SVC for resonance control in NamPower electrical power system

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Abstract
The extension of the Namibian transmission system results in a near 50 Hz resonance. To control the resonance a SVC was installed at Auas 400 kV substation. A new control principle for controlling the resonance was developed and tested. The paper presents the background to the resonance problem, the Auas SVC configuration, the resonance controller and finally the conclusions from extensive test results, both from simulator and site tests.

Keywords: Reactive power, static var compensators, sustained transient overvoltage, control design, resonance control, d/q-transformation, PLL, Real Time Digital Simulator

I. INTRODUCTION

The pre-2000 Namibian transmission network (as per Fig. 1 but without any 400kV interconnection) was unique in terms of line lengths and distribution of loads and generation. Due to its radial layout, the network was highly susceptible to voltage, quality of supply, transient and dynamic stability and Var compensation problems. The main sources of generation or in-feed are only connected to the periphery of the network. Therefore the fault levels were relatively low throughout the network and were normally the lowest at the main load centers in the central part of the country. However, voltage control problems in the central area were handled by a SVC close to the center, at Omburu Substation.

The Namibian transmission system is connected to the relatively “strong” network of Eskom, South Africa in the south and a hydro power station on the Namibian border in the north (Ruacana Power Station) which supplies “local” generation (the Ruacana Power Station is situated about 1500 km from the Eskom in-feed in the South).

The Pre-2000 network, especially the 835 km long 220kV southern link to Eskom, was often loaded to its stability limits when Ruacana generation levels were low or zero. With the growing Namibia load it became increasingly difficult to maintain stability and to keep losses along the network within economical limits.

To meet the growing power demand of the country and to reinforce the Namibian network a 400kV super-grid was planned of which the first phase was completed in May 1999.
The second phase was completed in October 2000. The two phases together consist of two approximately 450 km long 400 kV line sections and connect Eskom’s Aries substation via Kokerboom substation to the newly built Auas substation (situated approximately 35 km from Namibia’s capital Windhoek).

From switching, contingency and fault studies conducted for the 400kV supergrid it was clear that large parts of the NamPower network could easily “slip into” a near 50 Hz resonance condition resulting in huge overvoltages. This would make the NamPower network almost inoperable unless very effective, fast and extremely reliable countermeasures were taken. The solution to the resonance problem was the installation of a very fast and large FACTS device at the Auas substation. As the whole network operation depends on this electronic device the reliable operation thereof is of utmost importance. Reliability was also the criterion guiding the tender specification and design philosophy in every respect. Preference was given to conventional and well-proven SVC technology rather than a STATCOM. All parties involved, ABB, NamPower’s consultants and NamPower closely controlled the design, manufacture, installation, verification and site acceptance testing of the SVC to ensure long-term reliability of this all-important device.

A large effort was given to develop and test a new type of SVC controller in order to control the system during resonance conditions. The result is a unique and patented control principle.

II. 50 HZ RESONANCE

As shown in Fig. 1, the NamPower network has a tree-like configuration with very long radial EHV lines. Only the 330 kV line is shunt compensated, whereas the 220 kV substations are equipped with breaker-switched shunt reactors. Due to this unique network structure and depending upon the number of generating units connected to the network at Ruacana, the system has a first natural parallel resonance frequency in the range of 55-70 Hz as depicted by curves 1&2 in Fig. 3.

With the addition of the new 400 kV line (Aries-Kokerboom-Auas) and its 4x100 MVAR shunt terminal reactors, the system first resonance frequency shifts to the range 60-75 Hz (curves 3&4 in Fig. 3). Note also the remarkable reduction of system impedance at 50 Hz due to the new line indicating the strengthening of the system. The system resonance can shift towards 50 Hz during system transients such as 400 kV line energisation or recovery after clearing of line faults. Fig. 4 (curves 5&6) shows the network impedance seen at Auas 400 kV bus at the instant of energizing the 400 kV line from the Auas side before closing the breaker on the Kokerboom terminal.

The impact of the near 50 Hz resonance problem in the NamPower system can best be illustrated by simulating the condition represented by curve 6 in Fig. 4 at Auas substation. As shown in Fig. 5, at time t=0.5 the breaker at Auas terminal is closed and it is assumed that the breaker at Kokerboom is synchronized at t=0.7 s. At first, due to the large charging capacitance of the line, the voltage dips before it overshoots.

![Fig. 3 System Impedance/Frequency Characteristics](image1)

![Fig. 4 System Near 50 Hz Resonance](image2)

![Fig. 5 Voltage at Auas during energisation of 400 kV line Section to Kokerboom](image3)
The extreme high overvoltages appearing at Auas with a peak value in excess of 1.7 p.u. and a sustained TOV of over 1.5 p.u. is attesting to the severity of the problem. It is clear that as soon as the 50-Hz resonance is triggered, very high dynamic overvoltages appear with large time constant depending on the system load and generation conditions.

### III. CHARACTERISTIC OF AUAS SVC

To ensure maximum reliability the Auas SVC is built utilizing redundancy to the maximum limit. The SVC 15 kV busbar is connected to the 400 kV grid via three single phase transformers with one additional spare, see Fig. 6.

![Single line diagram of Auas SVC](image)

The full SVC rating of 250 Mvar inductive power needed for resonance control is provided by three TCR's with a fourth TCR always energized (hot redundant). Each TCR branch has its own dedicated cooling system. Two identical double-tuned filters of 40 Mvar each take care of harmonics and supply capacitive reactive power in steady state operation. The control system is fully redundant based on the ABB MACH 2 control system. The SVC is designed for severe black start conditions including immediate resonance control at combined SVC & 400 kV line energization.

### IV. CONVENTIONAL CONTROLLER DRAWBACKS

A SVC has the ability to restore the fundamental frequency voltage following a disturbance. The conventional voltage controller used by ABB is of integrating type and is shown in Fig. 7.

![Conventional voltage controller, block diagram](image)

The positive sequence component of the fundamental frequency voltage is ideally the control signal for a voltage regulator. In reality low frequency oscillations (below 90 Hz) also becomes a part of the control signal.

The measured 3-phase voltage is first transformed into a rotating α/β system followed by extraction of the positive sequence component. The rotating positive sequence vector is thereafter converted into a DC level by multiplication with a reference vector, rotating with the same speed as the fundamental component of the measured voltage. This reference is obtained by a phase locked loop (PLL). As a result of the transformation all frequencies in the measured voltage is moved downwards and upwards by the fundamental frequency.

At any change in the network operating conditions the system has to move from one steady state condition to another. This transfer implies that the fundamental frequency voltage at one location has to change from one level to another. As the system is characterized as an RLC circuit, an additional decaying oscillation with the resonance frequency will be superimposed on the fundamental.

\[
V = A \cos(\omega t + \phi) + B e^{-\frac{t}{T}} \cos(\omega t + \phi_1)
\]

The resonance oscillation in Namibian system is observed in the controller as a low frequency oscillation superimposed on the DC level. During energisation of the 400 kV line and at fault condition the capacitance in the line is charged, which can be seen as a large sudden change in active power. Since the conventional controller is using a fast PLL as reference, the rotating vector representing the measured voltage will be mapped along the d-axis. This means that the conventional controller will only operate on changes in reactive power. The initial sign of a resonance condition will not be seen and the controller will instead incorrectly go capacitive during the initial undervoltage at resonance conditions, see Fig. 10.

### V. RESONANCE CONTROLLER

Conventional I-, PI- or PID-types of regulators have difficulties to efficiently counteract low frequency voltage oscillations and at the same time be stable for all system conditions. A new type of voltage controller was developed for the Auas SVC in order to improve the control of the resonance during energisation of the 400 kV line and recovery after line faults.

The new controller, resonance controller, is a supplementary function to the conventional voltage controller. The resonance controller is based on the same concept as the conventional controller, but a slower PLL is used as reference. By using a slow reference the phase shifts in the system voltage will be seen in the q-component, see Fig. 8.
The advantage of the new controller is that it will react already on the charging effect of the line capacitance, i.e. at resonance startup conditions, see Fig. 11. A block diagram of the resonance controller is shown in Fig. 9.

The developed resonance controller has been evaluated in a RTDS, Real Time Digital Simulator. The NamPower system was represented by a 20 bus system model. The machines at Van Eck and Ruacana were modeled with full representation, i.e. with field and damper windings and models of AVR, governor and PSS included. The modeled system was decomposed into six subsystems and transmission lines were used to tie the six subsystems together.

The control system used for the validation mainly consisted of the MACH 2 control system identical to the hardware implemented at site. This method of testing allowed the control system to be tested in a large number of contingencies, many of which can not be performed or would not be permitted on the real NamPower system.

The new resonance controller was compared with the result of a conventional integrator type controller. For comparison the worst resonance case was selected, energisation of the 400 kV line from the north. This is achieved by first closing the Auas 400 kV line circuit breaker on the Auas-Kokerboom line. As shown in figure 10 and 11, at time t=0.4 s the breaker at Auas is closed. At first due to the large charging capacitance of the line, the voltage dips before it overshoots.

Figure 10 shows the 400 kV line energisation from the north, in the 500 MVA system with a conventional controller. The resulting overvoltage at Auas is 1.62 p.u. Two resonance frequencies, 56 Hz and 81 Hz, can be seen in the result and corresponds to the first and second pole in the system.

The effect of using the new resonance controller has a very large impact on the system behavior as shown in Figure 11. The contribution of the resonance controller can be seen in signal Bref_add. The high voltage appearing at Auas is reduced to a peak value of 1.32 p.u. The new resonance controller is thus controlling the resonance.
VII. SYSTEM PERFORMANCE TEST

The verification of the Auas SVC played an important part in the commissioning of the new NamPower 400 kV interconnection system. In order for NamPower to operate the new interconnection between Eskom and themselves safely, it was crucial that the SVC be verified completely before considering the energisation of the last section of the 400 kV line between Kokerboom and Auas Substation. Of particular importance was the verification of the resonance control function. The following system performance tests were carried out with Auas SVC and the NamPower transmission system:

1. Voltage response test. Due to the large range in system fault level (300 to 1500 MVA), the impact of the voltage control of the SVC can easily be verified with the switching of an external 100 MVAR 400 kV busbar reactor. During these tests the benefits of the resonance controller was already demonstrated.

2. Q or MVAr control.

3. Black start of the SVC.

4. Maximum MVAr output

5. Staged fault tests. Various phase to earth faults where applied to the different branches inside the SVC such as the TCRs, filter and auxiliary. These tests verified the protection co-ordination as well as the ability of the SVC to correctly isolate the fault and return to service automatically.

6. Staged faults tests on SVC control and measurement system.

7. Simulated transmission line trips and auto reclosure.

8. Energisation of the 400 kV line and tripping. One of the most severe tests for both the NamPower system and the SVC is the energisation of the 400 kV line from Auas to Kokerboom. This test was carried successfully and verified the correct and fast response of the resonance controller.

The results shown in figure 12 shows the 400 kV voltage rise during the energisation of the 400 kV line as well as the voltage controller output and the additional contribution by the resonance controller. It can clearly be seen that the overvoltage is kept to a minimum by the fast and effective additional signal from the resonance controller.

The maximum transient overvoltage measured during this test was consistent with the results obtained from the design digital simulation studies as well as the RTDS simulator studies. The results of the RTDS simulator studies for a similar network is shown in figure 13.

Figure 12. Field test, energisation of the 400 kV system from north to south

Figure 13. RTDS, energisation of the 400 kV system from north to south, 300 MVA network and resonance controller

The overall results of the system performance tests demonstrated that the NamPower system can be operated effectively and safely under extremely challenging and different network conditions with the Auas SVC in service.

IX. CONCLUSIONS

A new resonance controller for SVC has been developed and tested both in a simulator and at site. It has been showed that the new controller is superior to classic voltage controllers in near fundamental resonant conditions. As a result the new 400 kV line between Namibia and South Africa can be operated in a safe way.
VIII. BIOGRAPHIES

Mikael Halonen was born in Västerås, Sweden, on July 31, 1970. He received his M.Sc. degree in Electrical Engineering from the Royal Institute of Technology, Stockholm, Sweden in 1996. He currently is working for ABB Power Systems within its AC System Division where he is involved in projects concerning reactive power compensation for voltage stability and control.

Staffan Rudin was born in Sweden in 1965. He entered his studies of electrical engineering at the Lund Institute of Technology, Sweden, and completed his M.Sc.E.E degree in 1990 at the Swiss Federal Institute of Technology in Zürich. In 1990, Mr Rudin joined ABB Power Systems to work with HVDC system design. Since 1994 he has focused on system design of SVC and TCSC applications. Mr Rudin was the technical project manager of the Namibia SVC project. At present he is manager of the system design department at ABB Power Systems, AC Systems Division.

Björn Thorvaldsson was born in Göteborg, Sweden in 1959. He received his M.Sc.E.E degree from Chalmers University of Technology in Sweden 1983. From 1983 to 1986, Mr Thorvaldsson was employed at the Power System Analysis department at the former ASEA, now ABB, in Västerås, Sweden. In 1986 he joined the Reactive Power Compensation Division. His work has been concentrated on main circuit design of SVC plants including control and relay protection systems. Since 1995 Mr Thorvaldsson works as SVC specialist within ABB Power Systems, AC Systems Division.

Udo Kleyenstüber was born in Windhoek, Namibia, on October 29, 1949. He received his B.Sc. degree in Electrical Engineering from the University of Pretoria, South Africa in 1972. He currently is working for NamPower (the Electricity Utility of Namibia), within its Transmission Department where he is involved in the operation of the HV network, network analysis, relay setting calculations, analysis of fault events, voltage and dynamic stability studies, specifying relaying systems and reactive power compensation for new network projects.

Septimus Boshoff was born in Zimbabwe, on March 10, 1962. He received his B Eng and M.Eng. degree in Electrical Engineering from the Rand Afrikaans University, Johannesburg, South Africa in 1983 and 1985. From 1986 to 1997 he was with Eskom, the South African power utility where he was responsible for various SVC projects, power quality and FACTS devices. Since 1998, he is a specialist consultant in the field of SVCs FACTS and power quality.

Chris van der Merwe is currently Corporate Consultant for Trans-Africa Projects, his main expertise being Insulation Coordination and System Studies. He received his B.Sc. (Hons.) at Rand Afrikaans University and his M.Eng. at the University of the Witwatersrand. During his employment with Eskom since 1979 he has been involved with many HV projects, including the insulation coordination and System Studies for the 765 kV network. Since 1997 he is a member of a core team of engineers responsible for the 400 kV international interconnector between Namibia and South Africa with special responsibility relating to the system studies. This included detail EMTP/EMTDC studies to determine design parameters for the Static Var Compensator to control near 50 Hz resonance due to weak system and long length of interconnection.

He is a Registered Professional Engineer in South Africa and a member of the South African Institute of Electrical Engineers as well as a member of Cigre.