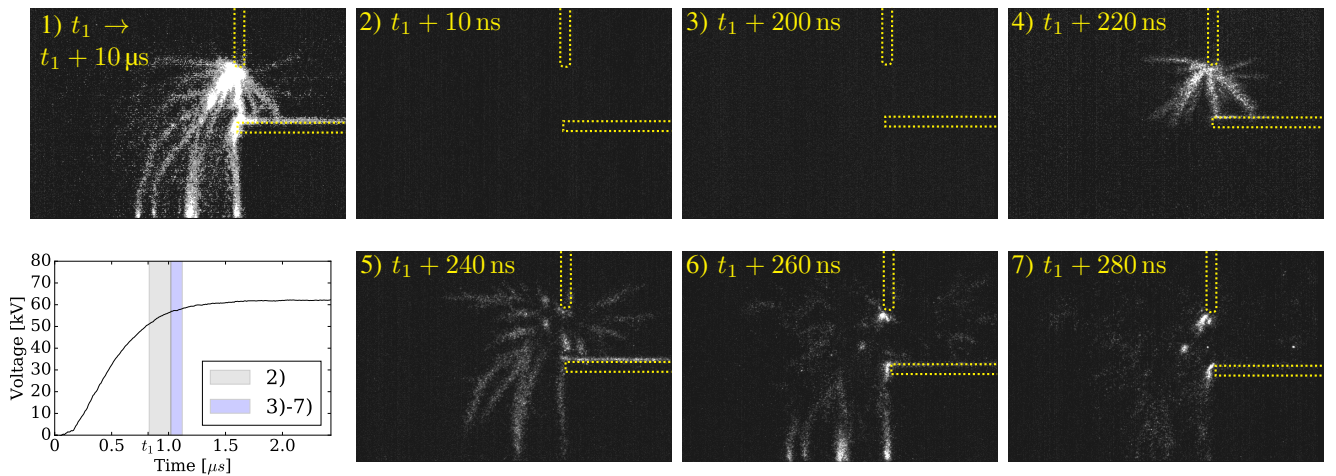
(b) Barrier overhang b = 0 mm with applied lightning impulse voltage U = 62.18 kV. Rel. air humidity 40 %, temp. 21 °C, air pressure 100.2 kPa.

Fig. 3. Streamers in a rod-plane gap with a dielectric barrier. Electrode-to-ground distance h = 60 mm, barrier surface height c = 40 mm and barrier thickness t = 5 mm. Frame 1) with exposure time 10 µs shows the accumulated discharge activity. Frame 2) is 190 ns long while frames 3)-7) are all 20 ns. The frame sequence start time t_1 is indicated in the voltage front plot in the bottom left corner of each figure. No breakdown occurred.

IV. RESULTS AND DISCUSSION

A. Images of streamer development

Fig. 3 shows streamer development in a rod plane-gap with two different barrier placements. The geometry is equal in Figs. 3a and 3b except for the overhang b, which is 40 mm in the former and 0 mm in the latter. In Fig. 3a, streamers are incepted at the rod during frame 2). They then propagate along the barrier surface in frame 3) before propagating toward the ground plane in frames 4) and 5). The discharge activity is reduced between the barrier surface and rod in frame 4) and remains sparse in the subsequent frames. This quenching of the discharge activity indicates a counter-field set up by deposited charge on the barrier. Although some streamers reach the ground plane, all the necessary conditions for electrical breakdown are not met.

Similarly, in Fig. 3b, a cloud of streamers touches the barrier in frame 4), before propagating toward ground in frame 5) and

6). Bridging of the gap seems to be faster in Fig. 3b than in Fig. 3a, which is within expectations as the shortest path x_s is 60 mm in the former and ∼85 mm in the latter. Streamer propagation velocity is, based on the development from frame 4) to frame 5) in Fig. 3b, estimated to ∼2 mm/ns.

Edge effects are observed in frames 6) and 7) in Fig. 3b where the discharge activity near the barrier edge is relatively high. Furthermore, discharge activity near the rod is not fully quenched as in Fig. 3a. Frames 1), 6) and 7) in Fig. 3b indicate that the discharge intensity is greater on the barrier-less side.

B. Simulations

The inception voltages in Table I are calculated as described in Sect. III-D. The inception strength is increased by a factor 5 and 2.5 for 40 mm and 0 mm respectively when the barrier is charged. The field lines from the rod tip to ground with and without a barrier potential are shown alongside equipotential

lines in Figs. 4a and 4b respectively. The surface potential is, based on (3), ca. $86\,\%$ of the impulse peak. In reality the potential distribution will be non-uniform and mostly lower than the value used here. The real distribution will reflect the streamer propagation paths in the air and along the surface. Charge density will likely be high directly beneath the electrode and lower further out as the streamer potential decreases with distance from the rod. A better evaluation of the barrier potential influence requires surface charge measurements or simulation models of discharge dynamics. Nevertheless, it is reasonable to expect that charge on the dielectric surface will in these cases alter the field significantly and reduce discharge activity near the rod.

Simulation results by Singh, Serdyuk and Summer [8] of the discharge dynamics for a similar configuration show qualitative similarities to the frames 2)-5) in Fig. 3a and an average streamer propagation velocity of $2\,\mathrm{mm/ns}$.

TABLE I
CALCULATED MINIMUM STREAMER INCEPTION VOLTAGE [kV]

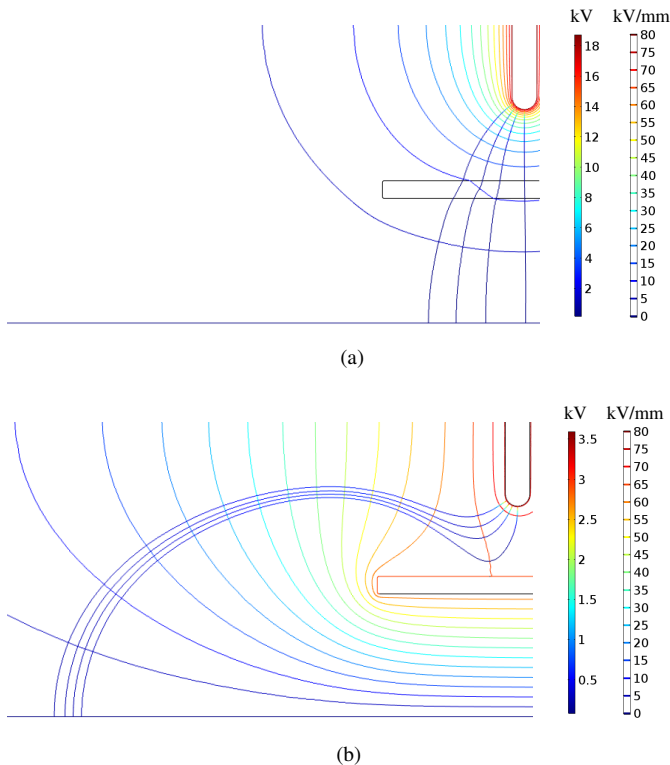| Overhang [mm]	Uncharged barrier	Charged barrier
40	27.51	139.81
0	28.49	69.19

(a)

(b)

Fig. 4. Comparison of electrical field and equipotential lines without (a) and with (b) voltage on the barrier surface and edge. Overhang $40\,\mathrm{mm}$.

V. CONCLUSIONS

Streamer propagation in a rod-plane gap with a dielectric barrier under positive lightning impulse stress has been examined with a high-speed camera. Two barrier placements with different overhangs ($40\,\mathrm{mm}$ and $0\,\mathrm{mm}$) were used. In both cases, streamers propagate from the rod to ground without causing electrical breakdown. A reduction in discharge activity near the rod after streamers reach the barrier was observed. Background field calculations demonstrate that the deposited charge on the barrier increases inception strength from the rod, in line with observations.

ACKNOWLEDGMENT

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