PRELIMINARY RESULTS OF AN INVESTIGATION INTO THE EFFECTS OF FLOATING OBJECTS ON THE ELECTRICAL BREAKDOWN OF AIR UNDER HIGH VOLTAGE DIRECT CURRENT STRESS

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Abstract: The South African Power Utility, Eskom, has indicated its intent to possibly construct new High Voltage Direct Current (HVDC) schemes. An aspect that must be considered during the feasibility study for such projects is the live line maintenance of the transmission lines. The air breakdown mechanism under HVDC conditions when considering live work and tower geometries, must be properly understood before live work may be performed. Experimentation using floating objects is often used to study the effects relating to live work in high voltage applications. This paper presents the results of HVDC air breakdown tests using a 300 mm diameter floating metallic sphere with a 30 mm protrusion, in a point-to-plane configuration with a total gap length ranging between 0.75 m and 1.4 m. Both positive and negative polarity cases were tested. The results indicated that the position of the floating sphere does not significantly affect the flashover voltage magnitude. There is, however, a definite reduction in the strength of the air gap, between 27% and 29%, for the cases tested. Further, the static charge on the floating object did not influence the breakdown voltage. There is also linearity in flashover voltages of simple point-to-plane air gaps.

1 INTRODUCTION

Eskom currently operates and maintains the South African section of the Cahora Bassa High Voltage Direct Current (HVDC) scheme. The nominal operating voltage of the scheme is ±533 kV. Further, there are plans to possibly implement additional ±600 kV or ±800 kV HVDC schemes within the country.

There is a high availability requirement for the Cahora Bassa scheme and this may be required for the new DC schemes as well. Currently, live work is not being performed at full system voltage. Long downtime durations for maintenance cannot be sustained and live work is becoming more critical. Further, proactive live maintenance tends to reduce potential outages.

It is generally accepted that there are some differences in the air breakdown mechanism under HVDC conditions to that of High Voltage Alternating Current (HVAC) [6,8], in particular the influence of space charge and the manner in which streamer development is initiated. These issues must be carefully considered before live work can be performed safely on the DC lines. These issues include the impact of space charge in the vicinity of the live worker, the air breakdown mechanism for the different polarity transmission lines, electrical behavior of a floating object in the air gap, correct minimum approach distance (MAD) factors and the risk of flashover (ROF) under HVDC and EHVDC conditions.

This paper focuses on the aspects pertaining to the behaviour of metallic floating objects under HVDC conditions. Floating metallic spheres are often used in experimentation to understand the behaviour of air gaps under high voltage applications.

2 HYPOTHESIS

Floating objects (whether metallic or not) that are positioned within a DC electric field will affect the average field distribution. The perturbation of the electric field may affect the characteristics of the electrically stressed air gap. If the floating object represents a live worker's approach to the HVDC transmission line/conductor bundle or to any of the hardware attachments on the line, its presence is likely to intensify the electric field and increase the risk of flashover.

It is reported that under switching impulse conditions there is a marked decrease in the flashover voltage when the floating object is positioned towards the centre of the air gap [5]. Under DC conditions the electrical charging of the floating object and space charge effects may result in a different trend.

This paper thus investigates the influence of a metallic floating object on DC breakdown voltage in a point-to-plane configuration.

The picture below shows an example of a live line worker being lowered onto the Cahora Bassa transmission line by a helicopter and is an example of a practical situation where the HV lines could be affected by floating objects.

Figure 1: Live worker being lowered onto the conductor

3 EXPERIMENTAL SETUP

The test setup involved placing a 300 mm diameter metallic sphere, with a 30 mm protrusion facing the earth plane, in different positions within a point-to-plane air gap ranging from 0.75 m to 1.4 m.

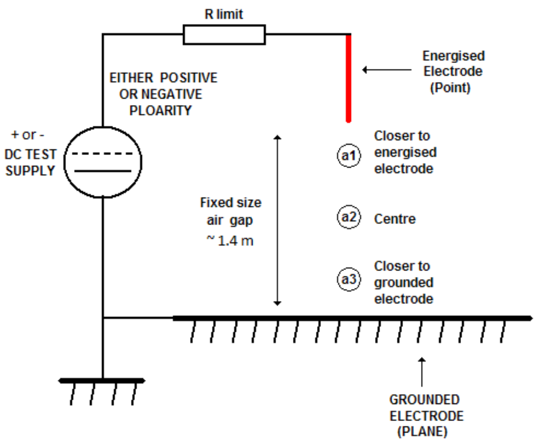


Figure 2: Schematic diagram of the test setup

The sphere was positioned in various places within the gap (as indicated from a1 to a3 in Figure 2). A 30 mm protrusion was implemented on the bottom of the sphere in to replicate practical situations where it is difficult to maintain smooth surfaces. The presence of the protrusion results in a lower breakdown and may suppress the accumulation of free charge on the sphere [5].

The power supply consisted of a ±500 kV DC (15mA), half wave rectified source. The rectifier was supplied by a 400 kV AC transformer. The diode stack was protected by a current limiting water resistor. Ripple voltage smoothing was provided by existing coupling and measuring capacitors that are used for AC corona cage research.

The metallic sphere was suspended between two 2 m substation post insulators, with nylon string. A grounded wire mesh was placed below the sphere. A copper pipe was used to create the point as shown in Figure 4. The tests were conducted outdoors.

3.1 Test circuit

The electrical representation of the test circuit used was as follows:

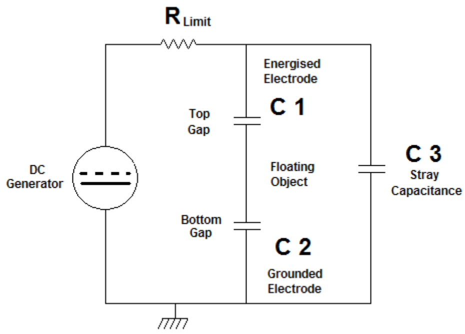


Figure 3: Schematic representation of the test circuit

Figure 4 is a picture of the experimental setup.

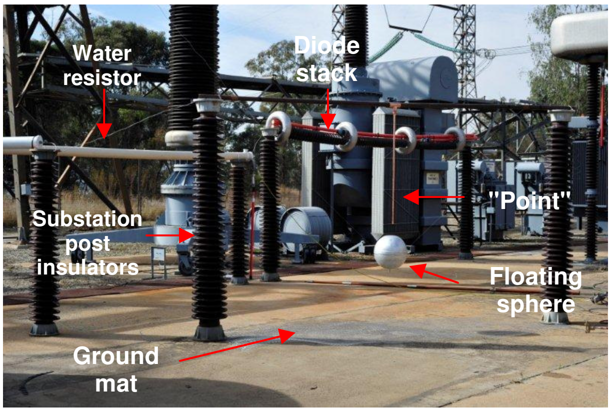


Figure 4: Photograph of the test setup

The test were conducted in accordance with the IEC60060-1 standard [1], and corrected per accepted industry practices for Standard Temperature and Pressure (STP) as well as for humidity.

3.2 Test methodology

Firstly, the flashover voltage of a point-to-plane air gap (without the sphere) was determined for reference purposes. The total gap size was determined by the maximum voltage that could be practically flashed over using the 500 kV source. Once the total gap size was set, positive DC voltage was applied to the 'point' and the voltage was slowly raised until a flashover occurred. The flashover tests were repeated between three and seven times at each position in to determine the repeatability. A time delay of one minute was allocated between each test.

Secondly, the sphere was inserted into the air gap, close to the point source, and the flashover tests were repeated. The position of the sphere was then systematically adjusted until it approached the ground plane. After a series of tests, the total gap size was reduced and the procedure was repeated.

On completion of the positive polarity tests, negative voltage was applied to the point source and the procedure was repeated.

4 TEST RESULTS

4.1 Flashover voltage of a point-to-plane air gap

The following results are corrected for STP as per [1]:

Table 1: Results for positive polarity

POSITIVE POLARITY	AVERAGE FLASHOVER VOLTAGE (kV)	MINIMUM FLASHOVER VOLTAGE (kV)
1.00 m air gap	484	476
1.25 m air gap	640	635

It was not possible to flashover the 1.4 m air gap using the 500 kV test power supply.

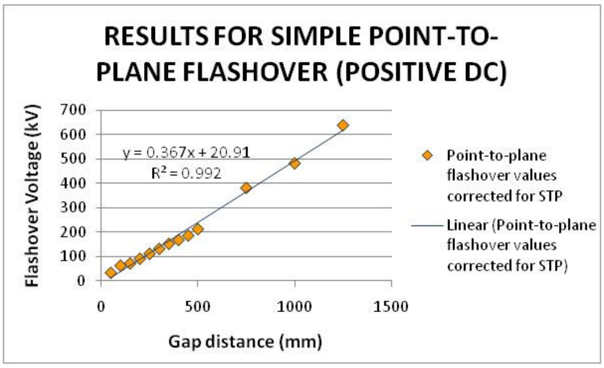


Figure 5: Graph showing linearity for positive polarity DC flashovers

When plotted together with data from previous gap testing conducted by the authors [3], a linear trend was observed for the range of point-to-plane gaps tested.

Negative polarity DC generally requires a higher voltage level to flashover the same size air gap than positive DC [2,3,4]. The power supply only allowed for the safe testing of a 0.42 m air gap.

Table 2: Results for negative polarity

NEGATIVE POLARITY	AVERAGE FLASHOVER VOLTAGE (kV)	MINIMUM FLASHOVER VOLTAGE (kV)
0.42 m air gap	408	382

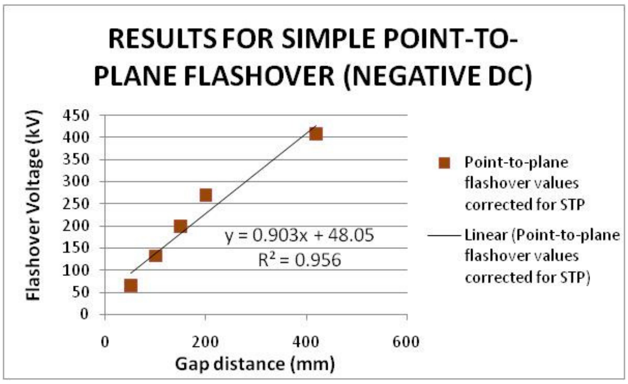


Figure 6: Graph showing linearity of negative polarity DC flashovers

When plotted together with data from previous gap testing conducted by the authors [3], a fairly linear trend was observed for the range of point-to-plane gaps tested.

4.2 Flashover voltage of a floating metallic sphere

The following results were obtained:

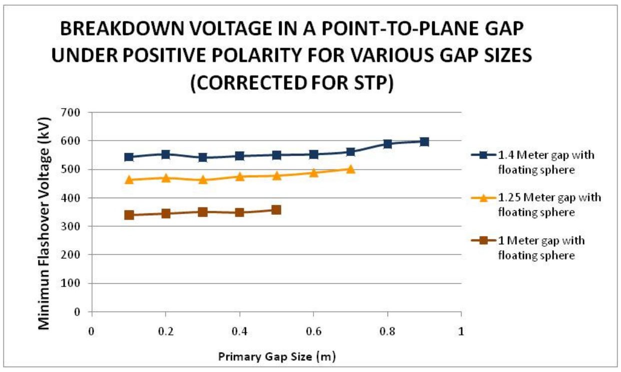


Figure 7: Graph showing results for positive polarity floating object tests

The flashover voltage was constant for the positive polarity case. For the smaller total gap size the position of the sphere did not impact the flashover voltage. It was observed that the flashover voltage had a tendency to increase as the primary gap became larger.

Only two test positions were possible for the negative polarity case. This was due to the limitations of the power supply and the size of the total gap.

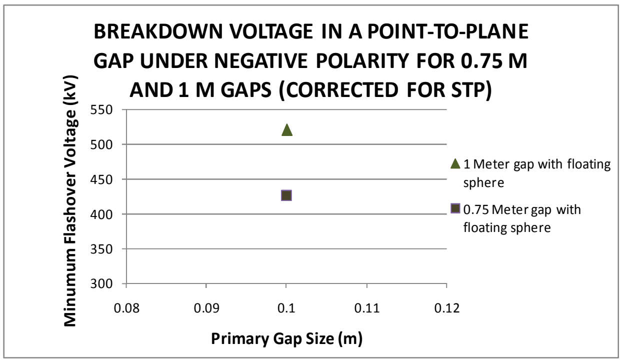


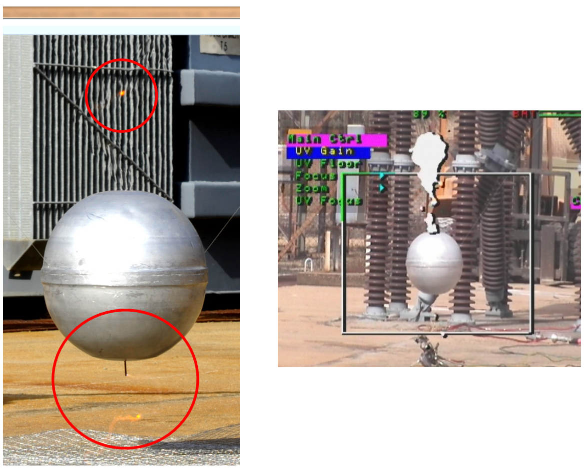
Figure 8: Graph showing results for negative polarity floating object tests

4.3 Reduction in air gap strength

The presence of a sphere in the air gap results in a definite reduction of the air gap insulation strength. For the positive case, in a 1 m gap, the gap strength is reduced by 109 kV, indicating a 29% decrease. For the 1.25 m gap, the flashover voltage is reduced by 133 kV, a 27 % decrease. No results were obtained for the negative case.

4.4 Observations during the tests

For the larger gaps, the emitted electromagnetic energy was visible in the primary and secondary gaps. For certain tests, visible and ultraviolet (UV) discharges were observed in the gap without the presence of a clear arc.



(a) (b)

Figure 9: (a) Visible electrical discharges in the secondary gap **(b)** UV discharges in the gap - No evidence of a complete flashover of the primary gap.

UV images taken using a CSIR CoroCam® (Figure 9 b) indicate discharge behaviour before the complete flashover occurred. Visually, the electromagnetic energy caused refraction of the light in the gaps resulting in wavy images being recorded. This is evident in the distorted image of the transformer cooling fins in Figure 9 a.

In many cases, the arc did not follow a straight or direct path between the electrodes. Figure 10 shows the elaborate arc path within the gaps.

(a) (b)

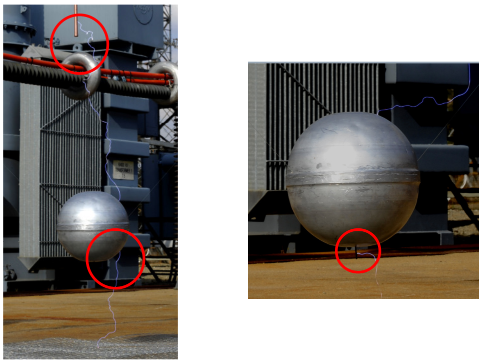
Figure 10: (a) Arc path in presence of floating object **(b)** Arc path in a simple point-to-plane gap

In two cases it was observed that the arc ignored the floating object and terminated directly on the ground mat. The sphere was positioned in the centre of the gap. This was not expected as the total gap size was 1.4 m and would have required a significantly higher voltage than that recorded for these tests.

Figure 11: Arc missing the sphere to the right

In certain cases it was observed that the arc did not originate from the tips of the electrodes, but rather along its length. In the case of the sphere, the arc was observed to originate from the sides and not necessarily from the protrusion itself.

The current limit of the power supply was 15 mA. For practical HVDC lines the fault current is in the order of kilo-amperes. The energy discharge during these tests were considerably lower than what would be achieved on actual transmission lines and as such the arcs observed were considerably less intense (visually and audibly). Initial tests included grounding the sphere after each flashover event to remove the trapped charge. Grounding between tests were compared to the case where the sphere was not grounded. It was noted that the sphere grounding process did not have an impact on the breakdown voltage and all further tests were done without discharging the sphere.



(a) (b)

Figure 12: (a) Arc originating on the sides of the rod and sphere **(b)** Arc originating on side of protrusion

Figure 13 indicates tortuous arc behaviour at the positive electrode. The picture was taken with a digital camera having a shutter speed of 0.12 ms. The image is therefore a sudo-steady state representation of the path taken by the electrons during the discharge.

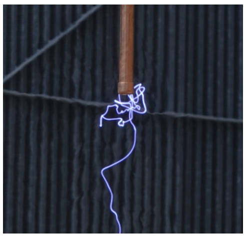


Figure 13: Tortuous arc behaviour close to the energised rod (positive polarity)

Figure 14 shows a discharge at the bottom of the sphere and intense electromagnetic energy in the primary gap, even though there is no visible arc in the primary gap.

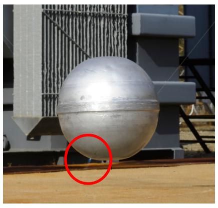


Figure 14: Electrical discharge activity on the side of the sphere

5 DISCUSSION

The maximum voltage of the test supply was 500 kV. This limited the maximum size of air gap that could be achieved. For positive polarity the maximum size of the air gap that could be safely flashed-over was 1.25 m. For the negative case, the largest gap was 0.75 m. For the same size of air gap, negative polarity requires a higher breakdown voltage than positive polarity. This was evident as illustrated in Figures 5, 6 and [2,3,6,7]. The power supply was unable to supply a high enough voltage to breakdown a larger gap. The test was stopped in order to protect the supply diodes from excessive current.

The voltage limitation did not allow for the replication of practical line and tower geometry gap sizes. Due to the scaling of the gap and floating object sizes, the tests therefore cannot be directly related to live working conditions.

Air breakdown is always initiated by streamer activity [7,8], however, for streamers to bridge the gap, the arc path taken is generally the shortest path between the electrodes (i.e. a straight line). The erratic arc path as observed during these tests may be an indication of a leader breakdown mechanism. Due to the tests having been conducted outdoors, wind could have contributed to the erratic arc direction by blowing out the plasma channel and or movement of space charges. Figure 10 shows arcs that occurred in opposite directions, however, there was no significant change in the direction of the wind during the tests.

Previous research using floating spheres under switching impulse conditions [5] indicated a distinct decrease in breakdown voltage for the sphere in the quartile of the gap closest to the high voltage electrode. The gaps tested in [5] were larger than that tested during this work and the voltage magnitudes were significantly higher. Further, switching impulses occur much quicker than constant DC and the mechanism of the air breakdown may be different.

The tests showed a generally constant flashover voltage irrespective of the position of the floating object. Using the characteristic linear equation shown in Figure 5, it was calculated that the breakdown voltage of the gap with the floating object was approximately the same as a smaller gap without the sphere (i.e. the total gap size less the diameter of the sphere and protrusion).

The ratio of the gap size to the sphere diameter may not directly represent a live worker in practical situations. The size of the sphere may therefore impact the breakdown voltage. A smaller sphere in the same gap or a large gap size may result in a different trend.

The negative polarity flashover voltage was more erratic and a higher standard deviation in the flashover voltages was recorded; 22 kV when compared to an average of 2 kV for the positive case.

6 CONCLUSIONS

The following conclusions are noted:

- There is a linear trend in flashover voltage for the rod-to-plane configuration for the ranges tested,
- The presence of the metallic floating sphere results in a 27-29% reduction in the strength of the air gap for the positive polarity case,
- The position of the sphere does not significantly affect the breakdown voltage value for this particular test configuration,
- The air gap can be stressed to an extent where there are electrical discharges within the primary and secondary gaps, without a complete flashover occurring,
- The charge on the floating object is important in determining the flashover of the primary air gap. Observations in certain cases revealed that the arc bypassed the sphere and terminated on the ground plane.
- Corona activity on the tips of the rod and the protrusion may result in a decrease of the local electric field strength. The arc then originated elsewhere on the rod or protrusion, a short distance away from the tip, where the local field was higher than at the tip,
- From these limited experiments, it appears that the behaviour of the breakdown of air gaps under sustained HVDC stress is different to that of switching impulses.

7 RECOMMENDATIONS

This research is the initial part of a greater study into the investigation of electrical breakdown of air under HVDC conditions. Although the exact dimensions of practical line and tower gaps could not be achieved due to limitations with the power supply, further work will be required with regard to gaining a better understanding of the test results obtained and their applicability to a representative live working condition.

Analysis of models of the breakdown of air that take into account space charge interaction as well as the static charge of the floating object must be compared to the empirical data obtained during experimentation. Further research could include utilisation of a high speed video camera to understand the development of streamer and leader activity at the two electrodes, to repeat the tests for larger gap sizes, to consider different gap factors, and to investigate the effect of higher current discharges on the breakdown voltage.

8 ACKNOWLEDGMENTS

The authors would like to acknowledge Mr C. Esterhuizen for the digital video and photography and assistance with the test setup, and Mr A.C. Britten for his guidance in this project. The authors would also like to thank Eskom for the support of this work and the High Voltage Engineering Research Group at the University of Witwatersrand, Johannesburg through the TESP programme. They would also like to thank CBI-electric, the department of Trade and Industry (DTI-THRIP) as well as to the National Research Foundation (NRF) for direct funding of the High Voltage Engineering Research Group at the University of Witwatersrand, Johannesburg.

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