INITIAL RESEARCH INTO QUANTIFYING THE EFFECT OF A SUSTAINED DC FIELD ON BREAKDOWN PHENOMENA USING HIGH-SPEED PHOTOGRAPHY

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Abstract: The importance of High Voltage Direct Current (HVDC) transmission lies in the fact that it is the only economically feasible option for power transmission over vast distances. As a result, the nature of HVDC transmission lines, and in particular the effect of the sustained field surrounding these lines, must be understood. In order to gain a better understanding of the effect of the sustained field surrounding these lines, the breakdown of air in a rod-plane gap was investigated under electrical stress of DC voltages of both polarities up to approximately 250 kV. Tests were done at an altitude of 1742 m in Johannesburg, South Africa. Results show that for negative DC voltages, breakdown of the gap required significantly higher voltages than that for positive polarity. This is suggested to be a result of the effect of the sustained field on space charge within the gap. High-speed photography (up to 775 000 frames per second) of breakdown with both polarities allowed analysis of visual evidence of the breakdown. The observed visible streamers differed considerably for both polarities, with the streamer propagating much further into the gap prior to breakdown under positive polarity and the formation of a second streamer branch.

1 INTRODUCTION

The number of proposed High Voltage Direct Current (HVDC) projects worldwide, as well as in Africa, is due to it being economical for transmitting power over long distances when compared to High Voltage Alternating Current (HVAC) power distribution [1]. Hydroelectric projects in particular lead to vast distances between the energy source (a dam) and consumer. For example, to import power from the Inga hydroelectric project would require close to 4000 km of transmission line, which is only realistically feasible by use of HVDC transmission lines [1]. With South Africa's national power utility, Eskom, investigating the importation of power from the Inga project, as well as importing additional power on the existing Cahora Basa line, an understanding of HVDC power transmission is vital.

While the field conditions surrounding HVAC lines have been extensively researched, this is not the case for HVDC lines. With HVDC lines, there are three types of configurations, namely monopolar, bipolar and homopolar. With these three types of configurations, the conductors can be at either positive or negative polarity, or with a conductor at each polarity as in the case of bipolar lines [2]. This results in HVDC lines with a sustained field at both polarities, leading to the constant presence of space charge which distorts the field, changing the critical values of breakdown for different geometries [3]. The polarity of the DC voltage also has an effect on the field distortion due to the behaviour of the space charge in a reversed field [3], leading to an increased number of factors which must be investigated in order to better understand HVDC transmission

In this paper, research is presented that aims at understanding the effect of a sustained field from HVDC on breakdown phenomena at both polarities. In particular the effect of this sustained field at high altitudes is investigated, with the research conducted at an altitude of 1742 m in Johannesburg, South Africa. The use of high-speed photography, with a maximum time resolution of approximately 1.29 μs is also employed in order to provide visual evidence of the breakdown under DC conditions.

2 METHODOLOGY

In order to aid the design of efficient and maintainable HVDC lines, it is important to understand the nature of air breakdown due to strong electric fields resulting from HVDC. Therefore, the research presented in this paper focuses on the analysis of fundamental breakdown principles when applied to a HVDC scenario. In particular, the research investigates the effect of a sustained field and the constant presence of space charge on air breakdown within a rod-plane gap. With the laboratory work having been done in Johannesburg, it also serves as an investigation into these breakdown phenomena at high altitude, with the laboratory at an altitude of approximately 1742 m.

The laboratory work involved looking at the breakdown voltage of a rod-plane gap as a function of the gap size, for both positive and negative DC voltages. In addition to these physical measurements, a high-speed camera was used to record visual evidence of the occurring breakdown phenomena.

3 EXPERIMENTAL SET-UP

A diagram of the experimental set-up is represented in Figure 1. An HVDC generator that is rated at 400 kV and 15 mA (however limited to 250 kV at the time of testing) was used to energise a rod-plane gap. An aluminium rod with a diameter of 16 mm and a rounded tip was used. The plane is approximated by a 1.2 x 2.1 m steel mesh. A labelled photograph of the test set-up in the laboratory is shown in Figure 2.

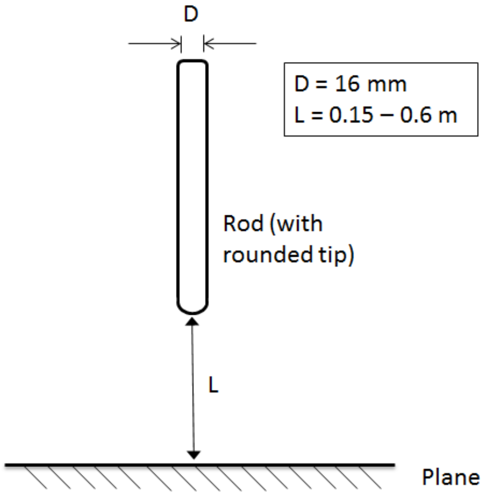

Figure 1: Diagram of the experimental set-up used for testing

Figure 2: Photograph of the test set-up at the HV Laboratory at the University of the Witwatersrand

4 TESTING CONDITIONS AND RESULTS

Tests have been conducted at the High Voltage Laboratory at the University of the Witwatersrand, Johannesburg. Atmospheric conditions during testing were recorded, and are presented in Table 1, along with the calculated relative air density. A correction factor is used to obtain a value of breakdown voltage at standard conditions, as defined by IEC standards [4], and is shown in Equation 1,

$$V = KV_0 \tag{1}$$

where V is the measured breakdown voltage, V_0 is the breakdown voltage in standard conditions and K is the correction factor, which is further defined in Equation 2,

$$K = k_1 k_2 \tag{2}$$

where k_1 is the air density correction factor and k_2 is the humidity correction factor [4]. For the purposes of this paper, k_1 is the equivalent of the relative air density while k_2 is ignored due to a lack of consensus on the effect of humidity on DC breakdown voltages and its application to the different polarities of DC voltage [5].

Table 1: Environmental conditions and correction factors measured during testing

Parameter	Value
Temperature (°C)	15
Pressure (mBar)	827
Relative humidity (%)	28
Relative air density	0.83

One of the main issues encountered during testing was establishing an accurate measurement of the breakdown voltage. The breakdown voltage was measured using the voltmeter on the control panel of the HVDC generator. The shortfall of this measurement is that there is no way to interface it with a ‘trigger and hold’ measurement. As a result, a suitable approach had to be taken so that there were very small increments on the output around the breakdown voltage of the gap, in order to ensure a more accurate measurement. The approach used for taking each measurement is outlined in Figure 3. The results from testing are presented in Figure 4, with the corrected values of breakdown voltage for both polarities plotted as a function of the gap size, alongside published data from Suzuki et al [6].

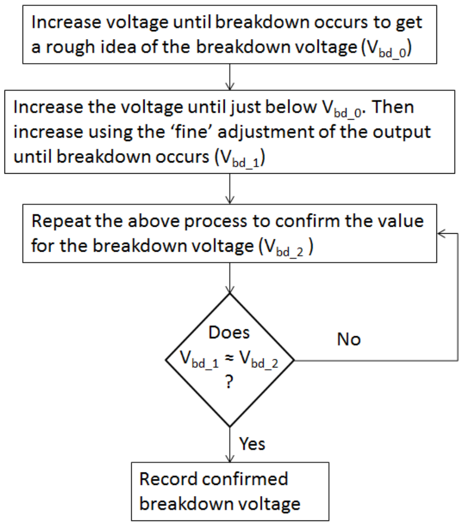

Figure 3: Process flow diagram for recording the breakdown voltage for each gap size

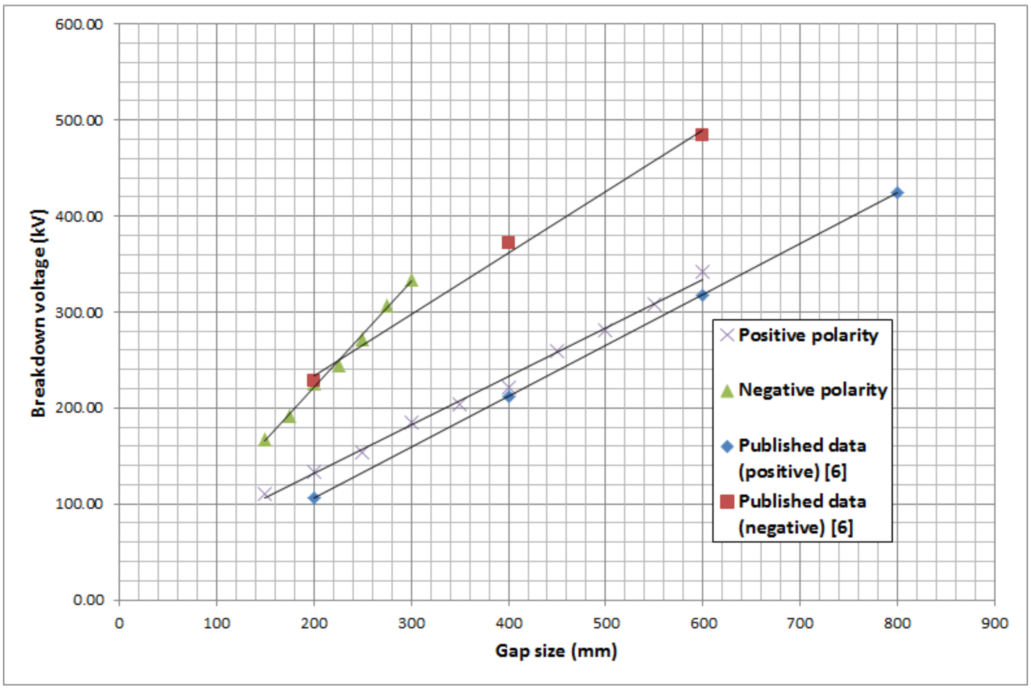

Figure 4: Breakdown voltage as a function of gap size for DC voltages of both polarities in a rod-plane gap, alongside data from [6]

5 HIGH SPEED PHOTOGRAPHY

High-speed photography was performed with a Photron SA5 high-speed camera [7] in order to obtain visual evidence of the breakdown of the gap under DC voltages at both polarities. To record breakdown under a positive DC voltage, a gap size of 350 mm was used with a frame rate of 525 000 frames per second. Five sequential, processed and colour-inverted photographs are presented in Figure 5, with breakdown of the gap shown in Figure 5(e). Breakdown under a negative voltage was recorded for a 250 mm gap size, with an increased frame rate of 775 000 frames per second. The processed and inverted photographs are presented in Figure 6, with three sequential frames of significant images obtained, with breakdown of the gap shown in Figure 6(c).

A time and distance scale is included in both Figures 4 and 5. The distance is along the rod-plane axis into the gap and is calculated from using the knowledge of the rod's diameter as a size reference. A graphical plot of visible streamer progression into the gap as a function of time for both negative and positive polarities is presented in Figure 6. Within Figure 6, the relevant frames in both Figures 4 and 5 are labelled on the graph. Note that the point at which Figure 5(d) occurs is not included in this graph due to progression of visible streamers being beyond the area of the frame. This may also be the case for the point at which Figure 5(c) occurs; however this point has still been included in the plot.

6 ANALYSIS OF RESULTS

Results are shown in Figure 3 alongside published data by Suzuki et al [6], which are from tests performed at sea level. From Figure 3, it is clear that breakdown of the gap occurs at much higher voltages for negative voltages as opposed to positive voltages with the same gap size. This is a trend that is consistent with the data from [5]. This can be explained by the influence of space charge within the gap.

With a non-uniform field, such as that in a rod-plane gap, breakdown occurs at much lower voltages, due to a localised high field region [8]. In the case of a rod-plane gap, this is close to the rod. With a positive DC voltage, the electrons formed during ionisation will move towards the rod, while the less-mobile positive ions remain within the gap. These ions distort the field, increasing the field at the tip of the space charge, and as the ions slowly move towards the earthed plane, the region in which ionisation can take place is extended further into the gap [3]. When a negative DC voltage is applied to the gap, the electrons from initial ionisation move towards the earthed plane, while positive ions remain close the negative rod. This leads to a highly enhanced field close to the rod, and a reduced field in the gap, resulting in a decreased region that ionisation can take place in. A result of this is that a higher voltage is required for breakdown of the gap [3].

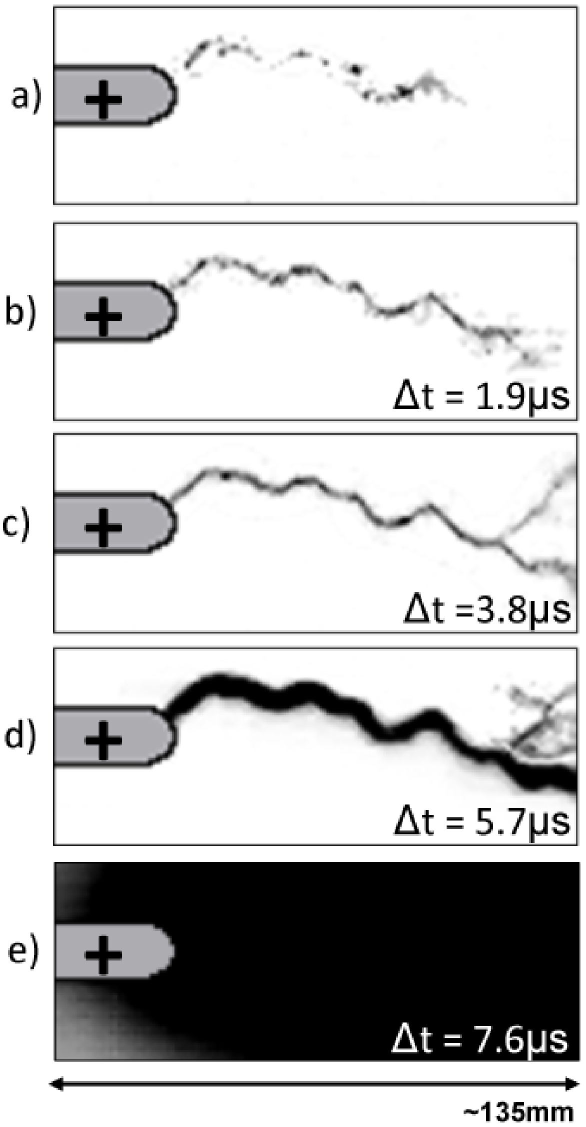

Figure 5: Processed and colour-inverted photographs of the breakdown of a 350 mm rod-plane gap under a positive DC voltage at 525 000 frames per second

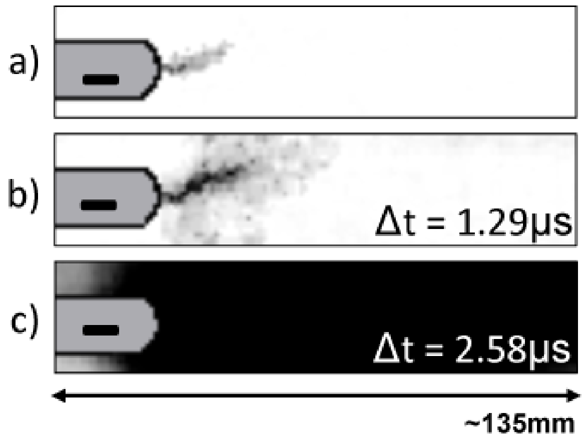

Figure 6: Processed and colour-inverted photographs of the breakdown of a 250 mm rod-plane gap under a negative DC voltage at 775 000 frames per second

From Figure 5, it can be seen that the visible streamer progresses much further into the gap prior to breakdown. Also, the formation of a second streamer branch approximately 80 mm into the gap, shown initially in Figure 5(b), and its development in Figures 5(c) and 5(d), suggests that there is additional ionisation further into the gap.

In Figure 6, it is clear that the visible streamer does not progress far from the region around the rod before breakdown of the gap occurs. Using Figure 7 to quantify the visible streamer progression in relation to time for both polarities, it becomes evident that the visible negative streamer does not propagate much further than approximately 22 mm from the rod before breakdown. This is in comparison to the progression of the positive streamer to approximately 103 mm, with a further 3.8 µs before breakdown. The inclusion of the extra frame of Figure 5(d) prior to breakdown suggests that the streamer propagates even further into the gap.

The reason for the difference in distance that each polarity's visible streamer propagates into the gap is not clear; however it is possible that it is due to the aforementioned difference in the size of the regions of ionisation due to the effect of space charge in the sustained field. If there is less ionised air in the gap due to the smaller ionisation region of a negative rod-plane gap, this could lead to less visible streamers in the gap prior to breakdown. With this observation, it should be reminded that as two different gap lengths were recorded, further experiments will have to be conducted with similar conditions in order to confirm that the differences are related to the polarity of the applied voltage to the gap.

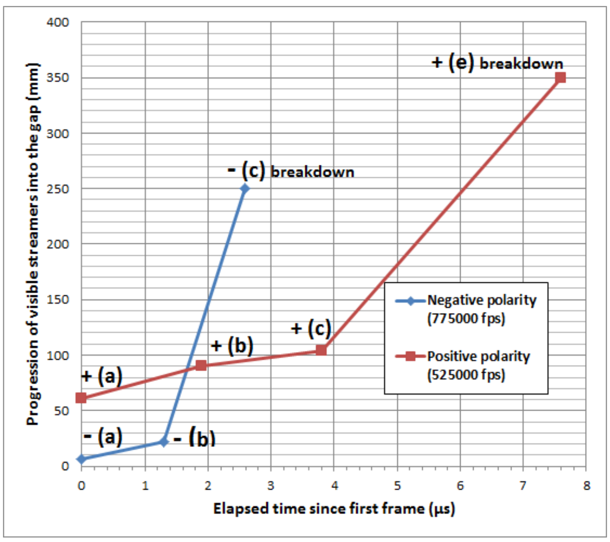

Figure 7: Visible streamer progression into the gap as a function of time for breakdown under both polarities

7 CONCLUSION

The breakdown of air in a rod-plane gap under DC voltages was investigated. Tests were conducted at 1742 m at the University of the Witwatersrand. The gap sizes ranged between 150 and 600 mm for positive DC voltages, and 150 and 300 mm for negative DC voltages. Results showed that a significantly higher voltage was required to breakdown the same gap size for a negative DC voltage relative to a positive DC voltage. This result is consistent with other published data from tests performed at sea level, which is also presented. The significant difference in breakdown voltage at either polarity was explained in terms of space charge, and the effect the sustained DC field has on the space charge in the gap. Visual evidence of the breakdown of the rod-plane under both polarities was obtained using high-speed photography, with a time resolution of 1.9 μs and 1.29 μs obtained for positive and negative polarity respectively. From these photographs, a difference in the distance of propagation of a visible streamer into the gap prior to breakdown was observed for both DC voltage polarities. The visible positive streamer progressed much further into the gap than the visible negative streamer. A second streamer was also shown to form within the gap under a positive voltage.

8 ACKNOWLEDGMENTS

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