GLASS CAP-AND-PIN INSULATOR STRINGS UNDER HVDC CONDITIONS: PRELIMINARY RESULTS OF INVESTIGATIONS INTO THE INFLUENCE OF SHATTERED DISCS ON INSULATION STRENGTH

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Abstract: Presently, limited reduced voltage live working is being done on the Apollo Cahora Bassa High Voltage Direct Current (HVDC) scheme. Due to a high availability requirement of the scheme, Eskom is investigating the possibility of undertaking live line maintenance at the full ±533 kV nominal operating voltage. The physical condition of the glass insulators and their insulation strength have been identified as key issues which need to be understood before live line work can be safely performed. Line inspections have revealed that some glass insulator strings have randomly positioned shattered discs within the string. Investigations have thus been conducted to quantify the relationships between the flashover voltage and the number and relative position of shattered discs in the string. The tests were conducted for Eskom at the EPRI High Voltage Laboratory, Lenox, USA. A single broken glass disc was systematically placed in pre-determined positions within the string of 13 discs and the flashover voltage for each position was recorded. The procedure was repeated with two sequential broken discs, under positive polarity. High speed video and corona photography images were captured during the tests. The results indicate that when broken discs are present, there is a definite reduction in insulation strength.

1 INTRODUCTION

The Apollo Cahora-Bassa High Voltage Direct Current (HVDC) scheme is a critical asset in the Eskom Transmission & Generation power system. The hydro-electric scheme operates between two countries. The converter station is located at Songo in the Republic of Mozambique, and the inverter station at Apollo, is located in the Republic of South Africa. Hydro-electrica de Cahora-Bassa (HCB) operates and maintains the Mozambique section (approximately 900 km) and Eskom maintains the South African section (approximately 520 km).

The nominal system voltage of the scheme is $\pm$ 533 kV. The South African sections operate at an altitude up to 1592 m above sea level). The lines are insulated with both HVDC glass (cap and pin) and composite insulators.

Glass insulators are prone to vandalism and line inspections have shown that some glass strings have randomly positioned shattered discs. It is assumed that this condition may affect the total insulation strength of the string.

It is proposed that live line maintenance work be conducted to repair or replace these discs or strings. At present, live work is not being conducted at full system voltage and is limited to minor maintenance work. The system voltage is reduced to 75% of rated voltage (400 kV) because of uncertainties of insulation and air gap integrity and to maintain the recommended safety clearances [1]. The effect of shattered glass discs on the total insulation strength is unknown and there are other concerns relating to the safety clearances.

This research forms part of a program to evaluate the technical feasibility of conducting this type of maintenance. Only positive polarity was tested as this was determined as having a lower breakdown voltage than the same negative voltage case [3,4]. Figure 1, below, show an example of the shattered glass discs on the Cahora Bassa transmission line.

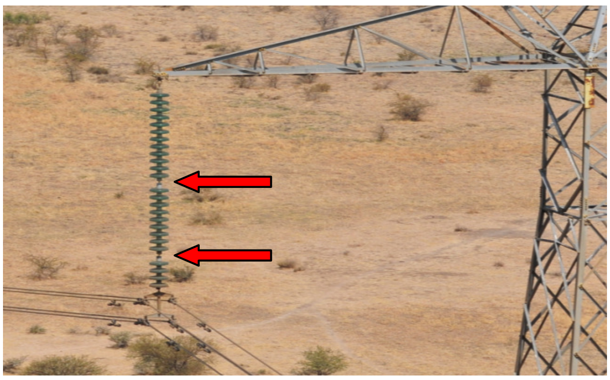


Figure 1: Photograph of shattered discs (indicated by red arrows)

2 EXPERIMENTAL SETUP

In order to conduct the experiment, a mock tower that closely resembled the Cahora Bassa tower top dimensions was constructed, shown in Figure 2.

The tests were conducted in the Ultra High Voltage (UHV) building at the EPRI HV Laboratory, Lenox. The power supply was limited to ±1100 kV direct current (DC). An iron beam measuring 12.2 m was suspended in the center of the building by two insulated winches. The tower configuration was replicated on the beam.

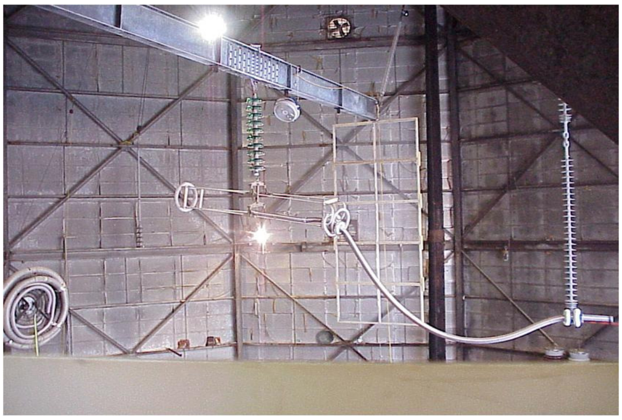


Figure 2: Photograph of the test setup.

All tests were conducted in accordance with the IEC60060-1 standard [2], and corrected as per accepted industry practices for Standard Temperature and Pressure (STP) as well as for humidity.

2.1 Test methodology

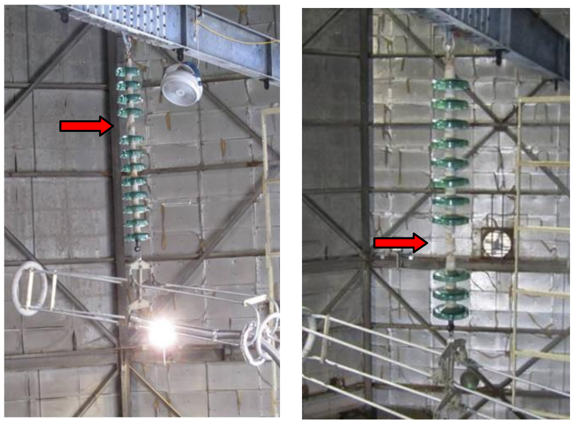
The tests were divided into full string breakdown tests (for the reference case) and thereafter shattered disc tests.

DC voltage was applied to the test string and stepped up in one minute intervals. This procedure was followed until a flashover occurred. After flashover, the room was vented and the charge on the test object was drained. The time interval between each test was 30 minutes.

Full string breakdown tests: The aim of this set of tests was to determine the breakdown strength of a full string insulator consisting of a various number of discs. The tests were done with an increasing number of insulator discs until it was no longer possible to obtain a flashover with the 1100 kV DC supply. The tests were done in order to determine whether there is linearity between the number of discs in the string and the flashover measured voltage.

Shattered disc tests: The aim of these tests was to determine the effect of shattered discs on the insulation strength of the insulators. The number of shattered discs, as well as the position of these discs in the insulator string were varied. The total number of insulators used in this string was determined by the maximum number of discs that was flashed over in the full string breakdown tests. The test program involved eight separate tests, namely:

- Test 1: 13 disc string with 1 broken disc at live end,
- Test 2: 13 disc string with 1 broken disc 1/3 up string,
- Test 3: 13 disc string with 1 broken disc 2/3 up string,
- Test 4: 13 disc string with 1 broken disc at dead end,
- Test 5: 13 disc string with 2 broken discs at dead end,
- Test 6: 13 disc string with 2 broken discs 2/3 up string,
- Test 7: 13 disc string with 2 broken discs 1/3 up string,
- Test 8: 13 disc string with 2 broken discs at live end.



(a) (b)

Figure 3(a): Photograph of test setup showing a broken disc located 2/3 up the string **(b)** two shattered discs 1/3 up the string.

2.2 Tower geometry

In order to properly simulate the tower and conductor configuration as used on the Cahora Bassa line, an earth plane was constructed and mounted approximately 6 m away from the insulator string to be tested, as shown in Figure 2. The earth plane was made of expanded wire mesh within a wooden frame. The dimensions of the frame were 6 m long by 2.5 m wide. In order to simulate the conductor bundle used on the DC line, a four bundle conductor arrangement made of metallic tubing of a similar diameter as the actual conductors on line were used.

The actual tower geometry is shown in Figure 4.

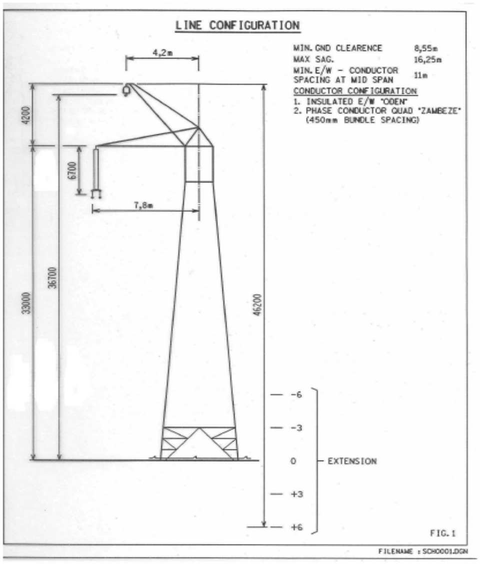


Figure 4: Actual tower dimensions

2.3 HVDC anti-fog glass discs

The glass disc used in the string was the Sediver F16 DC disc. The test samples were discs that had been removed from service from the Cahora Bassa transmission line. Corona rings are not currently used on the glass insulators.

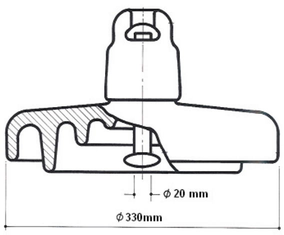


Figure 5: Drawing of the glass discs used in the Cahora Bassa string

2.4 Effect of temperature

The tests were done under controlled temperatures and therefore done indoors. This allowed for the test temperature to be controlled by heating the building. This was required in order to obtain results that would be comparable to South African weather conditions.

3 RESULTS

3.1 Full string insulator tests

Three tests were conducted on full strings of 6, 10 and 13 discs. The tests indicate that for the cases tested, there is a linear relationship between the total flashover voltages of the full strings and the number of discs in the string.

It is observed that the DC voltage required to flashover a string of 13 discs is 1216 kV. The flashover voltage results have been corrected for STP.

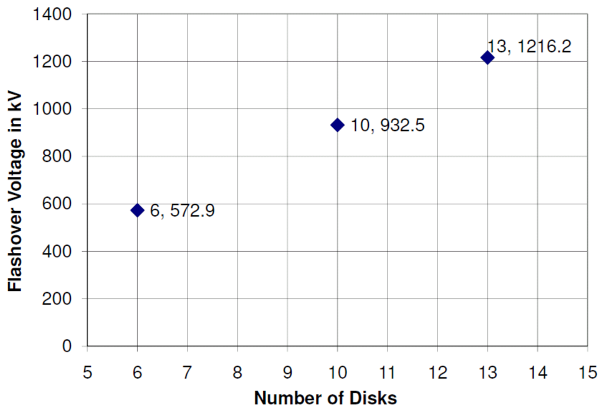


Figure 6: Graph indicating the linearity of the 6, 10 & 13 disc flashover tests

3.2 Shattered discs

Eight tests were done using 1 and 2 sequential shattered discs placed at pre-determined locations on a string of 13 discs. The graph below shows the results that were obtained.

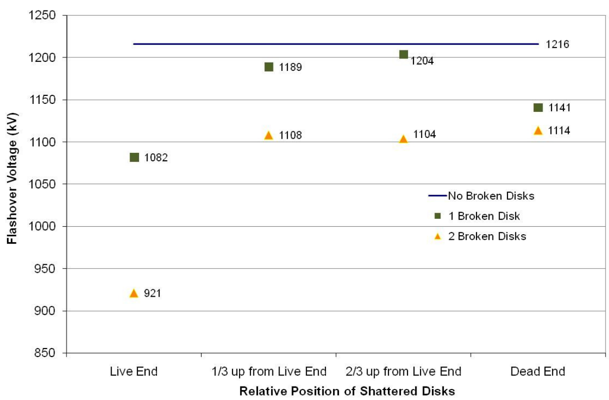
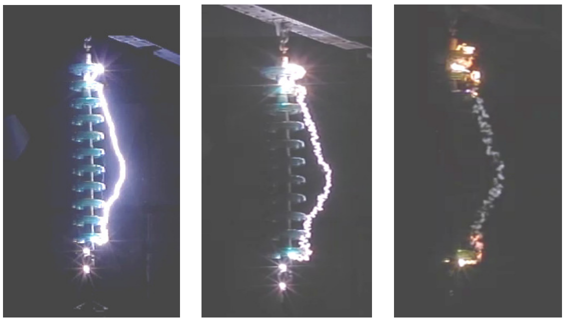


Figure 7: Results of the breakdown voltage in the presence of shattered glass discs placed at different positions in the string.

Table 1: Results indicating the flashover voltage and percentage reduction in insulation strength.

	FLASHOVER VOLTAGE (kV)	REDUCTION IN INSULATION STRENGTH (%)
	Live End Test	
1 broken disc	1082	11
2 broken discs	921	24
	1/3Test	
1 broken disc	27	2
2 broken discs	108	8
	2/3 Test	
1 broken disc	12	1
2 broken discs	112	9
	Dead End Test	
1 broken disc	75	6
2 broken discs	102	8

It is observed that shattered discs results in a definite decrease in insulation strength. The worst effect is seen for the case where the shattered discs are located at the live end of the string. The images below are recorded by a high speed digital camera. It is noted that there is a spark-over across the dead end disc prior to the breakdown of the full air gap.



(a) (b) (c)

Figure 8: Flashover event sequence - 2 broken discs at live end

It was observed that the flash occurs between the partial flashed over dead end disc and the first healthy disc at the live-end. High levels of corona emission were observed on the metal fittings of the two shattered discs.

Figure 9 shows a single broken disc located one third up the string

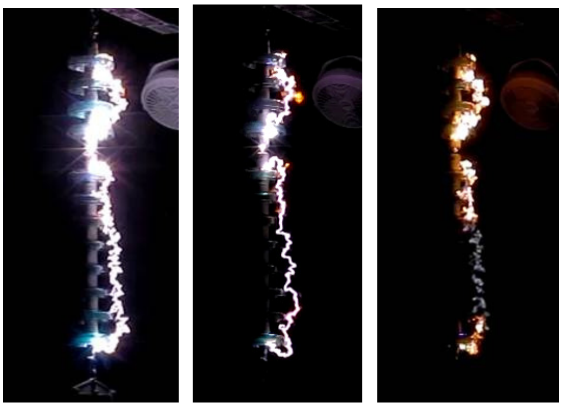


Figure 9: Sequence showing flashover when one single shattered disc is located one third up the string

It was observed that the flashover terminated on the shattered disc and did not bridge the entire air gap. Several discharge pulses were observed during one flashover event.

Figure 10 shows the resultant flashover for two broken discs located at the dead-end. It was observed that the arc was not continuous. It terminated before the fifth and tenth disc respectively.

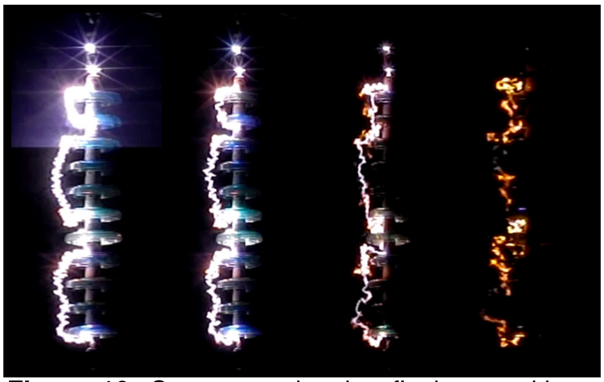


Figure 10: Sequence showing flashover with two broken discs at the dead-end

A thermal camera was used to investigate the infrared band during the tests.

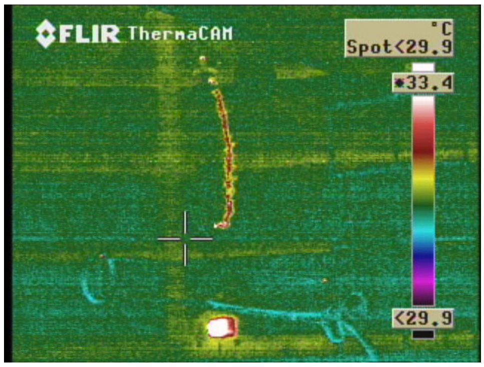


Figure 11: Infrared camera image (one broken disc at the dead-end)

Hot spots on the cap and pin of the damaged insulator were observed during the test. No noticeable heating was noted prior to the breakdown.

Excessive corona were observed on certain discs for the shattered disc cases.

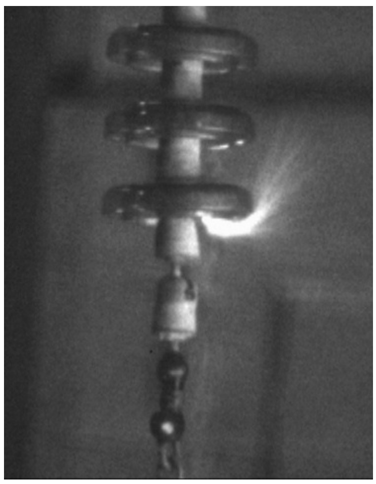


Figure 12: Corona emanating from first healthy live end disc (2 broken discs at live end)

4 DISCUSSION

Due to the limitations of the power supply, a string of only 13 discs could be tested. The South African section of the Cahora Bassa transmission line has typically 28 discs insulators in the string. The different strings tested shows that there is fair linearity in flashover results (in the region tested). Assuming that the linearity holds true for the 28 disc case, the flashover voltage of a full (healthy) string will be approximately 2623 kV.

It is unclear if the linearity for full string flashover will hold true for larger strings. A significantly higher voltage will be required to test this further.

All the tests conducted were at significantly higher stress levels than what would normally occur on an actual transmission line, therefore the corona and space charge activity is expected to be much higher than normal. As the effects of space charge and excessive corona are not properly understood as present, the conclusions from these tests should be interpreted while keeping in mind that some or all results have been affected by corona and/or space charge activity.

For some tests, partial flashover of some discs was observed prior to complete flashover of the entire string. This may be attributed to non-uniform voltage distribution across the string [5].

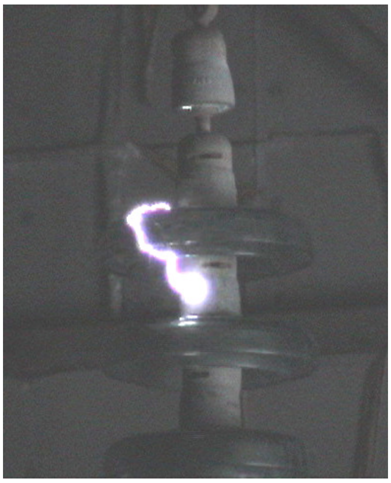


Figure 13: Single disc (partial) flashover for the case of one broken disc at the dead-end.

It was noted that for certain tests, the partial dead-end flashover occurred between 84-95% of the final flashover voltage. Further work is required in order to investigate and understand this phenomenon.

5 CONCLUSION

The following conclusions are noted:

- The flashover voltage of a string of glass insulators ranging between 6 and 13 discs is linear under HVDC conditions, however the assumption cannot be made that the flashover voltage will increase linearly for an increase in the number discs beyond what was tested.
- A broken disc located at any location in the insulator string will reduce the flashover voltage. This may need to be taken into consideration when determining the risk of flashover during temporary over-voltages.
- For a 13 string insulator, two broken discs at the live end of the string results in the worst flashover performance - a 24% reduction in flashover voltage.
- The flashover voltage when broken discs were present in the string, generally increased as the broken discs moved away from the live end.
- The highest voltage stress is developed on the first few discs at the dead end of a clean insulator string. This has an implication for live workers, working on the tower end.

6 RECOMMENDATIONS

- Negative polarity tests should be conducted in order to compare with the positive case,
- Corona effects on voltage distribution and flashover voltage will need further investigation. The tests will need to be carefully planned and undertaken to ensure that the applied test voltage is not much higher than the actual line voltage, i.e. the corona intensities in the tests should be representative of practical field conditions. An excessively high test voltage will lead to the masking of the corona source effects,
- Since the tests were performed under clean conditions the following further studies are recommended:
  - The effect of pollution on insulator flashover voltage,
  - The effect of pollution on insulator voltage distribution,
  - The combination of the effect of polluted insulator strings and shattered glass discs.
- Full string flashover voltage linearity needs to be studied,
- Electric field modelling of the environment around the insulator may be performed.

7 ACKNOWLEDGMENTS

The authors would like to acknowledge the Line & Servitude team from the Apollo Converter Substation (Mr E. Greyling and Ms L. Siboto) for the supply of glass discs used for the tests.

The authors also acknowledge Mr A.C. Britten for his insight and guidance on conducting this work. They would also like to thank Eskom - Research and Development department for their funding of the HVDC research program.

The tests were done at the EPRI High Voltage Laboratory in Lenox, Massachusetts, USA. The authors acknowledge the excellent work done by the Lenox technical staff in conducting these tests, specifically Mr D. Rueger, Mr C. Moore and Mr M. Clary and Dr G. Gela for their technical guidance and analysis.

8 REFERENCES

[1] K. Sadurski, T. Mihić, S. Narain: “Cahora Bassa Clearances and Live Line Upgradeability”, Eskom Research Report: RES/RR/10/31769, 2010.

[2] IEC 60060-1, “High Voltage Test Techniques – Part 1: General definitions and test requirements”. Edition 2, 1989.

[3] G. Gela, “Sparkover performance and gap factors of air gaps below 1 meter,” Electric Power Research Institute – TR 106335, Lenox MA, 1998.

[4] N. Parus, N. Mahatho, T. Govender, H.A. Roets, J. Badenhorst, J.P. Reynders: “Results obtained during gap testing under HVDC conditions”, Eskom Research Report: RES/RR/09/31452, 2010.

[5] R. Seethapathy, “Study of Voltage Distribution on Insulator Strings for dc Systems”, Master of Engineering Thesis, University of Toronto, 1986.