ELECTRICAL BREAKDOWN OF SHORT NON-UNIFORM AIR GAPS

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Abstract

The breakdown voltage of air in highly divergent electric fields in not very short gaps (a few mm and above) is typically higher for negative energisation compared to positive energisation. Volumetric negative space charge, created by attachment of electrons to electro-negative molecules in the case of negative energisation, reduces the field in the vicinity of the sharp cathode, resulting in higher breakdown voltages. This paper investigates self-breakdown voltages in short, mm and sub-mm gaps formed by point and plane electrodes and filled with atmospheric air at pressures 0.5-3.5 atm (abs). It is expected that space charge effects will change self-breakdown voltages for positive and negative energisation modes resulting in their different functional behaviour as compared with larger inter-electrode gaps.

I. INTRODUCTION

The breakdown voltage of air in highly divergent electric fields in not very short gaps (a few mm and above) is typically higher for negative energisation compared to positive energisation [1]. In an electronegative gas a volumetric negative space charge develops between the electrodes, screening the electric field and increasing the hold-off voltage in the case of negative energisation. This is utilised in repetitive breakdown switching modes such as corona stabilised plasma closing switches [2] to increase the hold-off voltage and decrease time between impulses to full voltage recovery after previous breakdown.

In electronegative gases the electron attachment process results in the creation of negative ions that move slowly compared with electrons due to their significantly higher mass. In a highly diverging field, such as the field developed in a point-plane topology, negative ions are created in a localised region in front of the sharp electrode. This space charge screens the electric field and reduces the field at the point cathode. In the case of the positive energisation mode the effect of space charge in significantly reduced and, as the result, the required voltage to reach the breakdown is lower than in the case of negative energisation. This is accurate for most applications where the inter-electrode gap is relatively large, a few mm and above. However, in the event of shorter gaps (~4 mm and below) it has been observed that the breakdown voltage is higher for positive energisation [3]. In this paper a comprehensive study of self-breakdown voltages in the point-plane topology stressed with a slowly rising voltage (230 V/s) has been conducted. Short inter-electrode gaps of 0.25 mm, 1.5 mm, 2 mm and 3 mm have been used. This research also compares breakdown voltages data for positive and negative energisation.

Breakdown voltage as a function of electrode separation, *d*, and gas pressure, *p*, is often displayed in the form of a Paschen curve. A Paschen curve shows the breakdown voltage against the product of pressure and inter-electrode distance, *pd*. First proposed by Friedrich Paschen in 1889 [4] using a uniform field with varying distances and pressures breakdown voltages can all fitted around one non-linear curve which exhibits a minimum in the breakdown voltage. Paschen curves have become a common method for displaying breakdown data for different gases [5]. Two branches of the Pashen curve (on the left and right hand sides from this minimum) shows that the breakdown voltage increases for larger and smaller values of *pd*. The Paschen curve shows the specific gap/pressure configuration to achieve breakdown at the minimum voltage [4]. At atmospheric pressure, the breakdown strength of air is ~30 kV/cm.

There are limitations to the conventional Paschen curve. The original curve is relevant for uniform fields achieved in simple topologies such as plane-plane and Rogowski profiles. Therefore, care must be taken when comparing the conventional Paschen curve [4] with any breakdown data collected from experiments with non-uniform fields. Literature also shows that when investigating very small inter-electrode air-filled gaps (below ~10 μm) the Paschen curve is not accurate and experimentally obtained breakdown voltage decreases with the decrease in *pd* at atmospheric pressure [6].

This research investigates an air-filled point-plane topology at a range of pressures (0.5 bar gauge to 3.5 atm abs) at gaps 3 mm, 2 mm, 1.5 mm and 0.25 mm. It is shown that in breakdown of short gaps positive energisation can have a higher breakdown voltage than negative energisation breakdowns. It is also shown that breakdown voltage changes linearly with air pressure and can be plotted near the right hand side of the conventional Paschen curve for atmospheric air.

II. THE EXPERIMENT

This experiment required high voltage DC to energise a point-plane topology with a rate of 230 V/s until self-breakdown has occurred. The distance between the point electrode and the plane electrode is 3 mm, 2 mm, 1.5 mm and 0.25 mm and the pressure of the gaseous dielectric (bottled air) ranges from 0.5 atm (abs) to 3.5 atm (abs) in 0.5 atm increments. Bottled air was used for all experiments in this paper.

The experimental schematic can be seen in Figure 1 where a Glassman high voltage DC power supply (EH series, 0-60kV) energised the point electrode via a charging resistor (1MΩ). The voltage out of the HVDC power supply is controlled by a LabVIEW [7] program that interfaces with the power supply via a National Instruments DAQmax (SCB 68). The voltage across the switch is measured using a Tektronix HV probe (P6015A) and a Tektronix TDS 2024 oscilloscope (200 MHz, 2 GS/s). The breakdown voltage was measured as the highest value before the collapse of voltage.

The LabVIEW program is designed to increase the voltage across the switch with a stepwise increase of voltage ramping up from 0 V till breakdown occurs. A 0-10 V signal from the DAQmax proportionally outputs a 0-60 kV from the HVDC power supply. For this experiment the voltage is increased at a rate of 23 V every 10 ms with gives a smooth rise of 230 V/s. A feedback from the power supply allows the LabVIEW program to monitor the actual voltage outputted and when the voltage collapses the program identifies this as breakdown and stops the voltage increase.

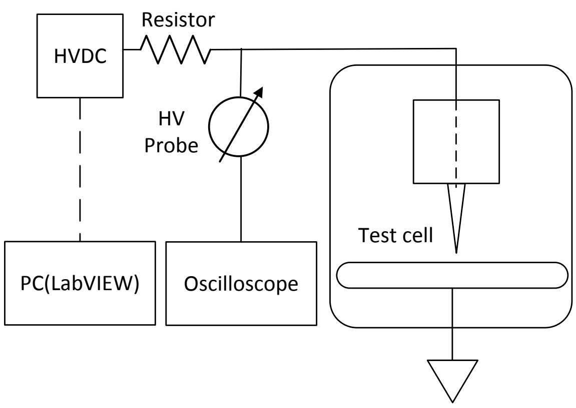

Figure 1. Experimental schematic.

The point-plane topology used in this experiment required a specifically designed test cell that could hold pressures up to 4 atm (abs) and set sub-mm inter-electrode gap spacing accurately. Therefore, a digital depth micrometer (RS, resolution 0.001 mm, accuracy ±0.003mm) was used to lower the electrode from a calibrated point. The control mechanism of the depth gauge sat outside the test cell and the end, to which the HV point electrode was attached, was inside a pressurised chamber. The point electrode was tungsten rod with a hemispherical point (radius = 0.8 mm) and the plane electrode was a piece of machined brass with a diameter of 40 mm.

III. RESULTS AND DISCUSSION

Displaying the results has been broken down into different methods. The breakdown voltage as a function of pressure is discussed with respect to the linearity and energisation polarity. The results are compared with the conventional Paschen curve for atmospheric air [8]. Each data point is an average of 30 measurements; all figures were plotted using Origin Pro 8.6 graphing software.

A. Breakdown voltage as a function of pressure

Figure 2, Figure 3, Figure 4 and Figure 5 show the breakdown voltage as function of dielectric gas (bottled air) pressure with gaps 3 mm, 2 mm and 1.5 mm and 0.25 mm respectively. Self-breakdown for 3 mm, 2 mm, 1.5 mm and 0.25 mm all show positive energisation mode to have higher breakdown voltage. This has also been identified in other publications [9] where there are regions where positive is higher than negative on Paschen curves in similar experimental conditions. In larger gaps (above few mm) filled with an electronegative gas it is known that the breakdown strength for non-uniform electric fields is higher for negative energisation due to the development of a volumetric negative space charge. However, in this experiment the breakdown strength of air in the case of positive enegisation is higher for almost every pressure and distance. Therefore it is expected that for larger gaps there will be a point at which the breakdown voltage curves for two energisation modes converge and cross over.

The breakdown voltage in the case of negative stress also has a much smaller standard deviation as compared with positive energisation. As mentioned above, each data point in the present work is an average of 30 measurements of breakdown voltage and from that the standard deviation has been calculated, the values of standard deviation for each breakdown voltage are shown in Figures 2-7 as vertical error bars.

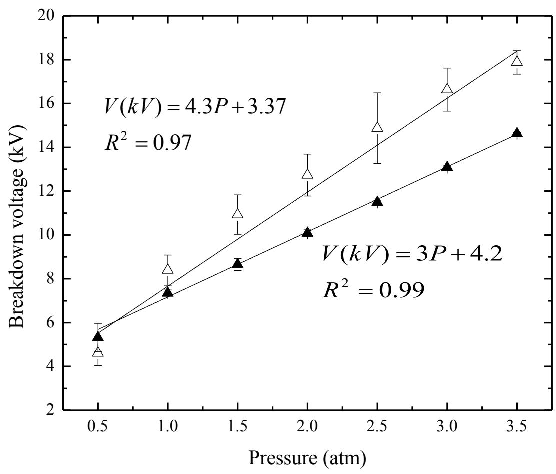

Figure 2. Breakdown voltage as a function of pressure for a 3 mm gap. Open symbols – positive, closed symbols – negative.

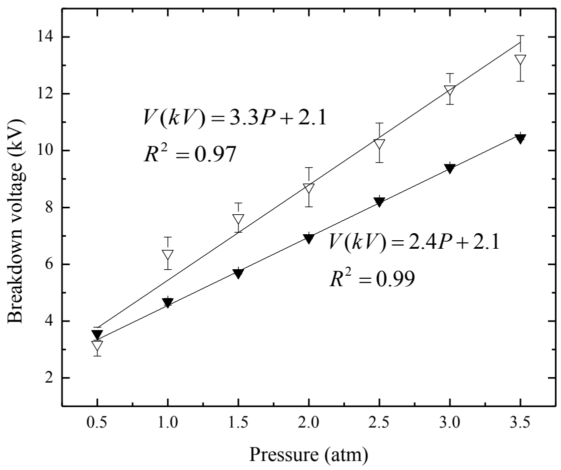

Figure 3. Breakdown voltage as a function of pressure for a 2 mm gap. Open symbols – positive, closed symbols – negative.

For negative energisation the standard deviation, σ, is quite consistent across all the pressures and distances with an average value of 0.1 kV (2.5%). This value is lower compared with an average standard deviation for positive energisation, 0.45 kV (6.1%). Standard deviation for positive energistion varies significantly between pressures and inter-electrode gaps. Therefore, it can be said that breakdown behaviour in the case of negative energisation is more predictable over a range of air pressures (0.5-3.5 atms): the breakdown voltage in the case of negative stress is much more consistent as compared with the positive energisation.

Paschen curve

Cumulative Figure 6 displays the breakdown data obtained in this study. The experimental points have been fitted with the analytical power fitting lines using Origin Pro 8.5 graphing software.

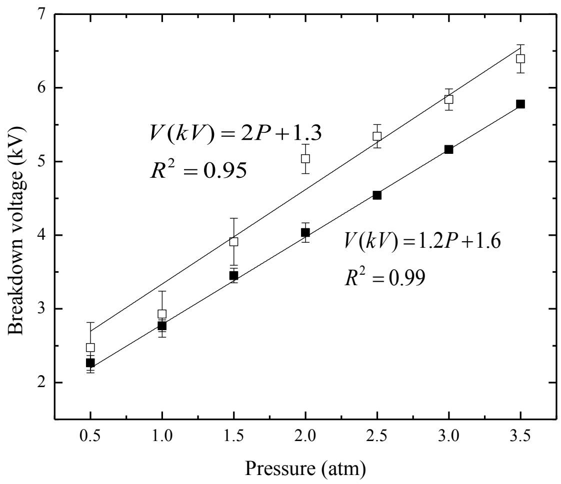

Figure 4. Breakdown voltage as a function of pressure for a 1.5 mm gap. Open symbols – positive, closed symbols – negative.

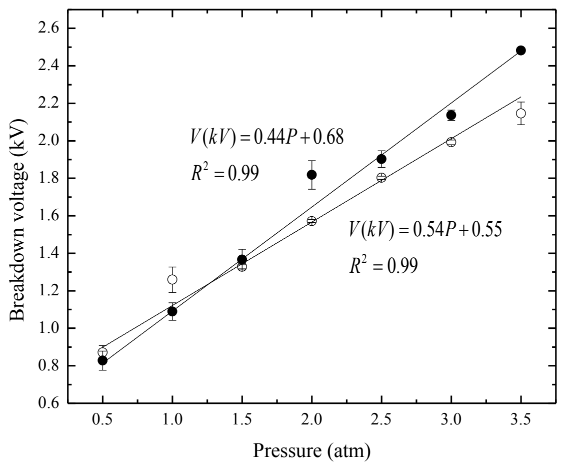

Figure 5. Breakdown voltage as a function of pressure for a 0.25 mm gap. Open symbols – positive, closed symbols – negative.

This graph shows breakdown voltage is proportional to $(pd)^n$, where n=0.8 for positive stress and n=0.77 for negative stress.

Figure 7 shows the comparison between the breakdown data obtained in the present study with the conventional Paschen data available from literature [8]. All of the results gathered in this experiment are positioned on the right hand side of the Paschen curve.

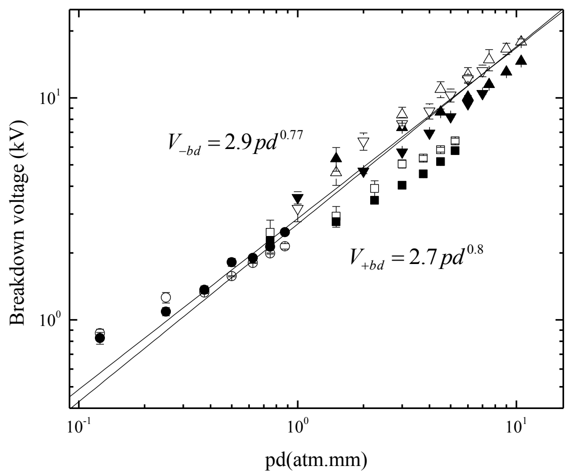

Figure 6. Experimental data plotted as a Paschen curve. up triangles – 3 mm gap, down triangles – 3 mm gap, squares – 1.5 mm gap, circles – 0.25 mm, open symbols – positive, closed symbols – negative.

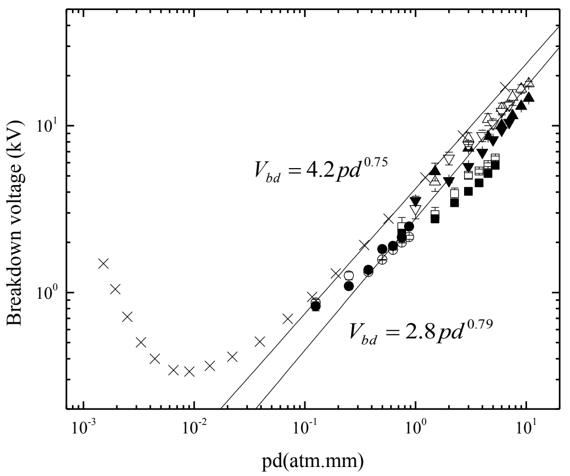

Figure 7. Experimental data plotted as a Paschen curve with a Paschen curve for uniform field from literature. up triangles – 3 mm gap, down triangles – 2 mm gap, squares – 1.5 mm gap, circles – 0.25 mm, open symbols – positive, closed symbols – negative. Crosses – Paschen from literature [8].

It can be seen that the experimental breakdown voltages obtained in the present work are located slightly below the conventional Paschen curve which potentially can be attributed to a highly non-uniform topology used in the present tests. However, the slope of the conventional Paschen curve is similar to the slope of the $V_{br}(pd)$ curves obtained in the present study.

IV. CONCLUSIONS

The self-breakdown voltages of bottled air in highly non-uniform electric field have been obtained for both, positive and negative energisation modes with varying electrode separations and gas pressures. It has been shown that for larger inter-electrode distances the difference between negative and positive breakdown voltages increases. For shorter distances the positive breakdown voltage can be higher than the negative breakdown voltage.

This paper has presented evidence that the negative energisation self-breakdown voltage is more stable than positive even in a *pd* region where the breakdown voltage is lower than the positive energisation. For positive energisation the self-breakdown standard deviation (average) is significantly higher at 6.1% of the breakdown voltage compared with 2.5% for negative energisation. It has also been shown that breakdown voltage increase with pressure almost linearly for the range of parameters used in the present paper. The breakdown voltage in the case of highly divergent electric field have been plotted as a Paschen curve and compared with a traditional V_{bd}(pd) data for uniform electric fields. It has been also shown that the breakdown voltage as a function of *pd* can be fit with a power fit with coefficients 0.8 and 0.77 for positive and negative energisation modes respectively.

ACKNOWLEDGEMENTS

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V. REFERENCES

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