

## **Zambezi (previously Caprivi) Link HVDC Interconnector: Review of Operational Performance in the First Five Years**

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### **SUMMARY**

The Zambezi Link HVDC Interconnector (previously named Caprivi Link HVDC Interconnector), located in Namibia, was put into commercial operation in October 2010. The monopole scheme rated at 300MW connects the electricity networks of Namibia and Zambia. The scheme utilises Voltage Sourced Converters (VSC) and was the first scheme to use VSC technology with overhead lines. The Zambezi 330 kV substation is connected to Gerus 400 kV substation via 952 km of overhead line operating at -350kV dc. The Link has been designed to allow for a future bipole extension with a final rating of 600MW in conjunction with ac network strengthening. The Zambezi Link HVDC scheme is an important regional interconnection in the Southern African Power Pool.

The scheme has been in operation for more than 5 years since commissioning and this paper reports on the operational performance of the scheme during this time. The scheme connects two very weak ac networks that have a high possibility of transferring to islanded/passive networks.

The scheme was designed with special control and protection functions such as transfer to passive/island operation and a dc line fault clearing scheme for VSC. The performance of the scheme in response to actual network events, and the operational experience of the dc line fault clearing scheme are presented.

The paper also presents the Reliability, Availability and Maintainability (RAM) performance of the scheme and reports on the performance of the test earth electrodes.

### **KEYWORDS**

Zambezi VSC HVDC Link, Performance, dc Line Fault Clearing, Passive/Island Networks, Reliability, Availability and Maintainability, Test Electrodes

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## 1. INTRODUCTION

The Zambezi Link Interconnector provides an HVDC link between the Namibian and Zambian electricity networks. This provides NamPower, the Namibian electricity utility access to hydro power resources in Zambia and its neighbouring countries, and ensures direct (low power loss and reliable) power transfer capability between the east and west of the Southern African Power Pool (SAPP).

The monopole scheme is rated at 300MW and has been designed to allow for a future bipole extension with a final rating of 600MW in conjunction with ac network strengthening. The scheme has an overload rating in monopolar mode of up to 350MW with low ambient temperature conditions. The converter stations, located at Zambezi 330 kV substation close to Katima Mulilo in the Zambezi Strip (previously Caprivi Strip) and Gerus 400 kV substation in the centre of Namibia, are connected by 952km of overhead line as depicted in Figure 1.

Both poles of the dc line were constructed for the initial monopole scheme and test earth electrodes were constructed ~32 km from Gerus and ~25 km from Zambezi substations. The scheme has been designed for operation in the following configurations in monopolar mode:

- Metallic return utilising the second pole of the dc line as the metallic return conductor
- Earth return with a single dc line pole conductor
- Earth return with paralleled dc line pole conductors

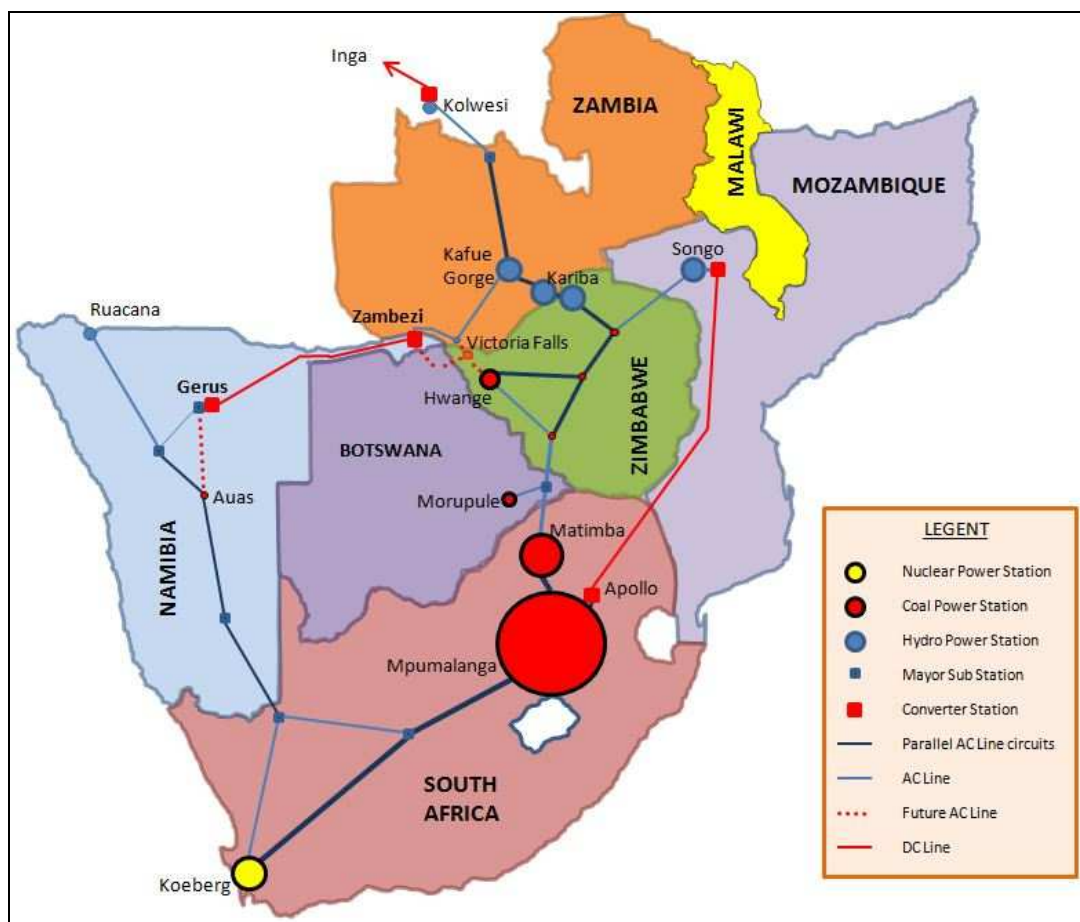


Figure 1: Geographical Location of the Zambezi Link Interconnector

The scheme connects two presently very weak ac networks where the fault levels are in the order of the rated power of the converters. These networks have a high possibility of transferring to passive as well as islanded ac networks. Islanded networks occur when part of the ac network with some generation source/s separates from the greater ac network, i.e. the South African Power Pool. The installation of the VSC HVDC scheme has enhanced stability and assisted with the prevention of blackouts by supplying energy to passive networks or providing frequency support to islanded network conditions. Moreover the VSC converter stations also provide robust voltage support whenever ac network disturbances such as inherent voltage collapse situations arise.

**2. SCHEME OVERVIEW**

**2.1 Circuit design**

Figure 2 shows a simplified single line diagram of the two-level VSC HVDC scheme that has been implemented for the initial monopolar stage of the Caprivi Link Interconnector. The core equipment of the converter stations are the converter transformers, converter reactors, converter valves and dc capacitors. The dc capacitors provide a stable dc voltage source and have the function of energy storage or buffer for the HVDC system. The converter valve converts this dc voltage to ac voltage by optimised pulse width modulation (PWM) switching techniques. The converter reactor provides the proper reactance for control of the active and reactive power flow. The converter transformer adapts the level of the generated ac voltage the level of the ac network voltage. The ac filters remove the harmonic content from the square shaped PWM wave form.

The high voltage terminals of the converter valves are connected to the HVDC overhead lines through dc breakers while the neutral is connected to the electrode lines. The dc breakers together with converter breakers are used to clear dc line faults. Two kinds of dc breakers are used. The first type interrupts the remaining dc fault current after the ac circuit breaker has opened after a dc line fault. The second type, a high speed switch, isolates the converter station from an earth fault on the dc line, and is then used to re-energise the dc line after fault clearing.

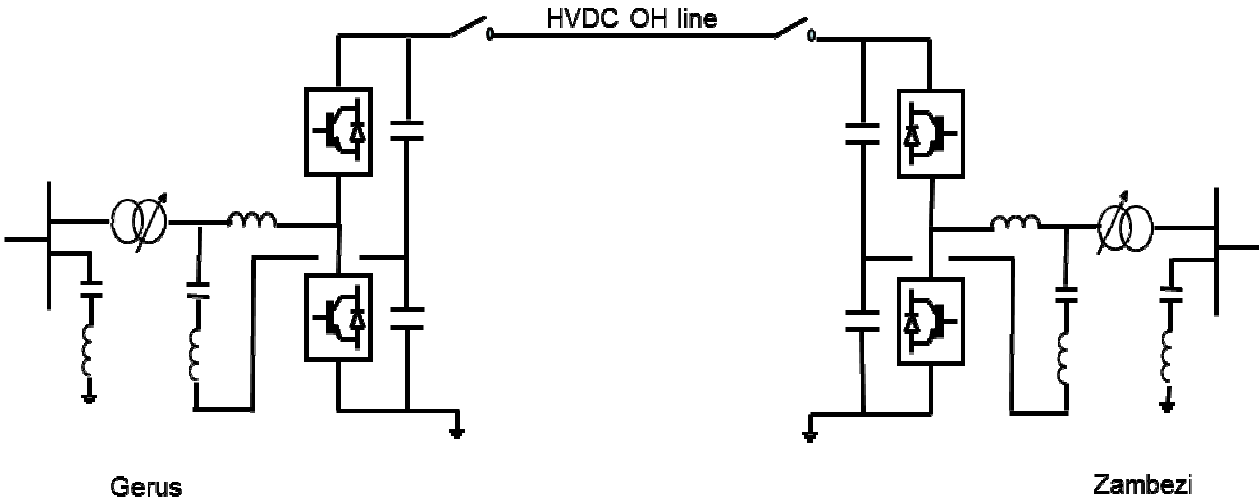


Figure 2. Simplified single line diagram of Zambezi HVDC Link

## 2.2 Main control functions

**Active power control** maintains constant active power transmission in either direction from zero up to the maximum rated power. **Reactive power control** is used to maintain a constant reactive power exchange between each converter station and the ac network. However, **AC voltage control** is normally used to maintain constant ac voltage of the ac networks connected to the converter stations.

**Reduced DC voltage control** enables operation at up to 80 % of rated dc voltage to reduce the probability of flashovers due to bush fires under the dc line.

In case of transfer to passive (without generation) or islanded (with generation) networks at the converter stations, the station will be set to **Passive/Island network operation** with frequency control. The other end of the HVDC scheme, connected to a healthy ac network, will provide the balance of the power required in the islanded network. However, a power demand that is too large (either transiently or in steady state) from the passive or islanded network may cause voltage collapse conditions in the healthy network as well as in the islanded network. Operator settable control functions, the **Transient power limiter** and **Steady state power limiter**, are used to limit the transient and steady state power needs of the passive/island network.

**Black start** of a converter station against a dead network can also be performed, using the other converter station as power supply.

## 3. DC LINE FAULT CLEARING PERFORMANCE

The dc line fault clearing sequence is initiated by the dc line fault protection which is comprised of three protection methods: **Differential protection**, **Impedance protection** and **Derivative protection**. Which protection picks up will depend on the characteristics of the fault. The fault clearing sequence executes a first restart attempt at full dc voltage and if this fails to clear the fault a second restart attempt is performed at reduced dc voltage (after automatic reduction of the dc voltage). For operation with already reduced dc voltage two restarts are attempted.

Upon detection of dc line faults, the converter stations are temporarily isolated from the ac grid and the dc line by opening the ac converter breaker and the dc breakers to interrupt the fault current. Immediately after a pre-set fault clearing time, the breakers are re-closed and the power transmission is resumed. STATCOM operation is resumed first within 500 ms and power transmission within 1500 ms (depending on ramping speed and pre-fault power level), see also [1] for further explanation of the dc line fault clearing sequence.

Despite energised system testing of the dc line fault clearing with a series of staged faults being successful, initial operating experience was not satisfactory. There were several reasons for this. First it was found that the dc line fault protection was not selective enough for real dc line faults and the dc under-voltage protection often triggered incorrectly. Consequently the selectivity of the dc line protection and the coordination between the two protections had to be improved.

The next problem that occurred when the dc line fault protection worked properly was that the fault clearing sequence frequently did not complete the restart of the HVDC link completely but was interrupted. One reason was that the sequence software did not taken into account all possible operational conditions at which dc line faults could occur. Another reason was that all circuit breakers in the fault clearing scheme equipped with double drive mechanisms did not work properly but got stuck at some stage of the switching sequence.

The circuit breakers were re-commissioned and carefully tuned and robust functioning was verified with an extensive dry-test program at site.

The sequence software was rectified and improved using a replica of the control and protection system, which was part of the delivery. An extensive test program on the replica followed by field testing of selected cases was performed to verify proper operation of the fault clearing sequence.

The actions to rectify the dc line fault clearing sequence were finalised in October 2013. After that the performance has been satisfactory. During the bush fire season NamPower operates the line at reduced dc voltage as a precautionary measure to reduce the probability of dc line faults.

Examples of the performance of clearing of three different types of dc line faults are discussed below: lightning fault, bush fire with fast voltage collapse and bush fire with slow voltage collapse.

### 3.1 DC line fault – lightning

The clearing of a typical lightning fault is demonstrated in Figure 3. This lightning fault was detected via the derivative protection. In the plot below the analogue signals are: ac rms voltage - UPCC\_PRIMSIDE\_RMS, active power - P\_PCCY, dc voltage - UD\_MEAN and dc current - IDL\_10. The digital signals shown are: converter valve status – BLOCKED, ac converter breaker open – CONV BREAKER OPEN, dc breaker closed – DCB\_Q1\_CLOSED\_IND and dc line high speed switch closed – DCB\_Q3\_CLOSED\_IND. As can be seen the fault is successfully cleared after the first attempt and power transmission starts being restored after re-energising the dc line.

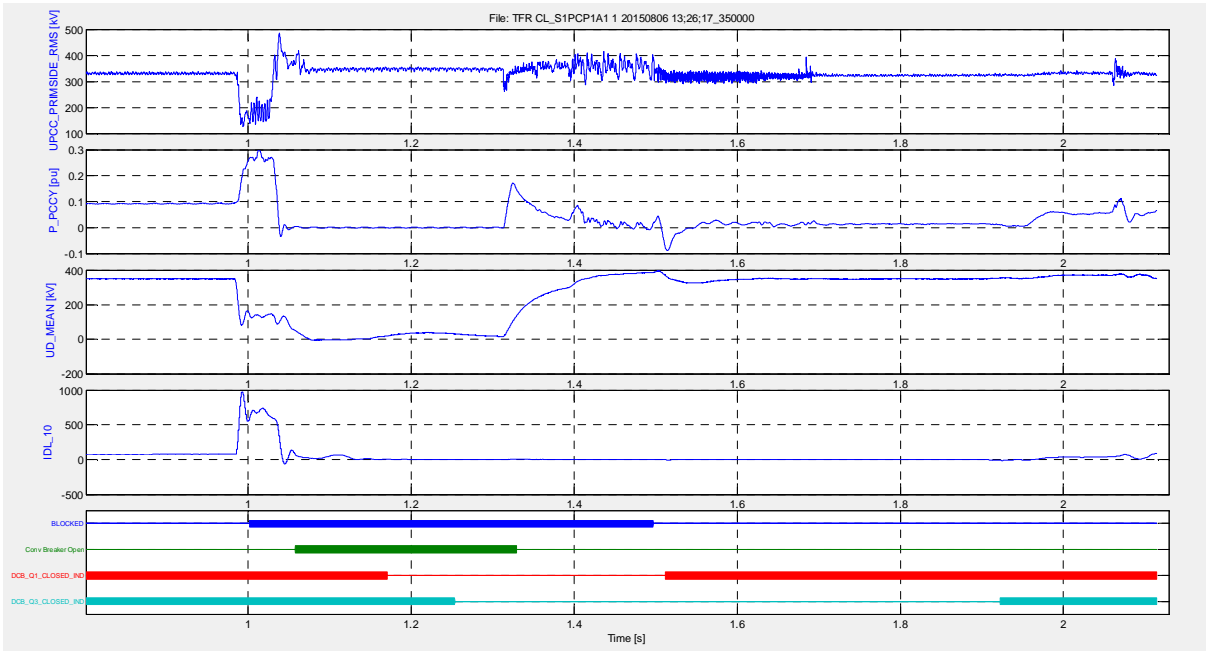


Figure 3. DC line fault – lightning

**3.2 DC line fault – bush fire with slow voltage collapse.**

Faults caused by bush fires depend on many different factors such as the intensity of the fire and wind speed. A typical slowly evolving bush fire fault is demonstrated in Figure 4. As seen the dc voltage drops slowly due to an increase in the leakage current from the dc line to earth. The detection of the fault by the differential protection took approximately 800 ms at which time the leakage power had increased from 10MW to 140MW. The fault clearing was successful after the first attempt. Signals recorded below are described in the previous section.

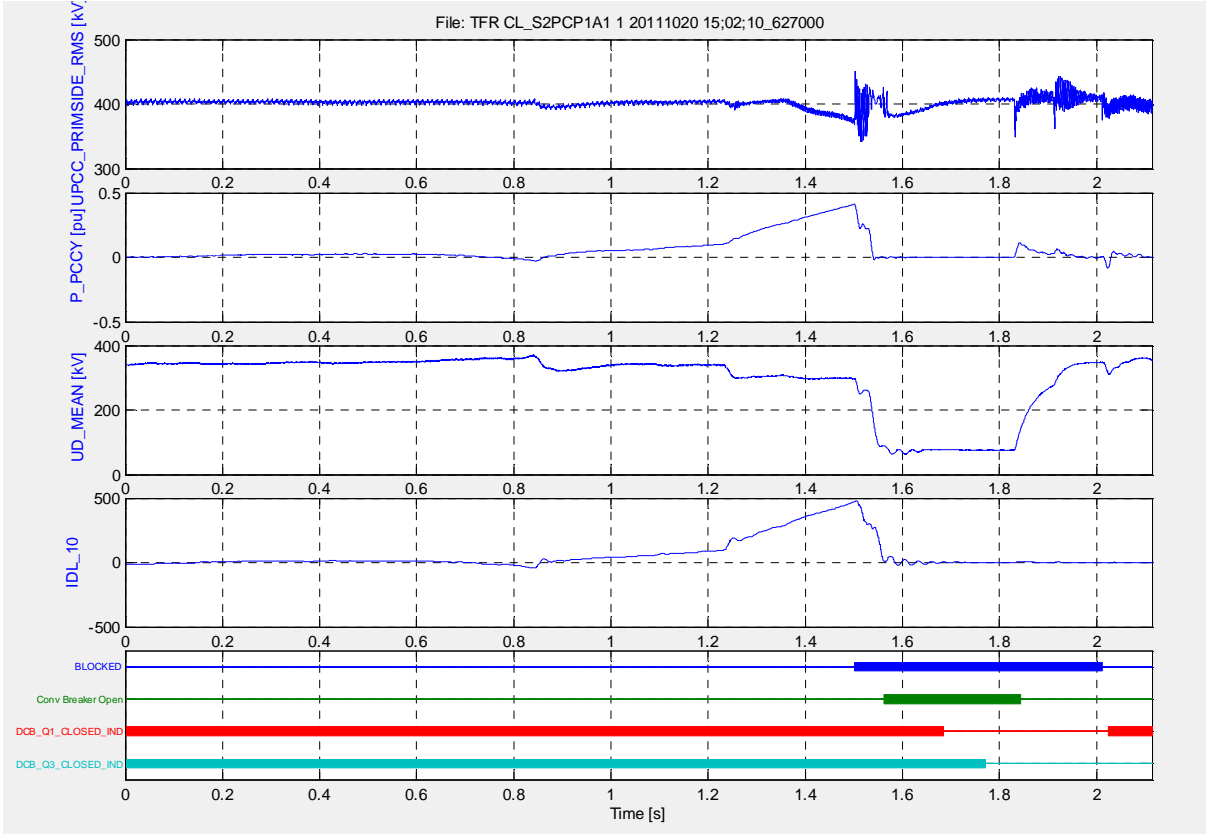


Figure 4. DC line fault – bush fire with slow voltage collapse

### 3.3 DC line fault – bush fire with fast voltage collapse.

The recording in Figure 5 shows a fast evolving bush fire fault. Initially the current started to leak for 200 ms causing the voltage to drop somewhat, after which the dc voltage collapsed to zero triggering the derivative part of the dc line protection. Signals are described in the previous section.

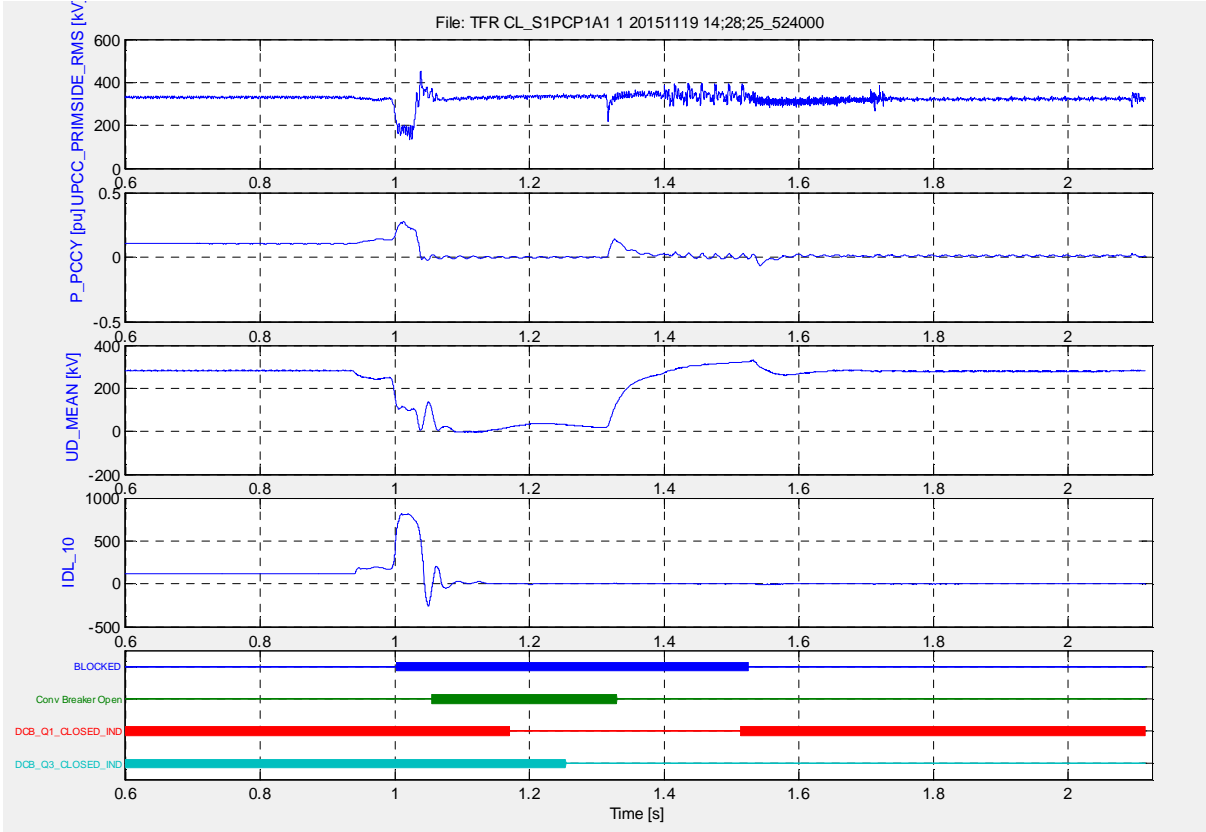


Figure 5. DC line fault – bush fire with fast voltage collapse

## 4. ANALYSIS OF MAJOR NETWORK EVENTS

### 4.1 Transfer to passive network

The recording in Figure 6 shows the loss of the ac connection to most of the Zambian network leaving the Zambezi Link connected to only a small load and no generation on the Zambian side. Prior to the fault, Namibia imported ~140 MW of power from Zambia. The island detection was activated by an under frequency criteria which changed the operation mode from normal to passive/island network operation with frequency control. The power was reversed to supply the small load (~2 MW) connected to Zambezi without interruption of supply. In the plot below the analogue signals are: ac rms voltage - UPCC\_PRIMSIDE\_RMS, active power - P\_PCCY, reactive power - Q\_PRIMSIDE, dc voltage - UD\_MEAN and frequency - FREQ. The digital signals shown are: converter valve status - BLOCKED and detection of passive/island network - ISLAND\_DET.

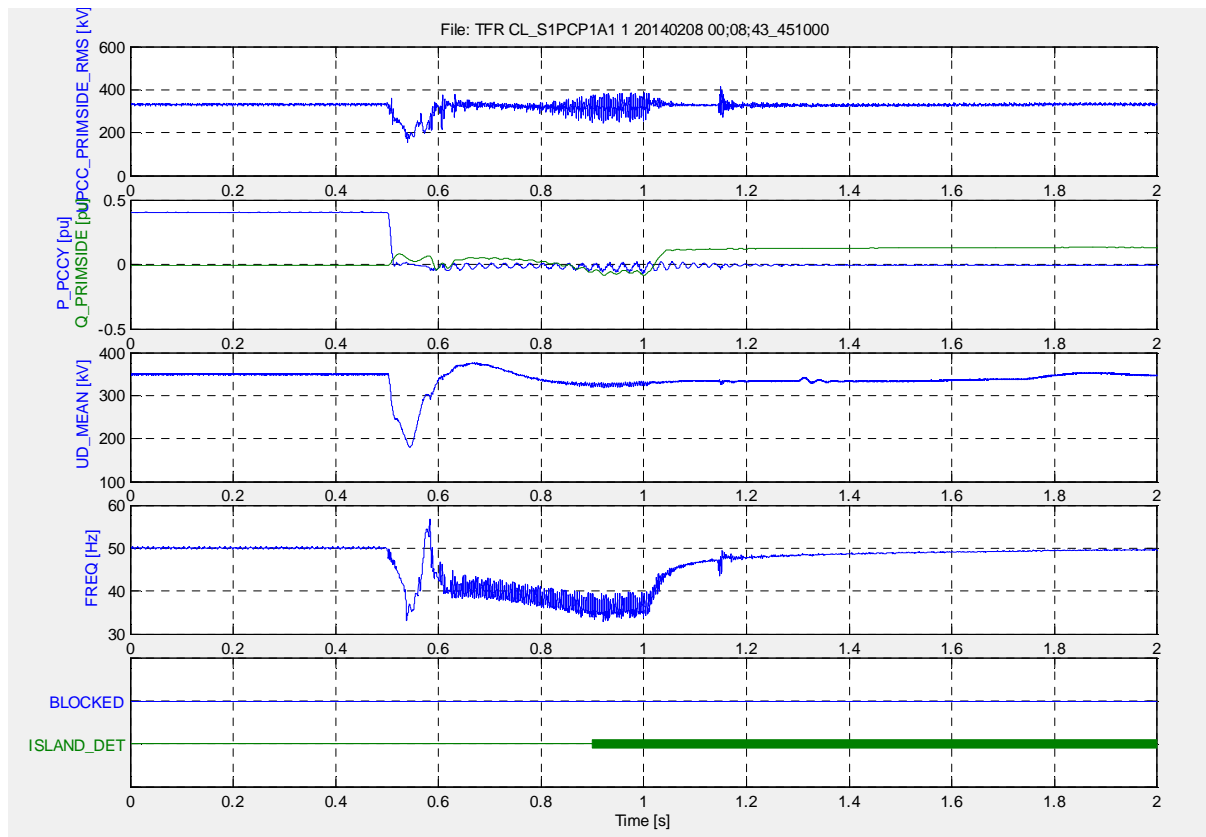


Figure 6. Transfer to passive network



## 4.2 Transfer to islanded network

Figure 7 shows an event where a part of the Zambian network (including generation) is islanded from the larger Zambian network together with the Zambezi Link. Prior to islanding power of 30 MW was being imported from Zambia to Namibia. A slow frequency change on the Zambian network as consequence of the islanding activated the transfer to passive/island network operation mode with frequency control. In order to try to balance the generation and load in the islanded network the import of power into the Namibian network was increased. The transient power limiter is activated, as indicated by the digital signal DFPLC\_ACTIVE. The transient power limiter restricted the power import to ~100MW being its set point (see description in Section 2.2 above). The frequency was therefore not restored to 50Hz. Signals recorded below are described in the previous section, with the addition of the following digital signal: activation of transient power limiter – DFPLC\_ACTIVE.

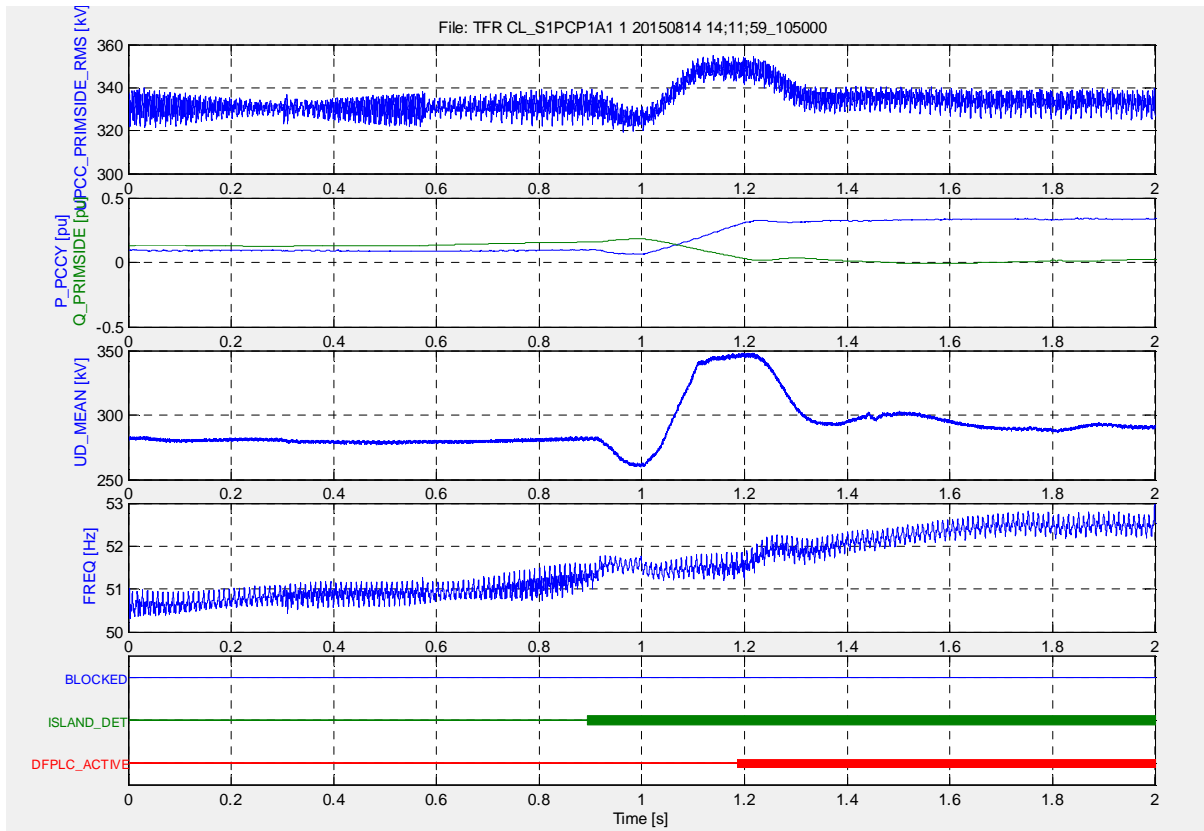


Figure 7. Transfer to islanded network

## 5. RAM PERFORMANCE

The commissioning of the Zambezi Link was completed in September 2010 and commercial operation started in October 2010. The Reliability, Availability and Maintenance (RAM) figures for October 2010 to September 2015 are shown in Tables I and II below. The figures are based on the 300MW monopole that was constructed. The performance recording and reporting are based on the CIGRE Protocol [2].

Table I. RAM Performance for October 2010 – September 2015

Period	Energy Transmitted, MWh	Energy Utilization, %	Energy Availability, %	Scheduled Energy Unavailability, %	Forced Energy Unavailability, %	Forced Outage Rate (excluding TL), no.
October 2010 - September 2011	530 910.18	20.20	94.23	3.94	1.83	28
October 2011 - September 2012	524 952.54	19.98	95.58	3.04	1.37	16
October 2012 - September 2013	554 394.54	21.10	96.79	2.99	0.23	7
October 2013 - September 2014	590 860.38	22.48	97.48	2.33	0.20	5
October 2014 - September 2015	417 693.08	15.89	98.63	1.25	0.12	2

Table II. RAM Performance for October 2010 – September 2015 showing number of outages and outage duration per equipment category

Period	AC-E		V		C&P		DC-E		O		TL		TOTAL	
	No	Hours	No	Hours	No	Hours	No	Hours	No	Hours	No	Hours	No	Hours
October 2010 - September 2011	5	39.45	2	7.83	7	25.55	3	10.83	11	50.63	13	28.03	41	162.3
October 2011 - September 2012	6	73.76	0	0	3	7.48	1	0.55	6	30.98	8	7.48	24	120.3
October 2012 - September 2013	3	6.08	2	4.7	0	0	2	0.83	0	0	8	8.28	15	19.89
October 2013 - September 2014	0	0	0	0	3	3.5	0	0	2	4.45	8	8.78	13	16.73
October 2014 - September 2015	0	0	0	0	1	3.77	1	6.98	0	0	0	0	2	10.75

In the first four years of operation several teething problems were sorted out including the dc line fault clearing sequence, modification of grading rings of the converter reactors, modification of the dc chopper valve at Zambezi, rectification of ac filter circuit breaker problems, addition of ac bus surge arrester at Gerus and replacement of frequency converters with higher voltage rating for cooling water pumps.

These corrective actions resulted in significantly longer scheduled outages in the first four years of operation. Moreover additional energised system tests were carried out in conjunction with the scheduled maintenance outages in the October 2010 – September 2011 recording period. The test earth electrodes were also commissioned in February 2012 and the outage time for this is included in the scheduled outage duration for the period from October 2011 – September 2012.

The contractual Reliability, Availability and Maintainability (RAM) monitoring period started in October 2013.

The contractually specified performance figures were as follows. Only monopole figures are shown as the bipole has not been implemented yet.

- Guaranteed Forced Outage Rate (FOR) for 300MW monopole:  $\leq 5$
- Guaranteed Forced Energy Unavailability (FEU):  $\leq 1\%$
- Scheduled Energy Unavailability (SEU):  $\leq 1\%$

Forced Outage Rate and Forced Energy Unavailability were below the guaranteed figures during the monitoring period while the Scheduled Energy Unavailability was above the guaranteed figures. The reasons for the extended scheduled outages during the 2014 and 2015 monitoring years are mainly:

- Suitable cherry pickers for inside/outside work have been hard to find and rent in Namibia. This has prevented parallel work in some work areas.
- The smoke from bushfires around the sites has result in more cleaning inside the converter buildings at Zambezi (mainly dc equipment).
- Requirement of extensive cleaning of ac equipment. This has been found not to be necessary and the maintenance instructions will be revised.

## 6. OPERATIONAL EXPERIENCE WITH TEST ELECTRODES

The Zambezi Link operation modes include operation in earth return which requires earth electrodes. The site selection process and preliminary design for the earth electrodes are described in [3]. Before designing and constructing the full earth electrode it was decided to build test earth electrodes in order to assess the suitability of the electrode concept especially with regards to the installation environment. The test electrodes rated to carry up to 130 A (15% of the rated scheme dc current) were commissioned in February 2012 at Gerus and Zambezi earth electrode sites. These have been in operation for a total operating time of one year mostly when the power flow on the system is low and when the link is operated at normal dc voltage. The performance results of the test electrodes have been satisfactory. The design for the earth electrodes rated for the full dc current is now being finalised. The equipment used in the test electrode will be incorporated in the full earth electrode and therefore no equipment will become redundant.

## 7. CONCLUSION

The dc line fault clearing scheme proved to be challenging. The initial performance was not satisfactory and modifications and improvements had to be made, which has now resulted in satisfactory performance.

The Zambezi Link HVDC scheme responds correctly to challenging network events such as transfer to passive and islanded networks, thereby enhancing the stability of the weak ac networks which it connects.

In the initial years of operation the RAM performance of the scheme was not satisfactory. Several corrective actions were implemented which has resulted in satisfactory performance in the 2014 and 2015 monitoring periods except for the scheduled energy unavailability. However, measures will be taken to reduce the scheduled maintenance outage time.

The replica control and protection system proved to be a powerful tool for optimising and testing improvements to the software prior to implementation.

Despite some initial challenges close work between the vendor and the utility has resulted in a scheme with acceptable performance.

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