COMMISSIONING AND OPERATIVE EXPERIENCE OF TCSC FOR DAMPING POWER OSCILLATION IN THE BRAZILIAN NORTH-SOUTH INTERCONNECTION

C. GAMA*                         L. ÄNGQUIST, G. INGESTRÖM, M. NOROOZIAN
ONS                                                        ABB Power Systems AB
Brazil                                                                     Sweden

SUMMARY

The Brazilian north-south interconnection was commissioned in the first quarter of 1999. The final commissioning tests involved verification of the damping performance of two TCSCs located at each end of the interconnection. This paper presents some results from the testing along with discussions about different controller algorithms for damping of power oscillations. The TCSCs showed to be a powerful means to damp power oscillations in the North-South interconnection. A novel power oscillation damping controller was developed and tested with very satisfactory results.

KEYWORDS

FACTS – TCSC – Controller Design – Power Oscillation Damping - Commissioning

1. INTRODUCTION

The Brazilian North-South interconnection, depicted in Figures 1 and 2, interlinks the South-Southeast and the North-Northeast power systems in the country. The installed generation capacities of these systems are 48 GW and 14 GW respectively. The two power systems are essentially hydroelectric and concentrate more than 95% of the total national production and consumption.

The interconnection is 1020 km long, and consists of a single 500 kV compact line between the substations Imperatriz in the north and Serra da Mesa in the south. The line is provided with 54% of fixed series compensation split into six banks, and two Thyristor Controlled Series Capacitors (TCSC) banks, each providing 6% of series compensation in steady state conditions. They are located at the substations Imperatriz (north) and Serra da Mesa (south). The shunt compensation is 95%, being a combination of line and bus reactors.

The interconnection is designed to permit a power transfer of up to 1300 MW in either direction. The purpose of the two TCSCs is to dampen the low frequency (0.2 Hz) inter-area oscillation which may be excited by any kind of disturbance in the system. Synchronous operation with reliable performance shall be sustained for all loading conditions ranging from no load to maximum flow in both directions [1].

2. BASIC CHARACTERISTICS OF THE TCSC IN IMPERATRIZ

The TCSC basically comprises a capacitor bank inserted in series with the transmission line, a parallel metal oxide varistor to protect the capacitor against overvoltage and a branch with a thyristor valve in series with a reactor in parallel with the capacitor. Mechanical bypass breakers are provided in parallel with the capacitor bank and in parallel with the thyristor valve. The main circuit is depicted in Figure 3.

In steady state conditions the reactance of the TCSC is maintained at -15.9 Ω (6% of the total line reactance). This value corresponds to a continuous capacitive voltage boost factor of 1.2, i.e. the apparent reactance at fundamental frequency is 1.2 times the physical reactance of the series capacitor. The reactance of each TCSC can be continuously controlled from -13.3 Ω with blocked thyristor valve to -39.8 Ω corresponding to a capacitive voltage boost factor of 3.0. Further, at power oscillations, the thyristor valve is utilized to temporarily...
bypass the capacitor bank. The TCSC reactance at bypass is 2.5 Ω inductive.

The TCSC features four different modes of operation:
• CAP (capacitive voltage boost)
• BLK (thyristor valve blocked)
• CBP (controlled valve bypass)
• PBP (protective bypass).

CAP is the normal operating mode in steady state. The control system maintains a constant reactance according to a given reference between -13.27 Ω and -39.8 Ω. The thyristor valve is blocked (BLK) when the steady state line current drops below 150 A. CBP mode is used to improve the TCSC damping performance during large power oscillations and PBP finally is used in fault-handling sequences. The TCSC reactance operating range is shown in Figure 4 and its basic parameters are shown in Table I.

Figure 1: Brazilian North-South interconnection - geographical location.

Figure 2: One line diagram of the transmission line between Imperatriz and Serra da Mesa.

Table I: Basic TCSC parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max system voltage (Φ-Φ)</td>
<td>550</td>
<td>kV</td>
</tr>
<tr>
<td>Nominal reactive power</td>
<td>107.5</td>
<td>Mvar</td>
</tr>
<tr>
<td>Physical cap reactance (1.0 pu)</td>
<td>13.27</td>
<td>Ω/\text{ph}</td>
</tr>
<tr>
<td>Nom cap reactance (1.2 pu)</td>
<td>15.92</td>
<td>Ω/\text{ph}</td>
</tr>
<tr>
<td>Nom. cap boost factor (X_{app}/X_c)</td>
<td>1.2</td>
<td>pu</td>
</tr>
<tr>
<td>Max capacitive reactance (3.0 pu)</td>
<td>39.8</td>
<td>Ω/\text{ph}</td>
</tr>
<tr>
<td>Reactor inductance</td>
<td>5.63</td>
<td>mH</td>
</tr>
<tr>
<td>Inductive react in bypass</td>
<td>2.5</td>
<td>Ω/\text{ph}</td>
</tr>
<tr>
<td>Rated line current</td>
<td>1500</td>
<td>A</td>
</tr>
<tr>
<td>Rated cont TCSC voltage (1.0pu)</td>
<td>23.88</td>
<td>kV</td>
</tr>
<tr>
<td>30-minute overload current (1.5 pu)</td>
<td>2025</td>
<td>A</td>
</tr>
<tr>
<td>10-second overload current (2.0 pu)</td>
<td>3000</td>
<td>A</td>
</tr>
<tr>
<td>Max therm short-circ current</td>
<td>23</td>
<td>kA</td>
</tr>
</tbody>
</table>

Figure 3: Layout of the TCSC in Imperatriz.

Figure 4: Operating range of the TCSC in Imperatriz.

3. POWER OSCILLATION DAMPING (POD) CONTROLLER

3.1. TCSC inner boost control

The TCSC capacitive reactance control system is based on the Synchronous Voltage Reversals (SVR) scheme [2]. This scheme was developed in order to give a TCSC a SSR mitigating behavior in steady state. The basis for the controller is to keep the capacitor voltage reversals equidistant in time while maintaining the commanded apparent reactance of the TCSC. The thy-
ristor valve firing time is calculated in run-time based on measurements of instantaneous capacitor voltage and line current in contrast to the conventional open-loop control system where the controller directly determines the thyristor firing angle. The SVR principle makes the boost control loop linear and inherently eliminates DC offset in the capacitor voltage. The rise time in the boost control loop is approximately 50 ms.

3.2. Reactance reference for power oscillation damping

The control system receives a reactance order, which is the sum of the steady state reactance reference and the output from the Power Oscillation Damping (POD) controller. The damping effect is obtained by modulation of the inserted TCSC reactance with a signal, which is proportional to and phase-shifted -90° relative to the measured power swing [4]. Either the active power or the line current could be used as the input to the POD. Digital studies indicated very small difference in damping performance between the two signals.

Since the effectiveness of the POD increases with the active power flowing through the TCSC, a variable gain strategy was developed in order to adapt the actual POD controller gain to different line loading conditions as shown in Figure 5. Let $K_{GF}$ be the optimum gain during conditions with high power flow (INF) and let $K_{GL}$ be the optimum gain during conditions with low power flow (INL) on the transmission line. The gain for any other power flow level is determined by linear interpolation between the above data. The input power level to the gain controller is obtained as a low-pass filtered version of the absolute value of the POD input. The time constant of the low-pass filter must be large enough to prevent interference in the power oscillation frequency range [4].

3.3 Realization of POD controller with washout and lead-lag filters

The traditional type of controller for power oscillation damping purposes uses cascade-connected washout filters and linear lead-lag links to generate the desired reactance modulation signal. The purpose of the washout links is to eliminate the average and extract the oscillating part of the input signal, while the lead-lag links provide the desired phase shift at the oscillation frequency. Such a controller is outlined in Figure 6.

Notice that the lead-lag filters are equipped with non-windup limiters. The reason is that there are limitations in the TCSC main circuit and that the dynamic control action of the POD must be kept within the controllable range of the TCSC in order to guarantee a dynamic influence of its reactance during power oscillations. Without limitations the output signal from the lead-lag filters drifts away from zero, i.e. it gets a DC-offset during system transients.

This could result in a situation where the POD output varies between values that are completely at one side of the TCSC main circuit limitations. This scenario is illustrated in Figure 7. Note that the TCSC reactance order will become saturated at the maximum capacitive limit of the main circuit (-13.27 Ω) affecting negatively the TCSC damping performance [5].

The limitations of the lead-lag filters, however, do not solve all problems. Depending on the size of the disturbance, the combination of the controller gain and power swing amplitude may generate a signal that keeps hitting the limitations in each cycle. As a result, the desired phase shift from the lead-lag filters cannot be maintained, greatly reducing the effectiveness of the TCSC. This behavior is shown in one of the plots from the system performance tests (Figure 11).

To conclude: the non-windup limitations on the lead-lag filters were introduced in order to avoid saturation of the reactance output at one side of the controllable range of the TCSC main circuit, but they caused new problems in the form of a degradation of the desired phase shift characteristics of the filters.
In an alternative approach the lead-lag filters could be non-limited and a washout filter could be added after them. In steady state conditions (small disturbances) this would work fine, but during transients another problem would be created. The washout time constant would have to be large enough to avoid influencing the phase shift of the signal too much. On the other hand, with such a large time constant the transient behavior of the filter would be rather slow, resulting in main circuit saturation during approximately 10 seconds in the actual case. This behavior has two major drawbacks: 1) a long saturation of the main circuit at maximum capacitive boost could utilize all the overload capability of the TCSC without adding any damping to the system; 2) the POD controller does not add damping to the system during the first two cycles of a power oscillation.

3.4 Realization of POD controller using Phasor estimation

In order to overcome the problems described above, a new POD controller was designed. In the new concept the a priori knowledge of the expected power oscillation frequency is being utilized. In the actual system the oscillation frequency is known to be 0.20 Hz with small deviations due to different network conditions. Based on the knowledge about the frequency of oscillation, one can assume that the measured active power on the interconnection can be described as the sum of two contributions:

- the average power flow
- the 0.20 Hz power oscillation.

The power oscillation can be represented by a phasor in a co-ordinate system which rotates with the expected oscillation frequency. The technique to extract the phasor is similar to the technique used in a Phase Locked Loop (PLL) that serves the purpose of extracting the instantaneous phase angle at fundamental frequency from periodic signals like line current, bus voltage etc. Once the phasor representing the power oscillation has been extracted from the measured input signal, it is an easy task to generate any signal with certain amplitude and phase-shift in relation to the measured signal [3].

A layout of the phasor POD is shown in Figure 8. Basically, a reference signal with a frequency of 0.2 Hz is generated and the same type of technology applied in a PLL is used to extract four different signals out of the measured active power:

- the phasor ($\Delta P_x, \Delta P_y$) representing the 0.2 Hz power oscillation
- average active power ($P_{av}$) on the interconnection
- amplitude of the power oscillation ($|\Delta P|$)
- phase angle of the power oscillation (arg($\Delta P$)).

With this information available, it is straightforward to generate a TCSC reactance that adds damping to the system. In Figure 8 the generated reactance signal is phase shifted -90°+$\alpha$ relative to the input signal. According to [4], the desired reactance output of the TCSC should have a phase angle of –90° relative to the active power, thus in this case $\alpha$ was selected to equal zero. The POD reactance output is proportional to the amplitude of the oscillation and since the signal is centered on zero there are no problems with saturation at one side of the controllable range of the main circuit. Note that the active power is used as the input signal with sign for either power flow direction. Figure 9 shows the result of a simulation of the controller in MATLAB where the input to the controller is a real measured power flow signal from one of the system performance tests.

Figure 8: Structure of a phasor POD controller.

Figure 9: MATLAB simulation of the Phasor POD

The POD in Figure 8 works with a fixed, predefined frequency of oscillation. However, an adaptive scheme which captures the actual frequency of oscillation can be easily implemented. Thereby the ideal phase shift can be preserved during the oscillation. One way of doing this adaptation is to look at the phase angle of the
estimated phasor. If its argument increases, the actual oscillation frequency is higher than the expected frequency and, hence, the frequency of the measuring system should be increased and vice versa [3].

4. SYSTEM PERFORMANCE TESTS

An extensive number of system tests was planned aiming at covering different types of fault scenarios and TCSC configurations. One of the goals was to verify that the TCSCs in Imperatriz and Serra da Mesa were working without any negative interactions. The testing involved the following TCSC setups:

- both PODs disabled
- the POD in Imperatriz active and the POD in Serra da Mesa disabled
- the POD in Imperatriz disabled and the POD in Serra da Mesa active
- both PODs active.

These TCSC configurations were tested in different system fault scenarios which were selected based on digital simulations. The pre-fault system load flow was arranged in order to create a situation with very low natural damping of the system. During the testing the load flow was adjusted to 700 MW from Northeast to North and 500 MW from North to South. The following system scenarios with this pre-condition were tested [5]:

- bypass of the fixed series capacitor C8 in line between Imperatriz and Colinas followed by reinserion after 30 seconds
- bypass of the fixed series capacitor C12 in the line between Serra da Mesa and Gurupi followed by reinserion after 30 seconds
- trip of 300 MW generation in Tucurui
- trip of 200 MW generation in Serra da Mesa
- single phase to ground fault on the compact transmission line between Marabá and Tucurui followed by permanent disconnection of the transmission line
- single phase to ground fault on one of the two transmission lines between Samambaia and Serra da Mesa followed by permanent disconnection of the transmission line
- power swing excitation by the TCSC in Imperatriz.

The disturbance created by the switching of series capacitors was rather small and the system showed a satisfying behavior both with and without the PODs activated. On the other hand, the trip of 300 MW generation in Tucurui with both PODs disabled came as big surprise. The system was unstable and the test caused a protective tripping of the North/South interconnection as seen in Figure 10. This scenario had been simulated in different digital simulation programs and all of them had shown positive damping for the system oscillations.

Being the critical contingency, it was selected to evaluate the impact of different control algorithms and setup of the two TCSCs. During the first tests both TCSCs were equipped with lead-lag POD controllers. The negative effects of the non-windup limiters were clearly demonstrated when the tripping of 300 MW generation in Tucurui was repeated with the POD in Imperatriz active and the POD in Serra da Mesa disabled. See Figure 11.

![Figure 10: Trip of 300 MW generation in Tucurui with both PODs disabled.](image)

![Figure 11: Trip of 300 MW in Tucurui, lead-lag POD in Imperatriz, Serra da Mesa disabled.](image)

Note that the POD output waveform has been distorted and does not appear to be sinusoidal. This is an effect of the limitations of the integrators in the controller. The desired phase shift in the POD controller signal was not maintained due to the same reason and it is clear that the this POD does not fully utilize the capability of the TCSC main circuit to add damping to the system. With these results in hand, the development of the phasor POD started and was implemented and ready for testing after one week [3].

The natural system damping during the realization of the second set of testing was much worse and this can be clearly seen in Figure 12. During the first 50 seconds of the testing, both TCSCs were equipped with the original lead-lag POD. Note that they were not able to stabilize the system. At instant 50 seconds, the controller of the TCSC at Imperatriz was switched over to the Phasor POD. Observe how both the amplitude and phase of the TCSC reactance are modified in order to damp the oscillation out, saving the system. Here, the valve bypass mode of the Phasor POD was not active.
5. CONCLUSIONS

The system performance testing showed that the TCSCs were very effective in damping the power oscillations in the North/South interconnection. The interconnection has been in reliable operation since March, 1999 with the TCSCs providing adequate damping for all scenarios, even for those with low power transfer (below 200 MW). A novel POD structure, the Phasor POD, was successfully implemented in the TCSC at Imperatriz. Its performance is very nonlinear and very effective, suggesting the possibility of using this type of controller in other applications such as SVC, PSS, HVDC, etc.

6. REFERENCES


