“System stability improvement in the RSA - Zimbabwe AC interconnection by installation of an SVC”

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The paper discusses background, design, installation and testing of an SVC in the Insukamini substation close to Bulawayo in Zimbabwe.

The SVC is required to provide high speed dynamic reactive power absorption and generation for system voltage control purposes under certain system outages and load conditions.

The paper also describes the design of the SVC, its configuration, control system, protection and auxiliary equipment.

A review of the system test including performance verification, harmonic verification and test of the power oscillation function is also made.

Background

The installation of the SVC was considered at planning of the 420 kV AC interconnection between South Africa and Zimbabwe from Matimba to Bulawayo.

A feasibility study was made by engineers of both of the utilities to be interconnected prior to the issue of the specification for the total interconnection project, of which the SVC was a part project. A model of the interconnected system representing the expected future complexity was studied. Also concerns from neighbour utilities in Mocambique and Botswana were considered during the study work. The study showed the necessity of an SVC with a continuos operating range between 200 Mvar capacitive and 100 Mvar inductive reactive power for voltage control of the Zimbabwe network in general and particularly of the 330 kV network. A fast speed of response was required in order to support the system during post fault recovery periods, i.e. to maintain the voltage by reactive power generation during a fault situation and by reactive power consumption immediately following fault clearance. The SVC is also required to provide power oscillation damping in the ZESA network, e.g. at loss of power transfer from one source and subsditute by import of power from another source.

The SVC is installed in the Insukamini substation and connected to the Zimbabwe 330 kV network close to the coupling point for the 420 kV interconnection to South Africa See figure 1. This 405 km long AC line forms a part of an AC connection in parallel to the Cahora Bassa HVDC interconnection. A control strategy with associated hardware at Songo to ensure stability between Cahora Bassa and South Africa is beeing developed. The installation of the SVC at Insukamini is necessary to control the voltage level and compensate for power oscillations in the Zimbabwe network. The SVC is particularly needed following outages of the import from Cahora Bassa (up to 500 MW on a single line connection). The loss of power from Cahora Bassa will immediately be substituted by imports from South Africa causing a major shift in load on the meshed grid in Zimbabwe (peak load 1900 MW).

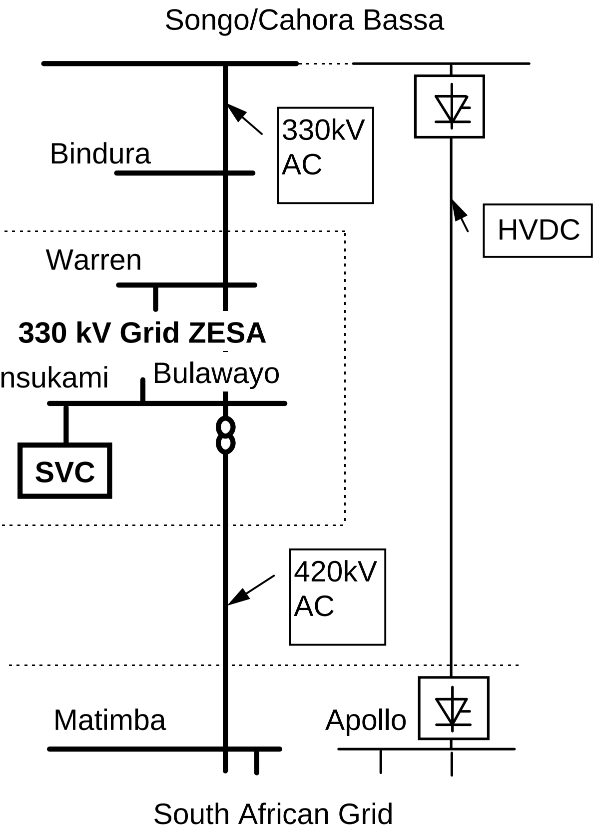

Figure 1. SVC location in the network

SVC configuration

The SVC concept chosen to fulfil the specified function is of the TCR/TSC/filter model shown in figure 2.

Connection to the 330 kV bus is made through a 330/17.5 kV, 200 MVA, step down power transformer. The different branches of the SVC are rated:

- One 150 Mvar TCR
- One 150 Mvar TSC
- One 50 Mvar harmonic filter group

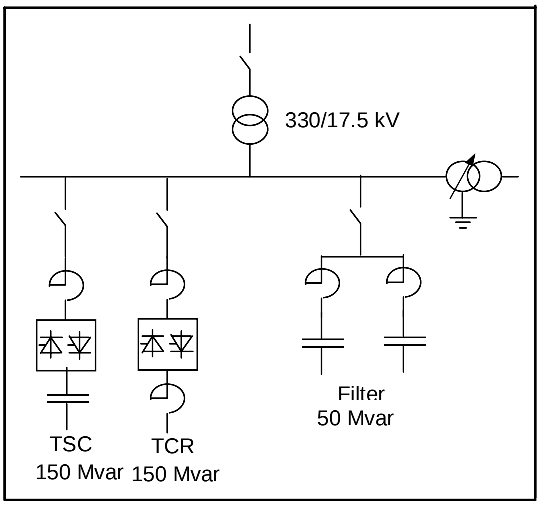

Figure 2. SVC configuration

The required operating range is achieved by control of these three branches. The TSC and the filters together generates 200 Mvar and the TCR after compensating for the 50 Mvar filter power still consumes 100 Mvar reactive power.

The SVC is designed for vernier voltage control over its entire operating range. The V/I characteristic of the SVC is shown in figure 3. The SVC operating range is defined by the following parameters:

- Reference voltage range 0.918 - 1.09 p.u.
- Slope setting range 2 - 10 % (on 200 MVA)
- TCR current limitation
- Primary current limitation

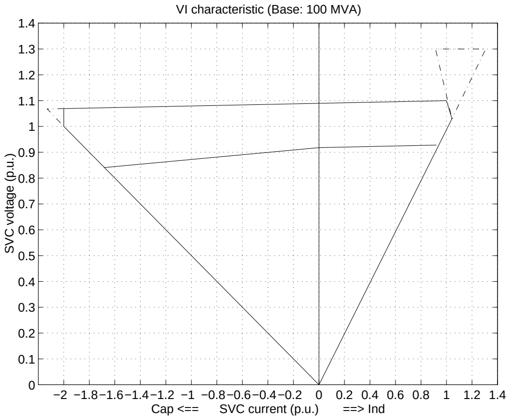

Figure 3. SVC V/I characteristic

The base for the p.u. system used is 100 MVA . The TCR current limitation corresponds to a primary current of 1 p.u. and the primary current limitation is set to 2.0 p.u.

These current limiting functions have certain time delays which means that transiently the operating range in the V/I diagram is not limited by anything but the installed component reactances.

Main circuit design

The main circuit components are designed and rated to cope with the following conditions:

- Max. continuous system voltage 1.1 p.u.
- Design fault current 25 kA (14000 MVA)
- Frequency variations 47 - 52 Hz
- Negative phase sequence voltage 2 %

Beyond that the TCR is controllable up to 1.3 p.u. primary voltage in order to enable efficient voltage control at post fault conditions.

The insulation levels chosen for the SVC components are LIWL 1300 kV at the primary side and LIWL 170 kV at the secondary side of the step down power transformer. Surge arrester protection is provided at both sides of the step down transformer.

Both the TCR and the TSC are Δ-connected while the harmonic filters are arranged in a double Y connection. The TCR reactors are divided into two coils for each Δ-branch, electrically one reactor coil is located on each side of the thyristor valve. The TSC is provided with a current damping reactor which together with the capacitor bank tunes the TSC to 225 Hz, i.e. 4.5 times the fundamental frequency. The TSC-valves are electrically located between the capacitor bank and the damping reactor.

The TCR generates harmonic currents due to phase angle control of the reactor current. The harmonic generation, I_n/I_1, versus firing angle is shown in the diagram in figure 4. Tripplen harmonics are normally short-circuited in the TCR delta connection at symmetrical control of a symmetrical network, therefore they need not to be considered in the filter design. This SVC is symmetrically controlled, however the 2 % negative phase sequence in the network had to be considered at calculation of filter performance. The SVC is allowed to inject less than 35 % of the totally allowed harmonic distortion of 2 % on the network. To fulfil the harmonic performance required, the filter branch is divided into one 35 Mvar 5th harmonic and one 15 Mvar 7th harmonic filter.

To lock the potential at the LV side and to enable selective ground fault indication a grounding transformer has been provided. A combined grounding/auxiliary power transformer design has been chosen. The primary Z-winding is designed to limit the ground fault current to 500 A and the secondary Y winding will supply 200 kVA auxiliary power to the SVC.

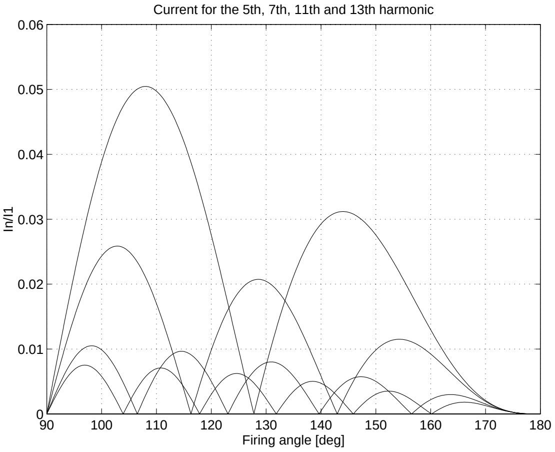

Figure 4. Harmonic generation from a TCR1

Thyristor valves

The thyristor valves are water cooled three phase valve units with indirect light triggered thyristors. The SVC voltage, 17.5 kV, is chosen for an optimal use of the current carrying capability of the thyristors. This resulted in a TCR valve with 10 and a TSC valve with 18 series connected thyristor levels. The current rating of the two valves is about the same. This means that the thyristor type, 4 inch silicon wafer diameter and voltage class 6.5 kV, is the same for both valves , which reduces the need of spare thyristors to be kept in stock. The thyristor type is an adapted standard thyristor commonly used in transmission application SVCs.

The TSC valve is rated for higher voltage handling as extinction of the valve current means that the valve voltage becomes the difference of the phase to phase voltage and the voltage of the charged capacitor.

The thyristor valves are protected against overvoltage. The TCR thyristors are provided with individual VBO-elements (Voltage Break Over) as overvoltage protection. VBO firing of TSC-valveis is undesirable as it involves large current oscillations. Therefore overvoltage protection has been arranged by surge arresters across the valve instead.

The TCR valve is designed to be controllable up to 1.3 p.u. primary voltage and the TSC valve to maintain its blocking capability up to 1.5 p.u. primary voltage

Protective relaying

The protective relay system installed is capable of protecting the SVC down to a minimum fault current level of 2.5 kA. The future expected fault current level is 7 kA.

The principal idea behind the protection scheme is that each part of the plant should be protected by one main and one back-up protection. All major faults should give trip signals to the SVC main breaker and isolate the SVC from the network. The SVC protection principle is shown in figure 5.

The relay with the largest protection zone is the overall differential protection. It covers the plant from the SVC side of the main breaker to the TSC/TCR and filter branches out from the SVC bus. An overcurrent protection acts as a back-up for this differential protection.

The transformer also has a ground fault differential protection and an overfluxing protection relay as well as the transformer guards. The grounding transformer is protected against high continuous current in the neutral.

The TCR and TSC branches are protected by differential protections covering the three Δ-legs. Back up for these are overcurrent protections. Beyond that the TCR-reactors are provided with a thermal overload protection and the TSC has a combined overload and unbalance protection.

The harmonic filter branch is protected by over current protections and capacitor overload and unbalance protections.

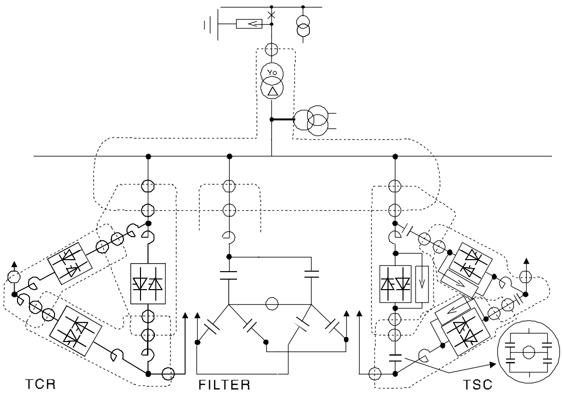

Figure 5. Protection principle

Control equipment

The primary task for the SVC is to provide high speed dynamic voltage control during certain system outage and loading conditions. A typical response time of the SVC on a small step change in voltage is shown in figure 6. A response time of 40 ms or two cycles is valid for small changes however the response time on major changes is shorter, one cycle is reasonable to assume.

One additional important feature of the SVC is the power oscillation damping function (POD), implemented in the control system, which effectively damps power oscillations between the Zimbabwe and South African networks.

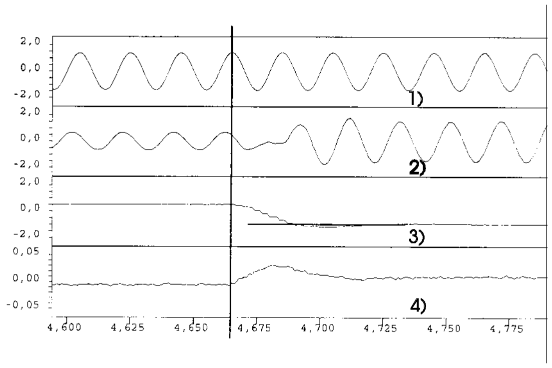

Figure 6. Step response

1) system phase to phase voltage
2) SVC phase current
3) succeptance (reference for the SVC control)
4) system voltage measured by the SVC

The control system receives information of the power flow in the form of three-phase active power. The input signals to the "POD" function are supplied from measuring transformers in the main substation. The signals are evaluated in a special program sequence. The output, the POD reference, is superimposed on the normal voltage control, and will counteract the power oscillations of the system.

The Power Oscillation Damping control is activated if large power oscillations or large power derivative (dP/dt) appear in the transmission system.

The POD transfer follows the formula:

$$\mathrm{POD}(s) = \left[\frac{0.072s}{1+0.32s} \mathrm{x} \frac{1+2.6s}{1+0.32s} \mathrm{x} \frac{1}{1+0.60s} \mathrm{x} 0.35 \right]$$

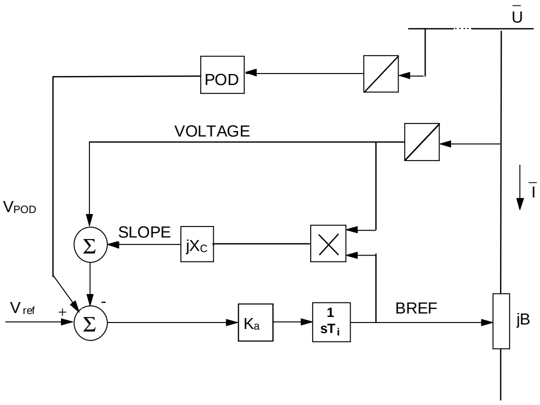

Figure 7. Control block diagram

The control system also includes protective functions such as overvoltage protection for valves and capacitors.

System test

At the end of the plant commissioning and as an addition to the normal commissioning test there were a number of acceptance tests carried out. Most important for the application was the harmonic performance test and the POD test.

The specified harmonic performance requirement was a total harmonic distortion of 2 % with no individual harmonic exceeding 1.5 %. Of these distortion levels the permitted contribution from the SVC was limited to respectively 0.7 % and 0.52 %.

The harmonic voltage distortion at the Insukamini 330 kV bus have been measured for two different network configurations, the first with the Matimba line in service and the second with the Matimba line disconnected.

The total voltage distortion was measured and is shown in tables 1 to 4. The measured levels were well within the 1.5% maximum for individual harmonics and also within the limit for total harmonic voltage distortion.

The recordings from the measurement at a firing angle of α = 98 °, which is the worst case from THD point of view, are shown in figure 8 and 9.

	SVC out	α= 97°	α= 98°	α= 103°	α= 107°	α= 120°
3	**1.20**	**1.30**	**1.30**	**1.20**	**1.25**	**1.37**
5	**0.75**	**0.60**	**0.67**	**0.65**	**0.67**	**0.70**
7	**0.45**	**0.30**	**0.37**	**0.37**	**0.36**	**0.35**

11	**0.55**	**0.30**	**0.47**	**0.40**	**0.40**	**0.55**
13	**0.20**	**0.25**	**0.20**	**0.06**	**0.35**	**0.10**
THD	**1.60**	**1.51**	**1.59**	**1.47**	**1.56**	**1.67**

Table 1: Voltage distortion with the Matimba line in.

	α= 97°	α= 98°	α= 103°	α= 107°	α= 120°
3	**0.10**	**0.10**	**0.00**	**0.05**	**0.17**
5	**-0.15**	**-0.08**	**-0.10**	**-0.08**	**-0.05**
7	**-0.15**	**-0.08**	**-0.08**	**-0.09**	**-0.10**
11	**-0.25**	**-0.08**	**-0.15**	**-0.15**	**0.00**
13	**0.05**	**0.00**	**-0.14**	**0.15**	**-0.10**

Table 2: Voltage distortion caused by the SVC with the Matimba line in.

	SVC out	α= 97°	α= 98°	α=103°	α=107°	α=120°
3	**1.07**	**1.08**	**1.12**	**1.12**	**1.04**	**1.06**
5	**0.31**	**0.20**	**0.19**	**0.17**	**0.21**	**0.25**
7	**0.62**	**0.30**	**0.29**	**0.34**	**0.35**	**0.27**
11	**0.17**	**0.25**	**0.27**	**0.21**	**0.15**	**0.17**
13	**0.19**	**1.27**	**1.25**	**0.38**	**0.71**	**0.81**
THD	**1.30**	**1.72**	**1.73**	**1.26**	**1.33**	**1.39**

Table 3: Total voltage distortion with the Matimba line disconnected.

	α= 97°	α= 98°	α= 103°	α= 107°	α= 120°
3	**0.01**	**0.05**	**0.05**	**0.03**	**-0.01**
5	**-0.11**	**-0.12**	**-0.14**	**-0.10**	**-0.06**
7	**-0.32**	**-0.33**	**-0.28**	**-0.27**	**-0.35**
11	**0.08**	**0.10**	**0.04**	**-0.02**	**0.00**
13	**1.08**	**1.06**	**0.19**	**0.52**	**0.62**

Table 4: Voltage distortion caused by the SVC with the Matimba line disconnected.

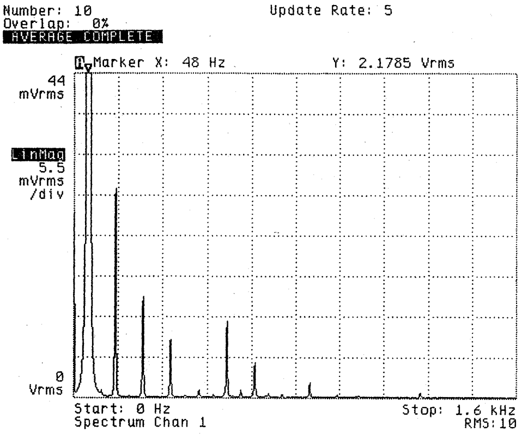

Figure 8. Recording from harmonic measurement at α = 98 °, with the Matimba line in service

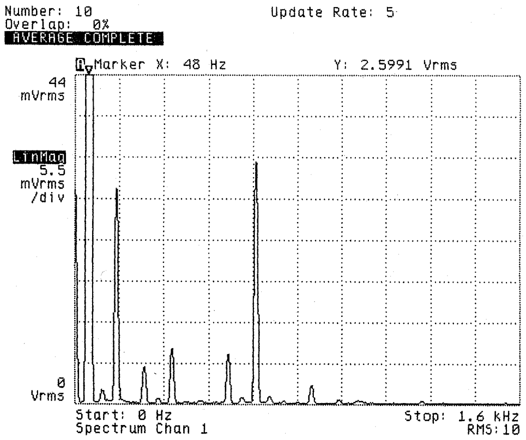

Figure 9. Recording from harmonic measurement atα = 98 °, with the Matimba line disconnected

The POD test was performed by tripping a generator in Kariba power station. The generator unit was carrying 100 MW load at the moment of tripping.

The test was repeated with different gain settings to evaluate the effectiveness of the POD function. The test also gave the planners in ZESA an opportunity to fine-tune their computer model of the system.

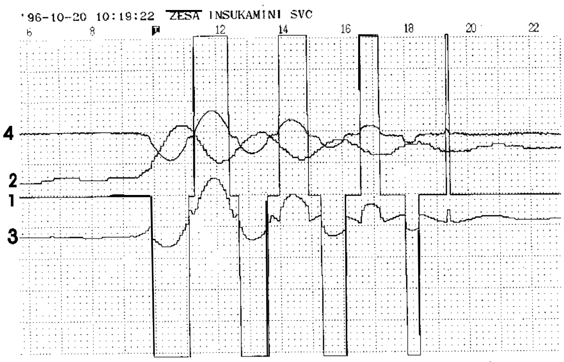

Figure 10. Recording from the POD-measurement

1) POD output window
2) Line power [90 MW / div, ,↑ import, ↓ export]
3) SVC output [40 Mvar / div↑ cap, ↓ ind]
4) Bus voltage [10 kV / div]

A sample recording is shown in figure 10. The duration of the power oscillation following the tripping of the machine at Kariba was about 9 seconds and the maximum bus voltage influence was 9 kV deviation from nominal voltage on the 330 kV bus, i.e. 2.7%. Further improvement of the damping could be achieved by increasing the gain of the POD, but at the cost of a higher influence on the voltage (and more frequent operation due to triggering of the POD even for minor oscillations). Other, more severe oscillations, will naturally cause a more abrupt regulation of the SVC. For the time being, i.e. until some experience has been gained after the commissioning of the line to Songo/Cahora

Bassa, the chosen settings give a reasonable balance between voltage control and improved power oscillation damping.

Operation experience

From the owners , ZESA, point of view the SVC has been reliable. A few outages only have been experienced during the first year in commercial operation.

With the SVC in operation margins on stability and power transfer are increased by approximately 150 Mvar which is illustrated by the following example:

The initial conditions are peak load 1997 and 500 MW import from Mocambique. Assuming that the maximum voltage deviation should be limited to 10 % at a possible loss of the Songo-Bindura line. . Even at 0 MW import from ESKOM without the SVC in operation the voltage deviation will reach the limit 10 % Thus no import can be allowed from ESCOM during these conditions.

At the same conditions except that the SVC is in operation, however 150 MW import from ESCOM can be allowed and still the limit for voltage deviations is not exceeded at loss of the Songo-Bindura line.

Conclusion

The installation of a conventional line commutated SVC in the ZESA transmission grid is a technically and economically attractive solution to eliminate expected disturbances due to the interconnection to neighbour utility grids.

The following major benefits have been defined:

- Increased stability margins
- Steady state voltage support
- Support during recovery from major disturbances
- Damping of oscillations between the interconnected systems
- Temporary overvoltage suppression

The SVC is a cost efficient mean to secure an optimal availability of the ZESA network.