Paper presented at the 6th Southern Africa Regional Conference,
in Cape Town, South Africa, August 17-21, 2009

21 rue d'Artois, F-7508 PARIS
http://www.cigre.org

Paper P107

Cigré 2009
6th Southern Africa
Regional Conference

UPGRADE OF THE APOLLO HVDC CONVERTER STATION

P. GOOSEN
Eskom Holdings Limited
(South Africa)

C. REDDY
Eskom Holdings Limited
(South Africa)

B. JONSSON
ABB AB
(Sweden)

T. HOLMGREN
ABB AB
(Sweden)

O. SAKSVIK
ABB AB
(Sweden)

H. BJORKLUND*
ABB AB
(Sweden)

SUMMARY

Apollo is the inverter end of the Cahora Bassa HVDC scheme. It is situated in RSA while the rectifier is at the Songo Station 1414 km to the North in Mozambique. The present rating of the HVDC link is 1920 MW at ±533 kV.

In 2006 Eskom placed a contract with ABB for the replacement of the eight six pulse converters and the two AC filters, while retaining the old transformers and the DC yard equipment including the smoothing reactors. A basic principle was that none of the renewed equipment should become obsolete in the future as the Cahora Bassa HVDC link has the potential to be uprated all the way to 3960 MW by using the present full current rating of the line and extending the voltage to ±600 kV.

The equipment supplied by ABB included outdoor, water cooled, thyristor valves capable to handle 3300 A using 5" 8.5 kV electrically triggered thyristors. They are presently rated for 533 kV operation but are prepared to be upgraded to 600 kV by adding thyristors inside the existing housings. The control system is ABB's well proven Mach 2 system that is exceptionally well suited for this kind of upgrades [1].

Due to the structure of the Apollo station with 8 series connected 6-pulse bridges it was possible to perform the installation and commissioning in two 6-pulse groups at a time in order to minimize the disturbance of the power transfer.

The system performance since refurbishment has improved remarkably as a result of the new valves and the new control equipment.

KEYWORDS

HVDC - Upgrading – Refurbishment

MOTIVES TO PERFORM THE UPGRADE

The main thrust of the specification and the selected solution was to enhance the RAM (Reliability, Availability and Maintainability) of the complete Apollo Inverter station and ensure that the new solution integrates seamlessly with the retained Songo Rectifier station.

The RAM target was in principle achieved by:

- reducing the total number of HVDC bushings (72 OIP to 24 RIP),
- housing the reduced number (48 gapped to 24 ZnO) of DC arresters inside the protected environment of the new valve containers
- eliminating the need for Over Current Diverters (I^2t protection for the old first generation thyristors),
- reducing the communication channels with the valves from 24 to 8,
- eliminating 24 pneumatically operated earthing switches
- eliminating 24 75Hz auxiliary transformers for the magnetic firing systems.
- Installing 1 728 five inch thyristors capable of 3300A vs the old 25 728 (12 864 pairs) of 35 mm thyristors each rated for only 900A. Almost 15 times fewer components.
- Whereas the old design required AC voltage measurement for each bay (10 bays with 30 magnetic VT units) in the station, the new integrated design derives the voltage from two sets (6 units) of low burden CVT's installed on the two bus sections exporting the power into the Eskom Grid. Eliminating these more than 30 year old suspect oil-paper insulated devices removed a worrisome risk and maintenance concern.

THYRISTOR VALVES

The first generation thyristors applied for the original design were critically rated because at that time the thyristor valve design had to match the top power and current ratings of the mercury arc technology at its zenith. Various extreme control and protection measures were therefore applied. E.g. two parallel thyristors, for each 900A were required for the 1800A rating; up to 280 pairs had to be connected in series for the 133kV voltage rating. It had to be ensured that all pairs were always conducting especially after transients. In special fault cases the I^2t rating were not to be exceeded while waiting for the opening of the AC breakers and thus so-called Over Current Diverters (switches unique to the scheme that could close in 4ms) to short circuit the converter transformers had to be applied. I^2t ratings applied during switching in and out of the converters (duration of bypass operation) had to be controlled and limited. Similarly I^2t ratings during commutation failures had to be strictly managed. For the latter fast and reliable communication was essential for transferring rapid commands to the rectifier in order to shut down or reduce the current during the commutation failures. Other special inverter protection also relied on these rapid current reduction orders. The protection for the inverters required responses within at most 30ms. This tight timing was imposed on protection related to the valve cooling system and failure of auxiliary supplies. With modern the replacement all these restrictions have been lifted and the water-cooled thyristors can now tolerate 10 seconds without water flow. Instead of employing motor-generators or high power UPS systems for 75Hz uninterruptible power supplies for critical systems, the new dual-redundant computer-based control and protection system now only needs dual redundant 220V DC batteries for all auxiliary supplies.

Picture 1 Inside a valve enclosure

One of the most important goals with the design of the new thyristor valves, was to integrate them into the present station layout, and to reuse as much of the surrounding equipment as possible. As ABB has a vast experience of using enclosures for valves in similar applications, the choice became to use ABB's modern state of the art thyristor valves and combine three transportable enclosures to make up one valve housing for a complete six-pulse group positioned on two of three old valve tables. The space saved by removing one old table for each valve group gave place for the new cooling towers. Enclosures containing both cooling system and valve control for two groups are also placed in close vicinity right below the valve groups. Cooling water and triggering signals (transmitted through optical cables) and dried air for ventilation are fed into the valve housings by using ABB's patented communication channel between ground and valve potential.

Despite the age, maintenance requirements and rating issues of the retained plant (Converter transformers, DC yard pneumatic switchgear, smoothing reactors, telecommunication equipment with their HV coupling and filtering as well as the DC surge capacitors and the associated DC filtering), it was decided to invest in a higher rating for the thyristors and their cooling systems with the aim to retain all options of a future potential upgrade to 3300A/±600kV. In this process the insulation coordination systems were designed and tested to maintain the upgradeability to ±600kV (additional 12.5% above on original +/-533kV transmission voltage). The choice of 3300A is based on the fact that the original conductors are designed for 3300A/ in support of the parallel mode operation and the judgement that it should be possible to upgrade the line insulation as other HVDC systems have done successfully (for example the Pacific Intertie [2]) in order to reduce future losses at the higher current – Line insulation studies are presently in progress.

The converters are also designed for a future gradual exchange with uprated transformers that may have different characteristics and ratings.

Eliminating the 2 million litres of oil associated mainly with the oil-filled and oil-insulated valves and their cooling systems, removed an important environmental, fire and safety risk. An explosive failure of any of the large population of suspect OIP bushings had the potential of triggering an avalanche of oil fires between the converters and thus potentially destroying the complete converter station.

AC FILTERS

The old ac filters had 2 banks, each 167 MVAr, with branches tuned to 5th, 7th, 11th, 13th and High Pass. One old filter could handle the harmonics from 1 pole and left little margin for absorption of network harmonics. Thus both were required to support the full DC power. Their RAM imposed severe restrictions on the reliability of the HVDC import. Combined with the restriction of being able to operate only in a narrow frequency band of approx. ±1Hz they imposed an unacceptable risk for creating an avalanche of power loss following other major incidents in Eskom. The filter capacitor replacement decision was also strongly motivated by the externally-fused mixed-dielectric PCB capacitors and their tailor made protections which were becoming increasingly detrimental to the station RAM.

The two new AC filters with air-core reactors and fuseless capacitors each have sufficient rating to filter the harmonics associated with the full imported power whilst providing for 6-pulse filtering for one bridge.

Both filters also have the capacity to handle an ultimate rating of 3960MW, but one additional filter would be needed to provide redundancy.

On top of this generous capacity is provided for the harmonics potentially imposed by other customers. The total reactive power generation per filter has also been increased from 167 to 300MVar. This matches the ratings of the existing capacitor banks.

The filtering and MVAR redundancy has already been proven very valuable in sustaining the DC power and the Grid during the project construction phase as well as for maintenance and project retention work.

CONTROL AND PROTECTION

For maximum flexibility and best RAM of any possible power, the new control and protection systems are designed for any conceivable configuration of the main system topology: This includes normal bipolar and monopolar operation; crossed over monopolar operation utilising the internal cross over link in either station, utilising any one of the two lines for any mode of monopolar operation. It was also possible to reintroduce the original parallel operation of two Apollo Poles on one line which had been unavailable for many years. This feature may proof of significant benefit if there would be extended outages of any of the two monopolar lines for the sake of upgrading it to higher power/voltage/current. In that event it would be possible as per the original design of the scheme to operate both poles together with up to the 3300A which is the design rating of the lines. This would also require of course that the earth return current and the earth electrodes in both stations sustain this current.

Control features

Without point-on-wave switching on the 275kV breakers for the converters the closure of the transformers often imposed extraordinary inrush current and stress on the equipment and in particular on the transformers. In the refurbished system where the original air-blast breakers have now also been replaced in a parallel project aimed at eliminating maintenance intensive station compressor systems, point-on-wave switching has been included in the controls. Furthermore the new converters can be left connected in a standby mode with AC and DC voltages on the transformers and valves, and thus not only are the number of switching operations for different components reduced but when breaker switching is necessary the transformer inrush currents are significantly attenuated.

An important feature of protecting and repairing the main line and insulated EW (Earth Wire) is to locate the position of faults (imagine 2 x 1414km of 11kV insulated EW to be maintained for the sake of good power line carrier telecommunication!). The Line Fault Locating system (LFL) is now designed for the automatic exchange of data from sensors at the terminals and the PLC repeater station and to present the operators with the fault location to within one line span. The measurements on the EW can only be done under dead line conditions when flashovers are induced with a separate DC source.

As fulfilment of statuary requirements, an earth fault detection and alarm system (ELIS) has been installed on the 17km of the Apollo earth electrode line. It operates on the principle of measuring the impedance seen by an injected 14 kHz signal.

Another new functionality for the system is that the converters and the controls are designed to allow open circuit voltage testing of the DC lines and of the bridges.

Of course features to easily take bridges in and out of operation while the pole is running is available as well as a very useful new feature that allows two bridges to be swapped (one inserted and one removed from the circuit at the same time). With this feature bridges can be taken out without any influence on the rectifier.

Converter starting procedures

Due to their I^2t sensitivity, the old converters required rapid and complex starting sequences involving measurement of DC voltages. The new converters start in a short-circuited mode and balance this current with the load current before finally linking the converter into the DC circuit. The new design made the eight voltage dividers inside the two Poles redundant, however, it was decided to retain them for additional performance analysis after their secondary circuits were greatly simplified with new electronics. These measurements will be sacrificed for cost reduction during a future voltage upgrade of the Poles when the DC yard switchgear and other equipment would have to be replaced. The original and essential line voltage dividers were retained for the present upgrade but will have to be replaced and ideally duplicated to complete the dual redundancy concept of the Mach 2 control and protection system.

By retaining the original station layout and outdoor platforms based on eight 6-pulse converter bridges, the reuse of existing civil works could be maximised. The new dual-redundant control and protection systems are now based on pseudo 12-pulse converter pairs formed by combining adjacent star-star and star–delta converter transformer converters into common systems while yet maintaining the independence of the original 6-pulse topology. This control topology has been extended to the thyristor cooling where each “12-pulse group” now has one cooling system. This simplification reduced the total number of cooling systems (fans and pumps) from eight to four while enhancing the redundancy and RAM, providing 100% standby variable-speed water pumps and 25% fan capacity based on 40ºC ambient. Having two converters on one cooling system also creates additional redundancy when one converter is off. For the control and protection the topology means that the controls and protection are halved by sharing systems for two bridges yet at the same time it is doubled for the dual redundancy.

The original converters required operation of all the associated switchgear of a bridge for energising or isolation sequences. This imposed a large number of switchgear operations especially since the number of converters per pole in opposite stations need to be matched for the best operating conditions. That is whenever a converter in Songo is switched a corresponding converter in Apollo has to be switched and vice versa.

Operation without telecommunication

Despite all ongoing efforts to ensure most reliable communication, the control and protection is now designed to operate safely and reliably also without any data communication between the stations using ABB's patented back-up synchronous mode of operation. Apollo can now be configured and started (provided Songo bypasses some original interlocking) and operated during a total lack of communication bar verbal coordination to set up and verify start up configurations. This capability is valuable because neither the remote power line carrier repeater in RSA, nor the insulated earth wires essential for the communication, can be relied on to function 100% of the time. They simply cannot be maintained /repaired or restored in a short time. The HVDC power can no longer "be held at ransom" by lacking or poor quality communication. If communication is lost during operation, power transfer continues undisturbed although the exchange of information per HMI screens will no longer be updated. If the system is stopped under such conditions some interlocking in Songo will have to be overridden while the Apollo operators will be able to set up the preconditions through the normal HMI.

Although the HVDC system can safely remain in operation, the fact that the data from Apollo to Songo would be interrupted with the loss of telecoms means that so-called "Angle Control" of the GMPC scheme [3] cannot be safely maintained. This operation mode requires measurement of the voltage angle between Apollo and Songo to allow damping to be applied.

OTHER EQUIPMENT

A few other pieces of equipment were exchanged, like arresters which are able to handle future rating, CVT:s for ac voltage measuring, new DCCT for dc current measuring. The flexible connectors between transformers and valves were upgraded to a future rating of 3300 A.

INSTALLATION AND COMMISSIONING

The installation of the new thyristor bridge enclosures was the most challenging part of the installation work for the electrical equipment as it should be performed in a live AC/DC yard. The concept was to replace the existing thyristor bridges by reusing the existing foundations and support insulators for the new thyristor bridges. The installation work implied replacement of two existing thyristor bridges simultaneously in following sequence:

1) Dismantling work of two existing bridges
2) Installation of new thyristor bridge enclosures for two bridges
3) Installation of one common thyristor bridge cooling system for two bridges
4) Installation of thyristor valve control and other control and protection equipment

The work was performed while other thyristor bridges as well as neighbouring bridges were in service. First the thyristor valves were assembled into the enclosures, done at the side while the containers were at ground potential. Then the valves were equipped with bushings and other accessories.

Picture 2 Installation of bridge 3 while bridge 5 and 7 is in operation

The old valve tanks had first to be emptied from oil and then lifted from their positions on to a truck. Then other equipment as auxiliary power feeding and signalling transformers for the valve electronics (attached to valve tanks, at HV potential) was removed.

All flexible connections between transformers and valves were taken down to be rearranged and to give access for the cranes to lift new valve enclosures to their positions.

Each separate valve enclosure containing 2 valves were lifted onto the support porcelains, and three enclosures were docked together and thereby forming a 6-pulse bridge.

Commissioning of the new converters was organised in such a manner that it was never necessary to interface new and old control and protections systems in any Pole although there were periods where old and new equipment were operating in separate Poles. Pole 2, the first Pole to be tackled, was taken out of operation coincident with the decommissioning and installation of the new equipment for the first AC filter. During this time the Power had to be restricted to that supportable with the capacity of a single AC filter. After the first Filter became available it was possible to operate any number of bridges without restriction. The refurbishment of the second Pole (Pole 1) was made on two bridges at a time with the others in operation. During this time there was an opportunity to increase the number of converters in operation because Songo had an extended outage of a bridge in Pole 2 due to transformer failures. By physically crossing over the two monopolar lines outside Apollo the full pole 1 capacity in Songo could be matched to Apollo's pole 2 capacity.

This operation was successfully carried out and by modifications in the controls and the communication systems the power of an extra bridge (240MW) was gained for a period of some 60 days during the time that Eskom had severe restrictions on its generating capacity. As soon as all the converters were available in Apollo the system was returned to normal bipolar configuration. The features developed for the so called X-over operation are now a permanent feature of the design and if suitable switch gear would be installed at Apollo this topology could be configured as a standard operating option. This would be of benefit if there should be a double contingency outage i.e. a mismatched outage in opposite poles in the opposite stations.

Picture 3 The Apollo station with new outdoor thyristor valves

SYSTEM PERFORMANCE

The system performance since Apollo refurbishment has improved remarkably. One of the main elements is that the previous high sensitivity of the control and protection to protect the highly sensitive thyristors has been eliminated. The old system was designed to protect a valve with "emergency firing", which is inducing a controlled commutation failure. Also to retrigger the valve in the event of suspect recovering conditions that may compromise proper blocking of the valve. There was only one measuring and firing system per valve. This meant that even mild voltage dips on the AC voltages lead to commutation failures and this triggered the automatic response of the VDCR (Voltage Dependent Current Reduction) which function it is to reduce the current transiently for the safe recovery of the commutation process. These violent control reactions which mostly occur on both Poles simultaneously are equivalent to a full load rejection of the Cahora Bassa generators. They required the rectifier poles to run through the range of control angles with the generation of high harmonics while the filters may be lost due to the consequential loss of the filters by the frequency excursion. The severe distortion normally challenges all the systems and often there may be some control issues that lead to tripping of an oversensitive system. With the large reduction in the number of such events the overall HVDC system has become much quieter. Overall the improvement seems disproportional to the fact that only one half of the system (that is Apollo) has been refurbished. The fact that long standing oversensitive control issues have probably also been resolved in Songo, seems to be also a factor in the overall good performance to date with the new systems in Apollo.

BIBLIOGRAPHY/ REFERENCES

[1] Bjorklund, H,"Upgrading the Control System of the Square Butte HVDC Transmission", (2007 Cigre Symposium, Osaka Japan)

[2] Eriksson C. "Critical Intertie", Power Engineering International, September, 2005

[3] Goosen, P.V.; Riedel, P.; Strauss, J.W, "GMPC enables energy transmission over interconnected SAPP grid", (IEEE Transactions on Power Delivery, Volume 18, Issue 3, July 2003 Page(s): 945 – 952)