Streamer discharges along dielectric surfaces – experimental investigations

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Streamer discharges along dielectric surfaces play a crucial role in high voltage (HV) devices, since they can form a conductive channel, which (under sufficient electric field) develops into an arc, leading to short-circuiting and damage of the device. The exact conditions of the formation of these streamers are, however, poorly understood and require detailed investigations. The goal of the present work is to provide physical understanding of the processes leading to surface streamer development. Experiments were performed in a specially designed set up with the samples of a structure most typically used in an industrial HV device. Time-resolved imaging and current shapes measurements were performed, as well as inception voltage estimation. During the experiments AC and pulsed voltage supplies were used to power the set-up. Experimental investigations show that the presence of a dielectric surface changes the initial parameters of the environment (compared to the processes in bulk gas) – making it "easier" for a discharge to develop. The reduced electric field is larger than that expected in bulk gas. Velocities of streamers propagating along the surface were estimated based on the time-resolved imaging of the processes.

1. Introduction

Streamer discharges are attracting considerable interest due to their important role in various technological processes – air and water purification, plasma treatment, switchgears, flow control [1 - 3]. Being the determining mechanism of different implementations, these discharges may, on the other hand, cause negative effects in respect to high voltage (HV) technologies. One of the critical issues in designing HV appliances is proper isolation of conducting parts, meant to prevent detrimental breakdowns. Thick dielectric layers are generally used for this purpose, nevertheless they do not always provide the necessary level of protection; unwanted discharges can occur despite the presence of an insulating layer [4]. These discharges prefer to propagate along the surface of a dielectric, rather than through the volume of bulk gas. The initial stage of discharge development - the streamer phase – attracts the main attention and is the center of this work, since after streamers have formed a conductive path full breakdown can hardly be prevented.

2. Experimental set-up

Experimental investigations of surface streamers were performed with the sample configuration presented on figure 1 – dielectric (epoxy resin) rods with two embedded metal electrodes. Such a configuration leads to a significant enhancement of the electric field on the surface of a dielectric, resulting in a surface discharge inception. The central axis of the metal electrodes was shifted from the central axis of a dielectric cylinder for the convenience of optical investigations. The detailed description of the samples can be found in [5 - 7].

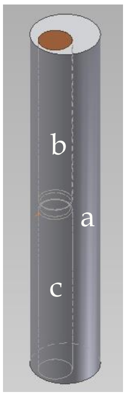

Fig. 1: Experimental sample – dielectric rod (a) with embedded electrodes (b,c).

Experiments were performed in a vacuum vessel allowing to set up and maintain the conditions of the surrounding environment. In the current series of experiments the sample was surrounded with nitrogen at the range of pressures (50 - 1000) mbar for AC power supply and (100 – 400) mbar for pulsed voltage supply. The overview of the experimental set-up is presented at figure 2. Electrodes were specially designed to provide required electric field distribution within the vessel and manufactured out of alumina. The detailed description of the experimental set-up can be found in [5, 7]. Discharge currents were measured by means of sub-divided cathode with the help of 104MXs-B LeCroy oscilloscope. Imaging of discharge processes is performed using a 4Picos-

DIG ICCD camera. Voltage was applied to the HV (top) electrode through the vacuum feed-through and measured using the North Star 1:1000 high-voltage probe, the signal from which is recorded on the oscilloscope.

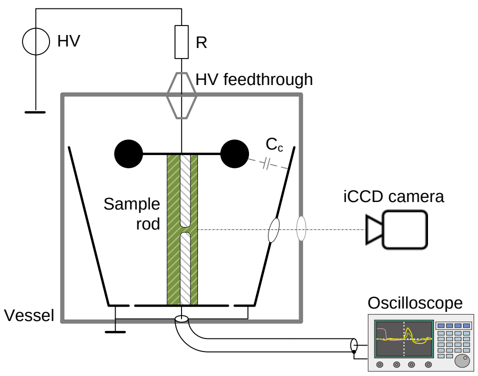

Fig. 2. Layout of the experimental set-up

3. Experimental results

3.1. Experiments with AC voltage supply

During the experiments with AC power voltage supply the applied voltage was gradually increased until the first current activity was observed on the oscilloscope. The maximum voltage of the AC cycle under which the first discharges took place is referred to as the inception voltage. The values of inception voltages were lying in the range of (5 - 32) kV for the pressures of surrounding nitrogen of 50 mbar and 1000 mbar respectively. During the experiments time-resolved current shapes measurements were performed; the obtained current shapes were later analysed to achieve the values of ionization rates and estimate the values of the reduced electric field, corresponding to streamer ignition in nitrogen at given range of pressures [7]. Results are presented at figure 3.

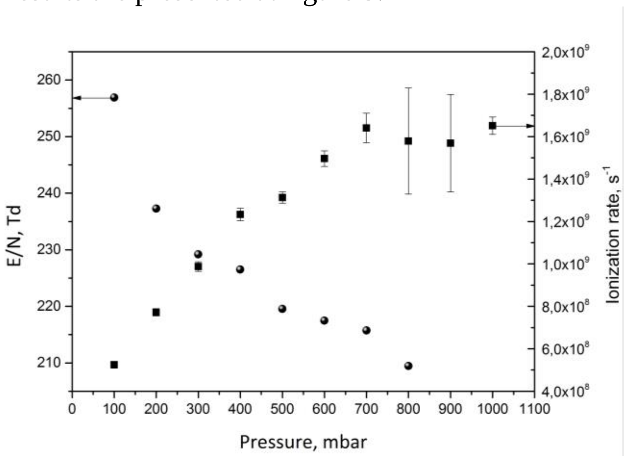

Fig. 3. Experimental results for streamer discharges developing under AC power supply. Squares represent the obtained values of the ionization rate; spheres – the estimated values of the reduced electric field, based on the ionization rates.

The values of ionization rates and reduced electric fields appear to be quite high as compared to values corresponding to streamer inception in bulk gas [8]. Higher values of inception field mean that dielectric layer prevents streamer ignition at lower E/N values possible in a bulk gas; however at the same time the dielectric surface enhances the electric field allowing the discharge ignition even at higher inception fields.

3.2. Experiments with pulsed voltage supply

To perform time-resolved imaging of discharge processes the set-up was powered with pulsed voltage supply. Behlke HTS 701-20-LC2 switch (maximum pulse voltage 70 kV) was used to power up the set-up. Pulse duration varied from 400 ns to 6 µs, pulse magnitude for current experiments did not exceed 25 kV. Example of the obtained image sequence for surface streamers in nitrogen is presented at figure 4. The circulate borders represent the edges of the window of the vessel – the range of visibility of the camera. The straight vertical lines represent the edges of the sample rod.

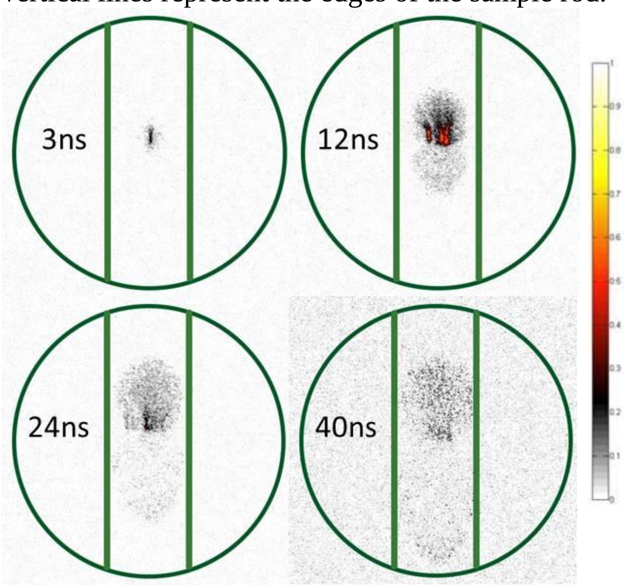

Fig. 4. Images of streamer development at nitrogen environment. Pulse duration – 2 µs; pulse magnitude – 13 kV; gas pressure – 100 mbar; time values represent the time after the streamer ignition.

The discharges originate at the surface area, corresponding to the 4mm inner gap between the metal electrodes and continue to propagate towards HV and grounded electrodes along the surface of a dielectric. It can be observed that positive (cathode-directed) streamers travel larger distances than the negative (anode-directed) ones within the same periods of time. Measuring the distances covered by the streamers within the time between the initiation of the current and the time when the camera gate was closed, one can estimate streamer velocities. The obtained values of streamer velocities are presented at figure 5. The values represent the average velocities of both positive and negative streamers, since only the total covered distance was taken into account. However, detailed imaging showed that at the initial point of time both upward (anode-directed) and downward (cathode-directed) streamers propagate with similar velocity. Later on, the further the streamers recede from the area surrounding the inner electrodes, the slower they become; however positive streamer’s velocity reduces at a slower pace.

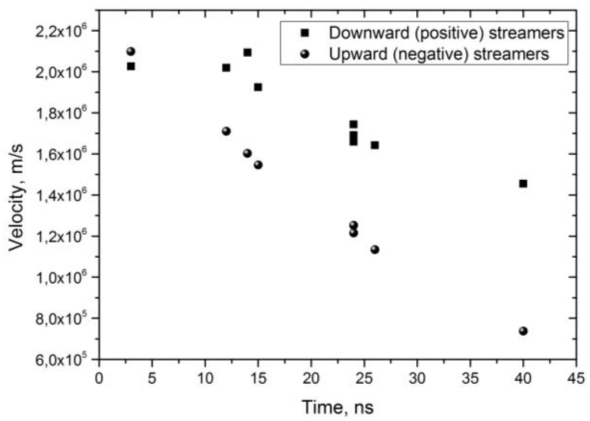

Fig. 5. Average velocity estimation for positive and negative streamer discharges along dielectric surfaces at 100 mbar nitrogen.

Streamer velocity tends to increase with the increase of the pressure of the surrounding gas - which can be explained by the larger amount of free electrons in the environment, making it easier for the initial avalanche to propagate. Experiments also demonstrated, that streamer discharges do not detach from the surface of a dielectric, but stick to it, following the rod-sample curvature.

4. Conclusions

Experimental investigations of streamer discharges, propagating along dielectric surfaces without any contact with conducting (metal) parts, were performed. The focus of the research was on the initial phase of streamer development and inception conditions estimation. The values of inception voltages, ionization rates and corresponding values of the reduced electric fields were determined for streamers propagating in nitrogen environment under AC voltage supply. The obtained values turned out to be higher than those, expected for discharges in the bulk gas, showing the enhancement of the electric field caused by the presence of a dielectric.

Experiments with the pulsed voltage supply allowed to perform time-resolved imaging of the initial phase of electrodeless discharge inception. Based on the images, the average velocities of streamer discharges were estimated. The data show, that positive streamers propagate faster than the negative ones; moreover, both positive and negative streamers propagate faster with the increased pressure of the surrounding gas, which can be explained by the higher concentration of free electrons in the environment.

5. References

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