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Connecting networks with VSC HVDC in Africa: Caprivi Link Interconnector

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Abstract *– The Caprivi Link HVDC Scheme in Namibia connects the AC networks of Namibia and Zambia with 950km of overhead line operating at 350kV DC. Commissioning of the 300MW monopole phase of the scheme was completed in October 2010. The scheme has been designed for a future bipole extension to 600MW. The scheme connects two presently very weak AC networks where the fault levels are in the order of the rated power of the converters. The scheme utilises Voltage Source Converter (VSC) technology and is the first scheme to use VSC technology with overhead lines. The scheme has also been designed for earth return operation.*

This paper provides an overview of the scheme, the AC networks that it interconnects and the features of VSC technology that are particularly suited to connecting weak AC networks. The process of selecting sites for and the design of the earth electrodes is described. Initial operating experience is also presented.

I. INTRODUCTION

Many of the electricity networks in Africa span vast distances and are often characterised by relatively weak AC networks. Line Commutated Converter (LCC) HVDC technology has been used for a long time for bulk power transfer over long distances. Two LCC schemes are in operation in Africa: the Cahora Bassa (Mozambique) – Apollo (South Africa) scheme constructed in the 1970's capable of transferring 1920MW and the Inga – Kolwezi scheme constructed in 1982 in the Democratic Republic of Congo capable of transferring 560MW.

Voltage Sourced Converter (VSC) HVDC is a relatively new technology that until recently has only been utilised with cables. Phase one of the first commercially operated VSC scheme utilising overhead lines, the Caprivi Link Interconnector (CLI) in Namibia, was commissioned in 2010.

The Interconnector provides an asynchronous connection between the Namibian and Zambian electricity networks and is an important regional interconnection in the Southern African Power Pool (SAPP). See Fig. 1.

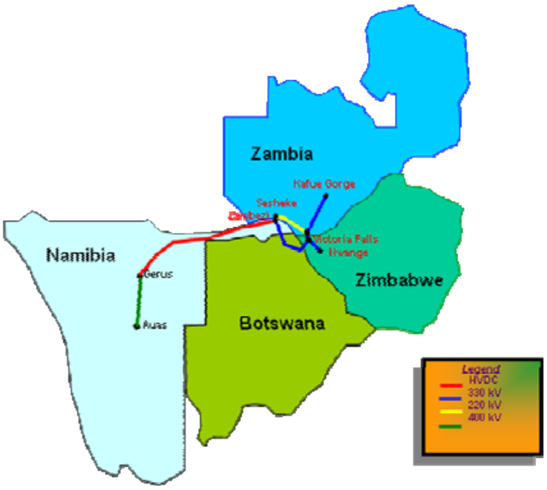

Figure 1. Inteconnector scheme and the ±350kV HVDC line route.

Phase one of the project comprises of a 951km ±350kV HVDC transmission line, 300MW monopole converter stations and associated AC substation extensions at Zambezi substation (near Katima Mulilo) and Gerus substation (near Otjiwarongo). Phase one also included the construction of earth electrodes and electrode lines. The project cost for phase one was N$ 3.2 billion (~US$ 400 million). Phase two consists of upgrading the converter stations at Zambezi and Gerus substations to a 600MW bipole scheme and a 285km 400kV AC transmission line from Gerus to Auas substation (near Windhoek). In Phase two further network strengthening in Zambia and a 330kV AC line through Botswana to Zimbabwe is also planned. This phase will be implemented if and when the need arises.

The AC networks connected to the HVDC converter stations are extremely weak at both ends, with fault levels in the order of the rated power of the convertors. The VSC HVDC technology provides certain advantages over LCC HVDC technology when connecting relatively weak AC networks.

The Caprivi Link scheme has been designed for operation with earth electrodes. Test electrodes were commissioned in early February 2012. An overview of the process for selecting suitable sites for the earth electrodes and the design of the earth electrodes is described.

An overview of the initial operating experience of the scheme and the earth electrodes is provided.

II. OVERVIEW OF CAPRIVI LINK INTERCONNECTOR AND VSC HVDC TECHNOLOGY

The Southern African Power Pool (SAPP) represents an AC interconnected power system with three HVDC systems. Major generation situated in South Africa consists mainly of thermal power stations, while the central area (Zimbabwe and Zambia) contain a large proportion of hydro power stations. The western corridor (Namibia) has only small hydro and thermal generation. The Caprivi Link forms a very important regional interconnection in the South African Power Pool by providing a central-west interconnection. See Fig. 2.

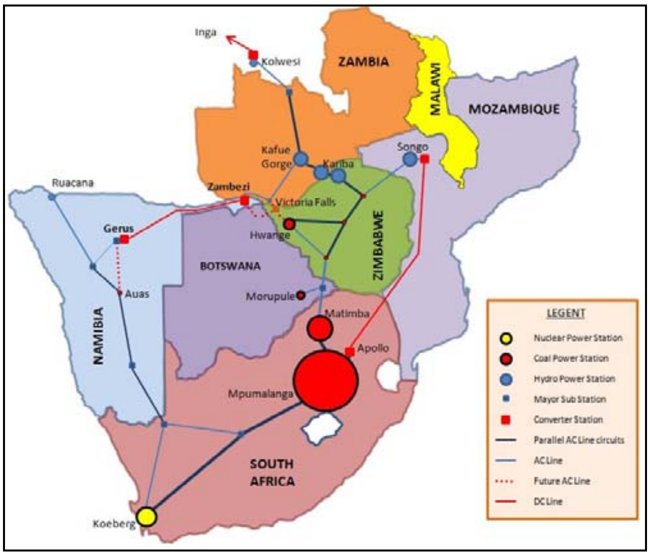

Figure 2. Southern African Power Pool with integrated HVDC schemes and lumped generation representation.

The presently weak networks have a high possibility of transferring to islanded/passive AC networks such as when the Kafue Town – Victoria Falls transmission line in Zambia trips and about 100MW generation at Victoria Falls islands together with the Zambezi converter. A similar condition can occur on the Namibian side when the AC link to South Africa is lost and the Gerus converter station islands together with Ruacana hydro power station. Similarly both sides can experience passive network conditions where no generation is present in the island. Without the HVDC link being installed, the outage of critical lines can easily lead to an eventual blackout of the area due to the extremely weak AC network conditions.

The Voltage Source Converter HVDC has proven to enhance stability and assist with the prevention of blackouts when two extremely weak AC networks are interconnected and operate in parallel with an AC network such as the Southern African Power Pool. It provides very robust voltage support when inherent voltage collapse situations arise due to its inherent SVC capability, while giving stable frequency support to island or passive network conditions, thereby preventing eventual blackout. The Caprivi Link converter stations can provide up to ±200Mvar SVC capability throughout nearly the entire power transfer range from 0-300MW. The active and reactive power capability chart for the Zambezi converter station is shown in Fig. 3.

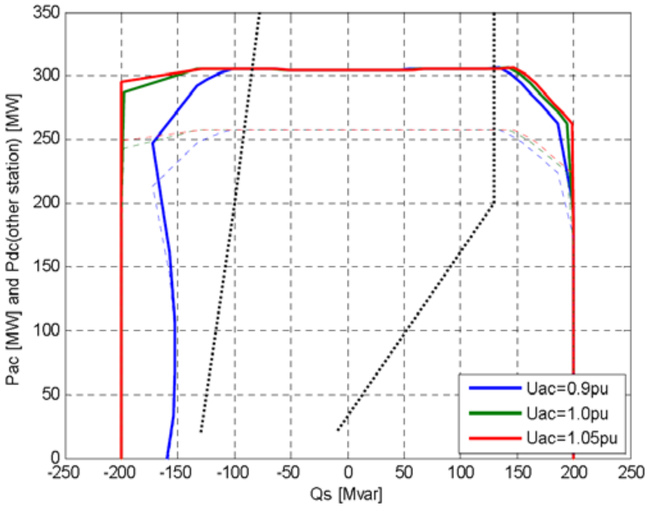

Figure 3. Power capability chart for Zambezi converter.

The Interconnector also caters for the diverse network conditions that are planned for the future eventually providing n-1 network security when the bipole is implemented.

Due to the fact that the Caprivi Link Interconnector is an overhead line connection which is prepared for a future bipolar extension, the implemented VSC technology is somewhat different from the earlier delivered cable links. The output from the converter stations of the Caprivi Link Interconnector is a high voltage DC voltage to earth, i.e. 350kV, while all previous VSC schemes, except the Valhall link, have produced a DC voltage of dual polarity, such as ±150kV. Another difference is that the Caprivi Link Interconnector is equipped with a DC line fault clearing scheme since the power transmission must not be interrupted for temporary faults on the overhead lines. A VSC scheme lacks the inherent ability of a conventional HVDC scheme to quickly reduce the fault currents to zero at DC line faults, but other methods are to be used.

Fig. 4 shows a simplified Single Line Diagram of the VSC scheme that has been implemented for the initial monopolar stage of the Caprivi Link Interconnector. A future bipolar system is obtained by adding another converter block or pole per station. Both poles of the DC overhead line (± 350kV conductors) and double circuit earth electrode lines have already been built for the bipolar expansion.

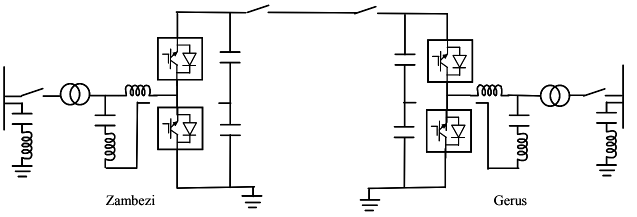

Figure 4. Simplified single line diagram of the Caprivi Link Interconnector.

The core equipment of the converter stations of Caprivi Link is the converter valve, the converter reactor and the DC capacitors. The DC capacitors provide a stable DC voltage source and have the function of energy storage or buffer for the system. The converter valve converts this DC voltage to an AC voltage by pulse width modulation (PWM) switching and the converter reactor provides the proper reactance for control of the active and reactive power flow.

The converter valve consists of three phase-legs with two single valves each. The single valves are built up of a number of semi-conductor devices connected in series, insulated gate bipolar transistors (IGBTs) with diodes connected in anti-parallel. The high voltage terminal of the converter valve is connected to the DC overhead lines and the low voltage terminal is connected to the earth electrode via the electrode lines or to the metallic return conductor. The metallic return conductor is earthed at Gerus either at the station earth grid or at the earth electrode.

The converter valve is connected to the AC grid through the converter reactor and converter transformer. The converter transformer adapts and adjusts the grid voltage to an optimal converter voltage and enables a reduction to 80% of the nominal DC voltage in case of insulation problems with the DC line (bush fires etc).

The AC filters remove the harmonic content from the square shaped PWM wave form.

The equipment and configuration of the DC sides of the converter station are similar to conventional HVDC schemes, except that DC breakers are included in DC line fault clearing scheme.

At a DC line fault, the converter stations are temporarily isolated from the AC grid and DC line by opening the AC and DC circuit breakers to interrupt the fault currents. Immediately after clearing the fault currents the breakers are re-closed and the transmission resumed. SVC operation is resumed within 500 ms and power transmission within 1500 ms.

III. EARTH ELECTRODES

The CLI 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

Fig. 5 shows the monopolar system with earth return.

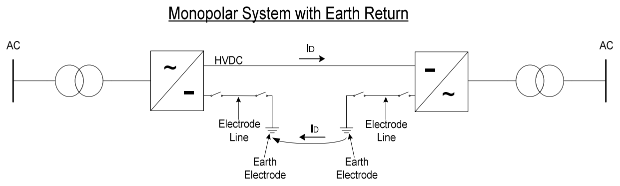

Figure 5. Monopolar system with earth return.

The advantages of operation with earth return in monopolar mode are reduced losses due to the low resistance of the earth return path and operational flexibility.

Earth return operation requires that suitable earth electrode sites be acquired in the vicinity of the converter stations.

The following criteria were taken into account when selecting the earth electrode sites for the CLI:

- Geological properties of the area
- Ground characteristics
- Buried and earthed metallic structures within the area of influence
- Electrical infrastructure within the area of influence
- Environmental/land use/landowner considerations
- Accessibility

The most important requirement for the construction of an earth electrode relates to the geological properties and ground characteristics. A low resistance connection to deep earth is required and both the surface soil conditions and the conditions several hundred meters and even kilometers deep are important.

The difficult ground conditions around the Gerus converter station turned out to be greatest challenge in the earth electrode design. The ground there consists mainly of granite bedrock which is a poor electrical conductor, but there are pockets of graphite bedrock, which is a good electrical conductor. The earth electrode station at Gerus is located at such a graphite deposit.

Around the Zambezi converter station the ground conditions are different. The soil consists of mostly sand with a varying high content of moisture. The earth electrode at Zambezi is located in a “pan” area where the sand is mixed with clay layers which maintain the ground water close to the surface with permanent low soil resistivity as a result.

The electric field around the earth electrode can cause stray currents on close metallic structures. The main concern is the risk of increased corrosion but also other forms of interference have to be considered such as transformer saturation and disturbances to the telephone network.

Impact studies were carried out for the electrode sites chosen for the Caprivi Link. The first site investigated at Gerus caused an unacceptable level of interference in the nearest town. A site further away was then investigated and found to be suitable. The electrode sites selected for both the Zambezi and Gerus electrodes are approximately 30km away from the converter stations.

Initially the CLI was commissioned for metallic return operation utilising the second pole conductor as a metallic return path and the station earth grid of one of the converter station as earth point, since the process to find suitable earth electrode sites and the design of the earth electrodes took longer than expected. It was then decided to construct the earth electrode stations in two stages: initially test electrodes with limited power rating to verify the design calculations, and finally the complete earth electrode stations.

The earth electrodes have been designed for at least 30 years operation with the initial negative DC line polarity and 350MW power import to Namibia, i.e. the earth electrode at Zambezi operates as an anode (the current leaves the electrode) and the earth electrode at Gerus operates as a cathode (the current enters the electrode). The conduction from the electrode at Zambezi to the soil is based on ionic conduction through the ground water. This causes an electrolytic process at the surface of the electrode which results in some consumption of anode material. The earth electrode at Zambezi is made of silicon chromium iron rods, a common anode material, and is sectionalised into about 30 vertical sub-electrodes, or 30 boreholes, which are all built up of several sub-elements (silicon chromium iron rods) connected in parallel. After installation of the sub-electrodes the boreholes are backfilled with coke.

The earth electrode at Gerus is designed with a different principle not based on ionic conduction through the ground water. The earth electrode is sectionalised into about 10 sub-electrodes or borehole electrodes. Each borehole has a copper tube conductor in the center. The space around this copper tube is backfilled with a mixture of graphite gravel and bitumen. The purpose of the graphite gravel is to make direct contact between the copper tube and the graphite bedrock of the ground. The purpose of the bitumen is to prevent ground water from entering the hole. With the direct conduction between the copper tube and graphite bedrock and no presence of water, no electrolytic process can occur in anodic operation and consequently no loss of electrode material occurs. The earth electrode at Gerus presently works as a cathode, but anodic operation in future at power import with the future converter block of positive polarity might be more frequent. At balanced bipolar operation there are no earth currents.

The sectionalising in sub-elements allows for maintenance work without reducing the normal power capability of 300MW (867A). The earth electrodes are designed to provide a resistance to remote earth of maximum 0.2 Ω.

The electrode stations are designed to meet applicable safety regulations regarding step voltages, i.e., the ground at the earth electrode can be accessed without restrictions during operation.

The test electrodes consist of two bore holes at Gerus and three bore holes at Zambezi. Besides adding the remaining borehole electrodes, the completion of the earth electrode stations also includes switchgear with motor operated isolators and current measuring devices, as a part of a current line differential protection with automatic disconnection of a faulty electrode line.

The test electrodes were tested and commissioned successfully in February 2012. Because of the limited amount of electrodes are used during this testing phase, the current is limited to 130A or around 46MW power transfer with the scheme operating at nominal DC voltage. In reduced DC voltage, power transfer is limited to around 36MW.

Part of the electrode line energised system testing was to test the current unbalance back-up protection on the two electrode line circuits for each site. For staged faults on the electrode lines it was found that the fault current is small due to the high earth surface resistivity and low power level and it was difficult to detect an unbalance current especially for faults close to the earth electrodes. The future line differential protection will be much more sensitive. Line fault location with the use of off-line cable fault locators was found not to work due to induced ac voltages in the electrode lines. A fault locator for overhead AC lines will be tested instead.

IV. OPERATING EXPERIENCE OF CAPRIVI LINK

Commercial operation of the CLI started on the 10 October 2010 after completion of the Energised System

Testing. The scheme has only operated in metallic return up to February 2012 and after that in earth return configuration after the testing and commissioning of the test electrodes.

The automatic DC line fault clearing scheme has turned out to be one of the most technically challenging items in the DC scheme. It was initially commissioned and tested with staged DC line faults with and showed good performance except for the passive network operation mode where it was found that the reliability and robustness of the fault clearing sequence had to be improved. For this reason the DC line fault clearing sequence was disabled until the beginning of March 2011 when it was re-commissioned. Thus when a DC line fault occurs the DC line was tripped and had to be switched back manually. October is the month where the prevalence of both bush fires and lightning activity starts increasing in Namibia. In the period from October 2010 to the end of February 2011 the DC line tripped 12 times due to suspected bush fires or lightning activity. During this period the automatic DC line fault clearing sequence was enabled for a short time and successfully cleared a DC line fault.

During the next season of bush fires and lightning activities, starting in October 2011, it was found that the coordination with other converter station protections had to be improved for the DC line fault protection not to cause incorrect trips of the scheme.

External factors in the connected AC networks also caused several outages of the scheme. The failure of a coupling transformer on the radial Zambian network north of Victoria Falls power station resulted in the south western and central Zambian grid being separated for an extended period of time. This meant that the CLI operated in islanded mode with the south western Zambian grid which included Victoria Falls power station as the only generating source from November 2010 to mid-June 2011. In the islanded mode the HVDC scheme operated in frequency control together with the generators of the separated network. Under this operating condition the power flow on the link is not directly controllable but depends on the surplus generation in the south western Zambian grid. In general operation in the frequency control mode has been successful.

The CLI has had two annual maintenance periods since the start of commercial operation performed by the utility and supervised by the manufacturer, and no major primary or secondary equipment defects have been noted. Although it has been noted that since the start of operation in earth return problems have been experienced with the DC line fault locator not registering distances to faults, as well as a problem with transient over-voltages at the Zambezi converter station during DC line faults causing cooling system pumps variable speed drive (VSD) tripping, this is being investigated and rectified by the manufacturer.

Another problem experienced is that rodents chew the fibre optic cables that provide the firing pulses to the IGBT's. Cables have had to be replaced and measures instituted to prevent this type of damage by rodents.

In order to reduce the number of bush fire related DC line faults during the months of August to December in the area where the DC line is constructed, a detailed line- and servitude inspection is being planned to optimally prioritise the 951km long servitude that needs to be maintained in an area where bush encroachment happens at an alarming rate.

The introduction of the Caprivi Link Interconnector has improved certain aspects of the quality of supply (QOS) of the Namibian system due to the improvement of voltage regulation and system unbalance. The voltage dip figure of QOS has increased in the parts of the Namibian transmission and distribution network close to the HVDC scheme especially for loads connected to long radial lines due the temporary blocking of the converter stations during the DC line fault sequence where no voltage regulation is available to the system for that time. A complete semi-conductor based DC breaker might be installed when the manufacturer has finalised the development of it. This circuit breaker will act much faster after detection of a DC line fault and will allow the converters to remain in SVC operation during fault clearing.

The HVDC scheme has operated in earth return for about 4 months and all field measurements pertaining to electrical field potentials, electrode temperatures, and nearby single wire earth return (SWER) transformers have shown no abnormalities. The bitumen and graphite mixture at the Gerus electrode site where the electrodes are around 100m deep has dropped by about 1m since the start of earth electrode operation.

The reliability and availability of the scheme is being monitored using the CIGRE reporting protocol for HVDC schemes. The authors intend to report more fully on the performance of the scheme in the future.

V. APPLICATION OF VSC HVDC TECHNOLOGY IN AFRICA

The VSC technology used for Caprivi Link is feasible for other potential overhead line power transmission projects in Africa where AC transmission is not found feasible. The great advantage of the VSC technology compared to conventional HVDC is the powerful capability to control the AC voltage at the connection points of the transmission line. As demonstrated by the Caprivi Link Interconnector, a VSC link can also provide frequency control to an islanded network or even supply a totally passive network without any generation. This is an important feature since AC networks are weak at many locations in Africa and dependent on a few transmission lines or generation stations. VSC HVDC links can enhance the reliability of the power systems.

The VSC technology can also be used in combination with conventional HVDC. Tapping stations on a conventional DC line can be built with VSC technology, for example at locations with weak AC networks or AC networks without any generation.

Due to the fact that overhead lines in Africa are frequently exposed to lightning strikes and bush fires, the DC line fault clearing system will be further developed. It is foreseen that the next project will be equipped with a semi-conductor based DC breaker which will act extremely fast for DC line faults and isolate the DC line without blocking the converter valves. Thereby the SVC functionality will remain during the fault clearing.

VI. CONCLUSION

The implementation of the Caprivi Link HVDC project has provided an important regional interconnection in the southern African electricity network. The installation of the VSC HVDC scheme has enhanced the stability and assisted with the prevention of blackouts of the extremely weak AC networks that were connected by the scheme. The VSC converters also provide very robust voltage support when inherent voltage collapse situations arise and give stable frequency support to island or passive network conditions, thereby preventing eventual blackout.

VSC HVDC technology is ideal for connecting weak AC networks and there are likely to be further applications for similar schemes in Africa.

It is important that proper geological, soil and interference investigations are carried out to select suitable sites for the earth electrodes at an early stage in the implementation of an HVDC scheme. Two different types of electrode design, based on differing ground conditions close to the converter station sites, have been described. One design is based on ionic conduction through the ground water and the other is based on electronic conduction from the electrode material to the graphite bedrock. Test earth electrodes have been constructed for the Caprivi Link scheme and initial operating experience with the test electrodes has been successful. There are significant advantages with operation with electrodes on a temporary or permanent basis. There can be significant savings in losses and they provide operational flexibility. With proper site selection and design it is foreseen that earth electrodes could be used for future HVDC schemes in Africa.

Although there have been some teething problems in the initial operation of the scheme, the operational experience of the Caprivi Link has been satisfactory.

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