Feasibility of increased power via Apollo Songo HVDC scheme

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There is a potential for new generation capacity in Mozambique due to availability of gas and hydro fuels. A possibility of transporting some of this power to South Africa exists. The key question that follows is how far can the existing Apollo Songo HVDC infrastructure be used to transport some of the expected power. In this paper feasibility results will be presented for the studies done on a number of possible scenarios for transporting of the power via the scheme from Songo to Apollo.

The Apollo Songo HVDC scheme was first commissioned in 1979 [1]. However, due to political instability in the region, it remained unavailable for operation, and could only be brought back into service in 1990. Fig. 1 below shows the location of the scheme and Fig. 2 shows the electrical layout of key components of the scheme.

Fig. 1: Location of Apollo Songo HVDC scheme.

A very high-level description of the scheme in its present form is as follows:

Power is generated at a Cahora Bassa, a hydro power station. The station is linked to the HVDC scheme via 220 kV lines that transmit power to the sending, rectifying side at Songo in Mozambique.

Songo Converter Station has 8 Graetz bridges (4 for each pole) that convert AC power to DC power. Each bridge is rated at 133 kV, giving the rated DC voltage of 533 kV for each pole. At present, the sending end power from Songo is 1920 MW.

Apollo Converter Station is the receiving end of the scheme for the power sent from Songo. It also has 8 Graetz bridges (4 for each pole) that convert AC power to DC power. Each bridge is rated at 133 kV, giving the rated DC voltage of 533 kV for each pole. At present, the receiving end power at Apollo is 1800 MW.

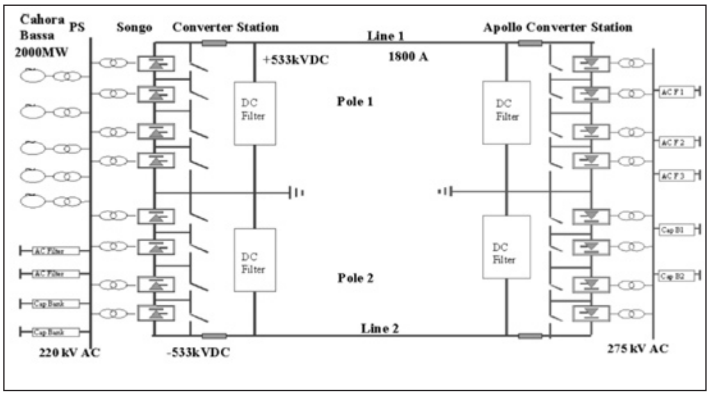

Fig. 2: Layout of Apollo Songo HVDC scheme.

The DC line linking Songo and Apollo is rated at ±533 kV. It has a length of about 1400 km, with about 900 km on Mozambican side and 500 km within borders of South Africa. The conductor used is of type quad Zambezi, with a current rating of 3600 A for continuous operation.

The existing Apollo Songo HVDC infrastructure has been performing unacceptably, and a refurbishment project is in progress at present. The refurbishment scope that is relevant to this paper is that converters will be upgraded to a thermal rating of 3600 A. Initially approved for upgrade from 1800 A to 2500A, a risk decision to upgrade from 1800 A to 3600 A was taken in light of future possibilities to increase imports. The additional cost of upgrading from 1800 A straight to 3600 A, rather than to 2500 A and then to 3600 A, was considered unfavorable, as overall it would have been costlier to upgrade in stages.

Problem definition

Some major developments in terms of generation are expected to take place in Mozambique. There is availability of gas and hydro fuels which can be used for creating this capacity. A possibility of transporting some of the power to South Africa exists through trading of electrical power. The generation is expected to be commissioned around 2014. The key question that follows is how far the existing Apollo Songo HVDC infrastructure can be used to transport some of the expected power from Mozambique to South Africa. The line has an ultimate thermal limit of 3600 A and at present it only operates at 1800 A. The specific questions that need to be answered are as follows:

- Is it possible to operate the HVDC link in year 2014 at ±533 kV at 3600 MW during peak and off-peak conditions, and if so what additional network infrastructure is required?
- Are there any benefits in raising the DC link rated voltage and operating it at ±600 kV at 3600 MW during peak and off-peak conditions, and if so what additional network infrastructure is required?
- Can the link be operated at ±600 kV at 3800 MW during peak and off-peak conditions, which represents the thermal limit of the line, and if so what infrastructure is required? Here, it is assumed that the loading will be limited to 3300 A.

This paper will give details of the assessment done and results obtained for the studies that were carried out to address the above questions. For each scenario, steady state and transient stability studies were done to asses if there are any constraints to operate the link. If any constraints exist, proposals of infrastructure to relieve them are made. Finally, the high level infrastructure needs are discussed.

Scenarios

The following scenarios were studied in steady-state:

- *Scenario 0 & 0a:* Year 2007 ±533 kV at 1800 MW peak and off-peak: To set the base for power flows and voltages.
- *Scenario 1 & 1a*: Year 2014 ±533 kV at 3600 MW peak and off-peak: To determine system requirements for operating in this scenario.
- *Scenario 2 & 2a*: Year 2014 ±600 kV at 3600 MW peak and off-peak: To determine benefits of uprating voltage to 600 kV at 3600 MW.
- *Scenario 3 & 3a*: Year 2014 ±600 kV at 3800 MW peak and off-peak: To determine system requirements for operating in this scenario which is the limit of thermal rating of the line.

Studies were carried for system healthy and N-1 contingency conditions. About seventeen N-1 contingencies around the Apollo end of the scheme were analyzed. The software PSS/E was used for steady-state analysis.

For scenario 1 and 2, losses were calculated and noted for further use in assessing the economics of uprating the DC line voltage from ±533 kV to ±600 kV.

Studies were also done for transient stability for scenarios 1, 2 and 3. Simulations were done for peak conditions as these are considered most severe for transient stability.

Transient stability studies were also carried out. Again, PSS/E software was used to simulate dynamic events. The HVDC link controls were modeled as a CDC4 [2] standard HVDC controller model that comes with the software. The main function of the CDC4 HVDC controller is to maintain a specified power (or current) transfer dynamically. Under abnormal conditions, the controllers take the necessary action to protect the link from commutation failures as well as high DC current.

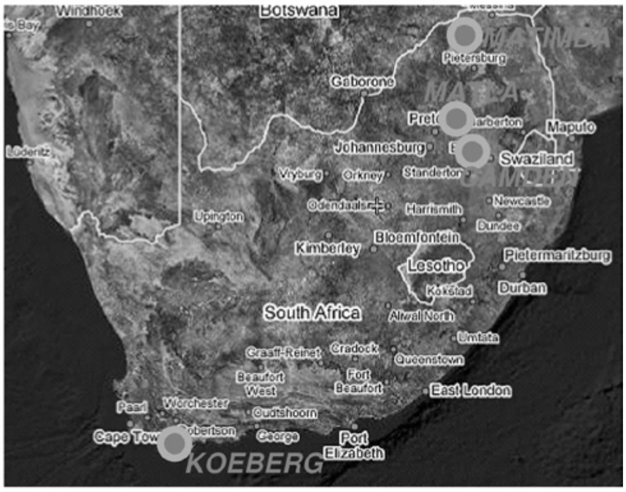

Fig. 3: Locations of substations for which machine angles were monitored.

A three phase fault at Apollo 275 kV busbar, followed by a trip of Apollo Njala 275 kV line, was simulated to test stability. The following procedure was followed in the simulations:

- Pre-disturbance run for transient stability studies up to 1s
- Apply fault at Apollo 275 kV busbar
- Clear disturbance after 100 ms
- Trip Apollo Njala 275 kV line
- Post-disturbance run is 30 seconds
- Matla machine 1 was used as the reference for all rotor angle measurements.

Monitoring

In the vicinity of Apollo substation, substation voltages and equipment loadings were monitored to assess if there were no violations of specified voltage limits and equipment loadings. All lines and substation up to two busbars away from Apollo 275 kV substations were monitored.

For transient stability simulations, network behavior was monitored as follows:

- *Machine angles*: Matla machine 1, Koeberg machine 1, Matimba machine 1, and Camden machine 1 (Refer to Fig. 3 for locations of machines).
- *Busbar voltages*: Apollo 275 kV and 400 kV, Njala 275 kV, Verwoedburg 275 kV, Esselen 275 kV, and Croydon 275 kV busbars. These locations are not more that 2 substations away from Apollo 275 kV busbar.

Results

Generally, the loadflows showed that equipment loadings and voltages remain acceptable in the system for both system healthy and contingency conditions. There is a reduction in the power (MW) that comes from the Eskom system via the Apollo 400/275 kV transformers into the Apollo 275 kV busbar as the imports increase from 1800 MW to 3600 MW or 3800 MW as demonstrated in Fig. 4. The effect is that the 400/275 kV transformers at Apollo experience a reduction in the power that goes through them as the imports increase. This situation is observable for all theree scenarios.

Specific findings relating to the various scenarios are summarized below.

Scenario 1 and 1a: Year 2014: ±533 kV at 3600 MW

The increase in imports via the HVDC scheme requires reactive power to be supplied for the conversion process to be increased by 1868 Mvar (from 2 x 595 Mvar to 2 x 1529 Mvar) at Songo and by 2614 Mvar (from 2 x 541 Mvar to 2 x 1307 Mvar) at Apollo.

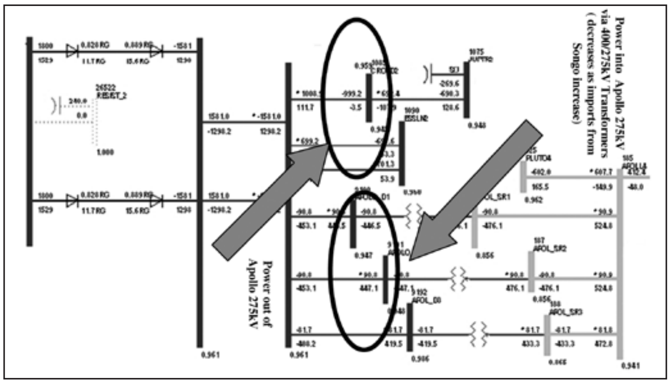

Fig. 4: Power via 400/275 kV transformers decreases as imports increase.

At present the AC to DC single phase transformers at Songo are rated 96,7 MVA and at 90,8 MVA at Apollo. These transformer will need to be replaced with bigger units to accommodate increased power imports of 3600 MW + j3058 Mvar (4723 MVA or 196 MVA per single phase transformer units) injected at Songo and about 3200 MW + j2614 Mvar (4131 MVA or 172 MVA per single phase transformer unit) at Apollo. Transient stability results are given in Fig. 5 and Fig. 6.

The results show that transient stability is maintained in the system following the fault and its subsequent clearing. The voltages also recover quite well to acceptable levels. The voltage profile can be further enhanced by utilising a fast acting device such as an SVC. The potential need for this will be further analysed and this may mean that a portion of required Mvar can be catered for by the device.

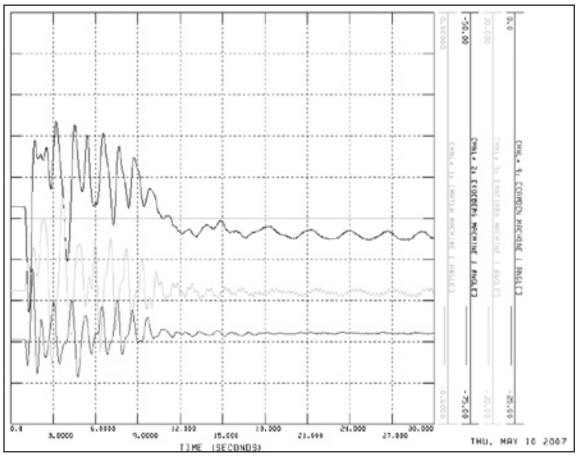

Fig. 5: Machine angles for scenario 1.

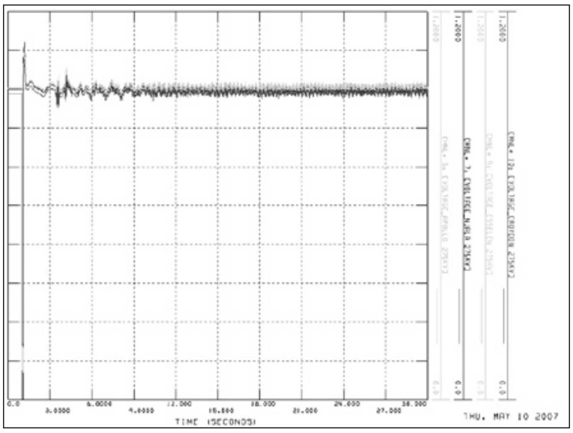

Fig. 6: Busbar voltages for scenario 1.

The high level scope of work involves the following:

- *Shunt capacitor compensation*

  Install new 1868 MVAr at Songo (portion of this possibly via SVC)

  Install new 1532 MVAr at Songo (portion of this possibly via SVC)
- *Upgrade busbar*

  Upgrade 220 kV busbars at Songo

  Upgrade 275 kV busbars at Apollo
- *Upgrade AC to DC transformers*

  At Songo, upgrade 96,7 MVA units to 197 MVA

  At Apollo, upgrade 90,8 MVA units to 172 MVA

Scenario 2 and 2a: Year 2014: ±600 kV at 3600 MW

The increase in imports via the HVDC scheme requires reactive power to be supplied for the conversion process to be increased by 1540 Mvar (from 2 x 595 Mvar to 2 x 1365 Mvar) at Songo and by 1278 Mvar (from 2 x 541 Mvar to 2 x 1180 Mvar) at Apollo.

The AC to DC transformers must be sized to accommodate 3600 MW + j2730 Mvar (4518 MVA or 188 MVA per single phase unit) at Songo and about 3300 MW + j2360 Mvar (4057 MVA or 167 MVA per single phase unit) at Apollo.

Transient stability results are given in Fig. 7 and Fig. 8. The results show that transient stability is maintained in the system following the fault and its subsequent clearing. The voltages also recover quite well to acceptable levels.

The voltage profile can be further enhanced by utilising a fast acting device such as an SVC. The potential need for this will be further analyzed and this may mean that a portion of required Mvars can be catered for by the device.

The network losses are calculated to be 2559 MW, which represents a saving of 92 MW in relation to scenario 1. These losses can be achieved if network voltage is raised to ±600 kV voltage at an estimated cost of R200-million, by upgrading the insulation to 600 kV and lifting the towers.

The financial cost of doing the voltage upgrade was compared to the benefits of savings in losses by using the Operating Cost Reduction method [3]. The following assumptions were made in establishing the net present value of saving in losses and net present value of implementing the upgrade:

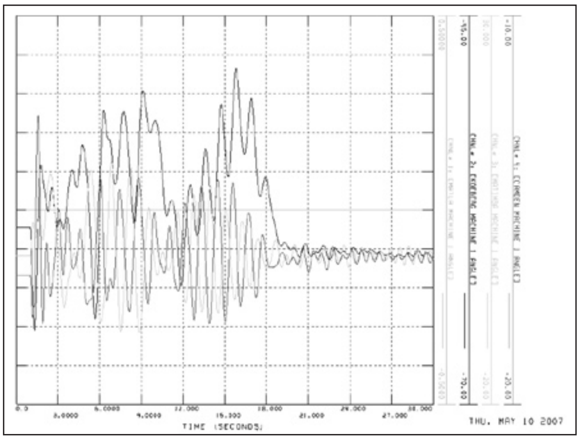

Fig. 7: Machine angles for scenario 2.

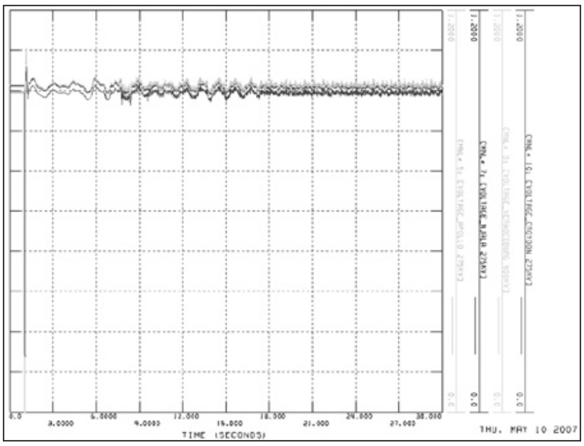

Fig. 8: Busbar voltages for scenario 2.

- The cost of uprating and lifting the line is R200-million.
- The saving in losses is 92 MW.
- The Annual Average Long Run Marginal Cost of Generation (AALRMCG) is used in the calculation of the value of losses [4].
- The system load factor of 0,73 is also used.
- Annual operating and maintenance (O&M) costs are taken to be 0,5% and 1,5% for lines and substation respectively of capital expenditure per annum.
- Corporate tax is 29%.
- Wear and tear for substation equipment is 40% in year 1 and 20% thereafter (next three years). For lines, wear and tear is 5% per annum for 20 years.
- The nominal discount rate is 11,5% per annum, giving annuity factor of 7,82%, with the life-cycle of equipment assumed to be 25 years.
- Costs are in nominal rands.

The year 2007 net present value (NPV) of project cost of uprating the voltage and lifting the conductors is R 493-million and that of savings in losses is R1 876-million. The project therefore has year 2007 NPV net benefit of R1 383-million. The key conclusion is that major financial benefits will be reaped by Eskom if the link is uprated to 600 kV due to a substantial reduction in power system losses.

The high level scope of work involves the following:

- *Shunt capacitor compensation*
  Install new 1540 Mvar at Songo (portion of this possibly via SVC)
  Install new 1278 Mvar at Songo (portion of this possibly via SVC)
- *Upgrade busbar*
  Upgrade 220 kV busbars at Songo
  Upgrade 275 kV busbars at Apollo
- *Upgrade AC to DC transformers*
  At Songo, upgrade 96,7 MVA units to 188 MVA
  At Apollo, upgrade 90,8 MVA units to 169 MVA
- *Uprate operation from 533 kV to 600 kV*
  Uprate insulation to 600 kV level
  Lift the towers

Scenario 3 and 3a: Year 2014: ±600 kV at 3800 MW

The increase in imports via the HVDC scheme requires reactive power to be supplied for the conversion process to be increased by 1884 Mvar (from 2 x 595 Mvar to 2 x 1537 Mvar) at Songo and by 1524 Mvar (from 2 x 541 Mvar to 2 x 1303 Mvar) at Apollo.

The AC to DC transformers must be sized to accommodate 3800 MW + j3074 Mvar (4887 MVA or 204 MVA per single phase unit) at Songo and about 3500 MW+ j2606 Mvar (4363 MVA or 182 MVA per single phase unit) at Apollo.

Transient stability was maintained for the fault considered (Fig. 9 and Fig. 10).

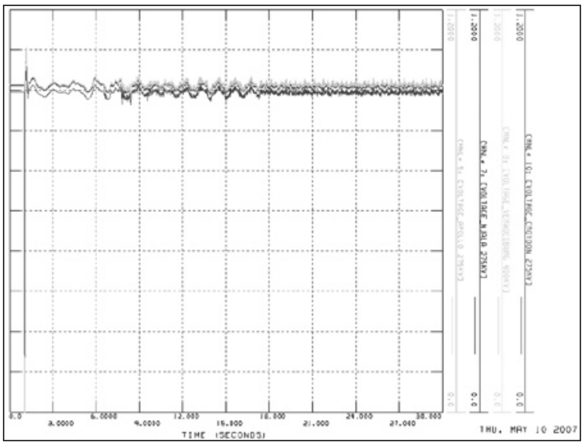

Fig. 9: Machine angles for scenario 3.

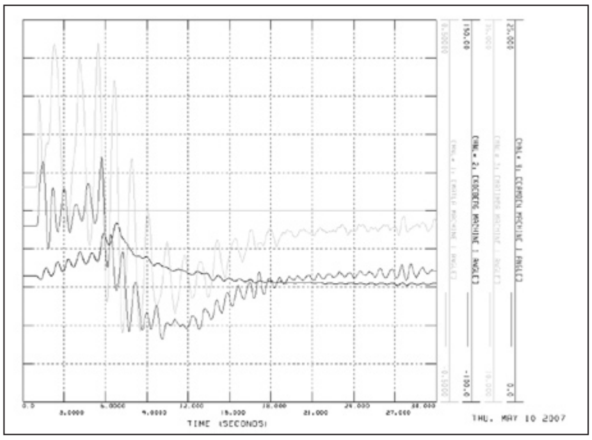

Fig. 10: Busbar voltages for scenario 3.

Voltages recover quite well following clearance of fault. Although voltages do recover, the profile obtained does show that the system requires some assistance to keep voltage within range. Further studies will be done to see if a fast acting device, for example, will be necessary to ensure a smoother voltage profile. This may mean that a portion of the reactive power may have to be provided via a fast acting device such as an SVC.

The high level scope of work involves the following:

- *Shunt capacitor compensation*
  Install new 1884 Mvar at Songo (portion of this possibly via SVC)
  Install new 1524 Mvar at Songo (portion of this possibly via SVC)
- *Upgrade busbar*
  Upgrade 220 kV busbars at Songo
  Upgrade 275 kV busbars at Apollo
- *Upgrade 24 single phase AC to DC transformer units*
  At Songo, upgrade 96,7 MVA units to 204 MVA
  At Apollo, upgrade 90,8 MVA units to 182 MVA
- *Uprate operation from 533 kV to 600 kV*
  Uprate insulation to 600 kV level
  Lift the towers

Conclusions

Feasibility studies have been done on the possibility to operate the existing HVDC link for various scenarios at higher import levels than presently is the case. The following conclusions can be made on the basis of the study. Studies show that it is feasible to operate the existing Apollo Songo HVDC link at ±533 kV at 3600 MW. The key requirements are additional reactive power for the conversion process, upgrade of AC to DC transformer, and upgrade of the AC side busbars at Songo and Apollo.

Major techno-economic benefits will be reaped if the link voltage is raised and the link is operated at ±600 kV at 3600 MW.

- The first and the biggest benefit is that of savings in losses over the life-cycle of the scheme which translates to major economic benefits. The benefits far outweigh the cost of re-insulating.
- Most of the power from the sending end is able to reach the receiving end.
- Smaller reactive power is required at converter stations.
- The transformer ratings are, as a result, also allowed to be smaller.

Finally, it is shown that operating at ±600 kV at 3800 MW can be realised. A note can be made that even at this higher operating point the losses are less than operating the link at ±600 kV at 3800 MW.

More studies will be done to refine the results presented. For example, voltage profiles seemed to suggest that voltage control is likely to be an issue, and thus one of the issues that will be addressed is assessment of whether there is a need to provide a fast acting voltage control device.

Acknowledgment

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References

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