Analysis of Subsynchronous Torsional Interactions with SVCs

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This paper presents the results of an analytical investigation aimed at assessing the potential for subsynchronous torsional interactions (SSTIs) between turbine-generator rotors and static VAR compensators (SVCs) in longitudinal power systems. An advanced linear state model of the power system is developed that allows detailed evaluation of the impact of FACTS controllers on SSTIs with turbine generators, as well as the identification of potentially undesirable effects associated with the application of multiple controllers. This approach is general enough to include the representation of complex systems and can be used in conjunction with efficient techniques for the analysis of large sparse linear systems. The proposed methodology is applied to quantify the potential for subsynchronous resonance (SSR) problems with series-compensated ac transmission lines and the study of SSTIs between a large SVC and major nuclear and thermal turbine-generator units in the Mexican interconnected system.

Keywords  FACTS devices, static VAR compensator, subsynchronous resonance, subsynchronous oscillation, small signal analysis

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1. Introduction

Flexible ac transmission system (FACTS) devices are increasingly being utilized in many power systems to enhance power transfers, as well as to provide voltage stabilization at critical system locations [1]. The application of FACTS devices, however, presents the potential for excitation of subsynchronous oscillations in nearby turbine generators. In recent years, subsynchronous oscillations in turbine generators have resulted from interaction with major control devices, such as excitation control in generators and with HVDC converter controls [2, 3]. Other system devices with the ability to control power or speed variations rapidly are also a potential source for excitation of system oscillations [4].

The possibility of unfavorable torsional interaction between static VAR compensator (SVC) controls and turbine generator shafts has been recently considered in both computer simulation studies and field investigations [1, 5]. Study results suggest that large SVCs could have a noticeable impact on torsional vibration modes of nearby generators, especially under high-stress conditions. The sensitivity of torsional damping to the SVC control action appears from these investigations, mainly related to the size of the SVC relative to that of nearby turbine generators, the ac system strength and operating conditions, and the control characteristics of the device at subsynchronous frequencies. Other aspects such as the SVC operating mode and the setting of the controllers, among others, have also been found to affect torsional interaction.

Subsequent study experience with a complex system indicates that the level of interaction between an SVC and a turbine generator could be significantly affected by the presence of HVDC systems and the characteristics of the ac system adjacent to the converter [6]. Moreover, the leverage of an SVC on torsional damping might also be increased by the presence of series capacitor compensation as suggested by several researchers (see discussion to [5]).

This paper presents some recent advances on the development of new analytical techniques for the analysis of subsynchronous torsional interactions (SSTIs) with FACTS controllers, namely, SVCs and thyristor-controlled series capacitors (TCSCs). For completeness, an overview of current methods for the analysis of SSTIs using conventional techniques is first provided. An advanced linear state model of the power system is then introduced that allows detailed evaluation of the impact of FACTS controllers on SSTIs, as well as the identification of potentially undesirable effects associated with the application of multiple controllers. This approach is general enough to represent complex systems and can be used in conjunction with efficient techniques for the analysis of large sparse linear systems.

The practical use of the developed methodologies is tested on a complex 54-bus, 12-machine test system using a special small-signal stability program called SSOAP (Subsynchronous Oscillations Analysis Program) developed by the authors. Emphasis in this research is being placed on the combined effect of series capacitor-compensated transmission lines and SVCs on turbine-generator SSTIs.

2. The Phenomenon of SSTIs with FACTS Devices

2.1. Principles of Torsional Interaction

Torsional interaction between an SVC and a turbine generator can be conceptually described in terms of the simplified diagram in Figure 1. As suggested by
Rostamkolaie et al. [5], the voltage control system of the SVC responds to the voltage modulation in the generator's terminal bus and hence at the SVC location, caused by the torsional vibrations of the turbine generator. SVC-SSTIs can then result from the effect of the SVC control system on the electrical torque ($T_e$) as explained in the diagram. The nature of the interaction phenomenon is rather complex and can be affected by control characteristics, the relative location between the SVC and the turbine generator, and the characteristics of the transmission system adjacent to the SVC.

2.2. Synchronizing and Damping Torques

Torsional interaction between a control system and a turbine generator can, conventionally, be expressed in terms of the open-loop transfer function from the generator rotor speed $\omega_g$, to electrical torque $T_e$ for the machine of concern as [3, 7]

$$\frac{\Delta T_e}{\Delta \omega_g} = \frac{\text{change in electrical torque}}{\text{change in rotor speed}} = D_e(j\omega) - j\frac{\omega_h}{\omega} K_e(j\omega), \quad (1)$$

where

$D_e =$ damping torque due to the electrical system

$K_e =$ synchronizing torque due to the electrical system.

The real part of this transfer function represents the effective point of interest for determining the damping of a torsional mode at the particular frequency, $\omega$. A torsional mode of vibration will become unstable when the damping torque exceeds in magnitude and is opposite in sign to the mechanical damping [7]. The above concept may be extended to analyze the impact of any power system controller on torsional modes of vibration and is used extensively in several production-grade computer programs.
3. Study Approach

3.1. State Representation in SSOAP

The power system state representation is seen here as constituted of dynamic sub-
systems interacting through physical and topological constraints. Major subsys-
tems being considered include synchronous machines and their mechanical systems,
FACTS controllers, and the ac transmission network. In this formulation, each dy-
namic device and transmission circuit in the system is represented by a component
connection model in the following form \[8, 9\]:

\[
\dot{x}_i(t) = A_i x_i(t) + W_i a_i(t) + b_i u_i, \tag{2}
\]

\[
b_i(t) = C_i x_i(t) + D_i a_i(t), \tag{3}
\]

where \(a\), \(b\), \(x\) represent appropriate vectors of component inputs, outputs, and
incremental states, respectively; \(u_i(t)\) is the control input to the \(i\)th dynamic device.
In this model the balanced three-phase device models are first resolved into d-q
components with respect to a synchronous rotating reference, then each device
is added to the network representation using topological and physical constraints
\[10, 11\]. The overall state representation can then be expressed as

\[
\dot{x} = Ax + \sum_{j=1}^{m} b_j u_j, \tag{4}
\]

\[
y_k = C_k x,
\]

where \(x \in \mathbb{R}^n\) is the overall state vector and \(y_k\) is the \(k\)th measurement signal; \(m\) is
the number of control inputs for FACTS devices. The above formulation is flexible
enough to include complex systems and can be used in conjunction with modern
techniques for the analysis of large sparse models of power systems.

Present capabilities of SSOAP include the following:

- D-q-o representation of a network, voltage-dependent load characteristics,
synchronous machines, and FACTS devices
- Detailed modeling of electrical and torsional characteristics of synchronous
machines
- Compatibility with EMTP data files and models
- Computation of synchronizing and damping torques and frequency response
analysis.

3.2. Modeling of System Components

The overall state representation is obtained from the interconnection of the individual dynamic subsystems. A brief description of present modeling capacities is
given below.

3.2.1. Synchronous machines. Synchronous machines can be represented in varying
degrees of complexity with up to 3 rotor circuits in each axis. Here the inputs to
this subsystem in equation (4) are the vector of stator currents, and the vector of
stator voltages is the output to the network representation. The turbine generator
rotor can be represented as a linear multimass shaft system in which the speed and
angle for each rotor mass are taken as state variables.
3.2.2. **AC network representation.** The ac network model is mainly composed of the dynamic representation of transmission lines, transformers, shunt controllers, and controllable L-C branches associated with FACTS devices. In this model the differential equations of the three-phase, balanced R-L-C network are transformed to a synchronous rotating reference frame. The interface with synchronous machine models requires coordinate transformations of machine quantities to the common reference frame [11].

3.2.3. **FACTS devices.** FACTS devices are represented by appropriate combination of (2) and (3). In this formulation the state vector consists of $d$-$q$ axis current injections, while the input vector accounts for the incremental deviation of coordinate voltage components. Figure 2 illustrates the equivalent circuit and major control blocks of SVCs used in the analysis of SSTI. This model includes the following:

- Detailed transfer function representation of the AVR and firing angle control
- the electrical transient dynamics of the thyristor-controlled reactor (TCR) and the thyristor-switched capacitor (TSC)
- the representation of a power system damping controller (PSDC).

The dynamic behavior of the inductive branch of each SVC including short-lived transients is given by

$$
\frac{d}{dt} \begin{bmatrix} \Delta i \\ L^D \\ L^Q \end{bmatrix} = \omega_o \begin{bmatrix} V_o^D \\ V_o^Q \end{bmatrix} \frac{\partial \beta_L}{\partial \alpha} \Delta \alpha + \omega_o \beta_L \begin{bmatrix} \Delta V^D \\ \Delta V^Q \end{bmatrix} \\
+ \omega_o \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} \begin{bmatrix} \Delta i \\ L^D \\ L^Q \end{bmatrix},
$$

where $\alpha$ is the firing angle of thyristors obtained from the control system and $\beta_L$ is the inductive susceptance of the TCR.

![Figure 2. Schematic representation of an SVC.](image)
Further, neglecting fast control actions, the transient behavior of shunt capacitors and mechanically switched capacitors is of the form

$$\frac{d}{dt} \begin{bmatrix} \Delta V_D \\ \Delta V_Q \end{bmatrix} = \frac{\omega_o}{\beta_C} \begin{bmatrix} \Delta i \\ C^D \end{bmatrix} + \omega_o \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} \begin{bmatrix} \Delta V_D \\ \Delta V_Q \end{bmatrix},$$  

(6)

where $\beta_C$ is the TSC susceptance. With appropriate considerations, the above equations are used to represent passive series and shunt inductances and capacitances in the network, as well as thyristor-controlled series capacitors.

3.2.4. Load characteristics. Static loads can be represented as either linear lumped RLC circuits or by equivalent differential equations accounting for the short-lived transient performance [12].

3.3. Overall System Representation

The overall state space power system model obtained from the interconnection of the individual subsystems representation is expressed in the form

$$\begin{bmatrix} \dot{x}_z \\ \dot{x}_{facts} \end{bmatrix} = \begin{bmatrix} A_{zz} & A_{zf} \\ A_{fz} & A_{ff} \end{bmatrix} \begin{bmatrix} x_z \\ x_{facts} \end{bmatrix} + \begin{bmatrix} B_{zz} & 0 \\ 0 & B_{ff} \end{bmatrix} \begin{bmatrix} \Delta V_{ref} \\ \Delta U_{ref} \end{bmatrix},$$  

(7)

where

- $x_z$ is a vector of states associated with synchronous machines and the network and load representation
- $x_{facts}$ is the vector of states associated with the representation of SVCs
- $V_{ref}$ is the vector of input signals to synchronous machines
- $U_{ref}$ is the vector of input signals to SVCs
- $A_{zz}, A_{zf}, A_{fz}, A_{ff}$ are connection matrices of appropriate dimensions.

3.4. Indices of Torsional Interaction

Controllability and observability characteristics in this research are utilized to quantify the level of interaction between a FACTS controller and a turbine-generator unit as well as to identify potentially undesirable effects associated with the application of multiple controllers. Following [13], the system in equation (7) is controllable by the control input $u_j$ if and only if rank

$$P_j^i = \text{rank} [A - \lambda_i I : b_j] = n.$$  

(8)

Conversely, the system is observable if and only if rank $Q_k^i = \text{rank} [C_k^T : A^T - \lambda_i I] = n$ for $i = 1, \ldots, n$. The minimum singular value of $P_j^i$ and $Q_k^i$ indicates the distance from the nearest singular matrix $S = [A - \lambda_i I]$. For a given input signal $u_j$ and location of the device, the combined use of these indices can be interpreted as the degree of coupling of the $j$th input to the controller using the $k$th supplementary signal with the $i$th system eigenvalue. This combined index provides a useful measure of the degree of interaction between an existing FACTS controller and a given torsional mode. Moreover, the above approach can also be used to analyze the impact of new FACTS devices on the degree of torsional interaction.
4. Application

4.1. Description of the System Studied

A simplified diagram of the study system illustrating the location of the main thermal and nuclear machines and several large SVCs is provided in Figure 3. The northern part of this network contains several large thermal and nuclear machines located near main load centers, while the southeastern part of this system is rich in hydroelectric generation. The transmission system linking these parts is characterized by several long series capacitor-compensated transmission lines. System studies in this research are based on 54-bus, 12-machine, and 3-SVC model of the 400/230 kV southeastern network of the Mexican interconnected system.

4.2. Dynamic Voltage Support within the Study System

Dynamic voltage support by means of large SVCs is provided at the Temascal, Topilejo, and Texcoco 400 kV substations. Paramount to system operation, the SVC at the 400 kV Temascal substation plays an important role in system dynamic behavior. A simplified one-line diagram of the SVC is shown in Figure 4 illustrating major control characteristics. The SVC consists essentially of four groups of thyristor-controlled branches, two thyristor-switched capacitor groups (TSC), one thyristor-switched reactor group (TSR), and one thyristor-controlled reactor group (TCR). Each of these groups has a three-phase rating of 75 MVar to produce a total dynamic range of ± 300 MVar. Voltage control is achieved by an integral

Figure 3. One-line diagram of the study system showing major system components.
controller with current feedback to obtain sloped V-I characteristics [13, 14]. No supplemental modulation controls are presently used in this SVC. The SVCs at the Topilejo and Texcoco substation, on the other hand, have similar characteristics and are represented by a common model. Each SVC has an overall rating of +90 MVAR (inductive) to −300 MVAR (capacitive) provided by a 150 MVAR TCR branch, a 150 TSC branch, a 90 MVAR mechanical switched capacitor, and two harmonic filter branches rated 60 MVAR.

4.3. Modeling Considerations

Table 1 summarizes the torsional characteristics of major thermal and nuclear machines within the study area. Detailed generator models including shaft dynamics

<table>
<thead>
<tr>
<th>Power station</th>
<th>Type/rating</th>
<th>Mass model</th>
<th>Torsional frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tuxpan</td>
<td>Thermal</td>
<td>HP, LP, G</td>
<td>24.7, 36.7</td>
</tr>
<tr>
<td></td>
<td>6 × 350 MW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Valle de México</td>
<td>Thermal</td>
<td>HP, LP, IP, G</td>
<td>22.4, 29.6, 52.7</td>
</tr>
<tr>
<td></td>
<td>3 × 180 MW,</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 × 330 MW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Laguna Verde</td>
<td>Nuclear</td>
<td>HP, LP_A, LP_B, LP_C, G, EX</td>
<td>7.7, 13.9, 18.2, 19.7, 25.2</td>
</tr>
<tr>
<td></td>
<td>1 × 675 MW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tula</td>
<td>Thermal</td>
<td>HP, LP, G</td>
<td>19.6, 26.1, 47.1</td>
</tr>
<tr>
<td></td>
<td>5 × 350 MW</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
were used in the analysis. In addition, the following system modeling criteria were used in all subsequent studies:

- The dynamics of excitation systems and speed-governing controls was disregarded.
- The mechanical systems of hydro machines in the southern part of the study system were represented by simple lumped-mass models derived from manufacturer data. Electrical characteristics were represented in detail for all hydro machines including subtransient effects.
- Interconnections with neighboring systems were represented by a Thevenin equivalent at the point of connection. Each equivalent consists of a voltage source and a fundamental frequency impedance obtained from a separate study.

Other passive shunt elements are not represented in the diagram but were fully considered in the studies. The overall state model amounts to about 400 states for the base operating case.

4.4. System Studies

4.4.1. SSR due to series capacitive compensation. Eigenvalue studies were conducted to assess the potential for SSR problems occurring for large turbine-generator units due to the use of high levels of series compensation on the 400 kV network. The analysis here focuses on the impact of high levels of series compensation in the Temascal-PBD transmission line (refer to Figure 3) on SSR, as the compensation level in this line was recently adjusted from 47% to 75% of the line’s inductive reactance. Various operating conditions involving line outages, the loss of voltage support at Temascal, and weak system conditions to this end were studied to determine worst-case operating conditions.

The operating scenarios selected for study included

- Summer peak-load level conditions and the network structure indicated in Figure 3
- Different load and transmission levels considering several network configurations and compensation alternatives.

Figures 5 and 6 show the variation of the real part of the torsional roots of the Laguna Verde and Tuxpan generating stations as a function of the compensation level in the Temascal-PBD line. Eigenvalue studies indicate that increased levels of series compensation tend to reduce the damping of torsional vibration modes of machines at the Laguna Verde, Valle de Mexico, and Tuxpan generating stations. Potential SSR problems were detected for high compensation levels in excess of 80%, but this is considered to be of little practical importance for the study system.

Further studies revealed that the level of torsional damping of major generators is heavily dependent on network structure and system loading. The possibility of unstable subsynchronous oscillations appears from these studies primarily related to extremely weak operating conditions associated with double contingencies and the amount of power transferred through critical interconnectors. In contrast, the potential for SSR problems under light-load conditions could not be properly analyzed, since several series capacitor installations are automatically disconnected.
for low power flow transfers. These aspects are to be further addressed in future investigations.

4.4.2. SSTI with the Temascal SVC. System studies were further directed to examining the potential for SSTIs with the Temascal SVC control system. Care was taken to represent the SVC control loop effects in the subsynchronous frequency range including firing control delays in thyristors [14]. Dynamic effects below 7 Hz, especially associated with the damping of electromechanical modes, were not studied since this is the lowest frequency of concern for SSTI evaluation.

Impact of this device on SSTIs is of interest because (1) the SVC has a large size and (2) voltage support is provided at a weak system location in the vicinity of several series-compensated transmission lines. Further, the recent commissioning of several large thermal and nuclear machines within the study area raised concerns about potential SSTI problems with the nearby SVC.

Operating scenarios selected for SSTI evaluation included 1) system operation with and without voltage support at Temascal, and 2) the potential impact of high-gain operation, which might result in significant response of the Temascal SVC to subsynchronous frequencies. To examine the sensitivity of torsional damping to SVC control action, interaction indices (IIs) were computed for several operating conditions and control characteristics following the procedure set out in Section 3.

Figure 5. Plot of the real part of torsional mode eigenvalues of the Laguna Verde nuclear generating station as a function of series capacitor compensation.
Figure 6. Plot of the real part of torsional mode eigenvalues of the Tuxpan thermal generating station as a function of series capacitor compensation.

Figure 7 depicts normalized II between the Temascal input signal (terminal voltage) and the torsional modes of vibration of major generators. The analysis shows that the SVC has a strong impact on the degree of interaction with the 36.7 Hz torsional mode of the Laguna Verde nuclear station and the 7.7 Hz mode of the Tuxpan thermal station. On this basis, detailed eigenvalue studies to assess the contribution of this SVC to the torsional interaction were performed.

Figure 8 illustrates the effect of the loss of voltage support at Temascal on torsional damping as a function of the series compensation level in the line PBD-Temascal. As shown, the loss of the Temascal SVC is seen to have a destabilizing effect on the damping of the 36.7 Hz mode of the Tuxpan generating station. It is also interesting to note from Figure 8 that the loss of voltage support is more critical for reduced compensation levels in the transmission line PBD-Temascal and hence increased capacitive output for the Temascal SVC. Conversely, the loss of voltage support at higher compensation levels was found to have a rather marginal effect on torsional damping. This trend, however, is reversed for inductive operation of the SVC, under light-load conditions. Other studies indicated that the contribution of the SVC to the torsional interaction could be enhanced under high-stress conditions resulting from increased power transfers across the 400 kV network.

To investigate the impact of the control action on torsional interaction, the SVC control system gain and time constants were adjusted, and the damping of the torsional modes was recorded for several selected operating conditions. Figure 9 shows the real part of selected torsional mode eigenvalues as a function of the SVC gain ($K_{svc}$). Values are normalized with respect to the nominal setting ($K_{nom}$).
Figure 7. Normalized interaction indices showing the impact of the Temascal SVC control action on torsional damping.

Figure 8. Plot of the real part of torsional mode eigenvalues showing the effect of voltage support at Temascal.
Figure 9. Plot of the real part of torsional mode eigenvalues illustrating the effect of SVC voltage regulator gain on SSTIs.

It is shown that high SVC gains can have a destabilizing impact on torsional mode stability, especially on the 36.7 Hz mode of the Tuxpan generating station, as suggested from the analysis of controllability and observability measures. Other torsional modes were found to be practically insensitive to the control action. Again, the impact of the SVC on torsional damping was observed from other studies to be strongly dependent on network strength, power transfer, and the SVC operating point.

Other phenomena such as electrical instability associated with the SVC’s control loop were also detected for various operating conditions. Additional studies are now being conducted to quantify the effect of network-dependent parameters on SVC electrical instability and SSTIs.

5. Conclusions

In this paper a comprehensive analytical technique for the analysis of subsynchronous torsional mode instability due to interaction with FACTS devices has been presented. This approach is general enough to include complex ac/dc systems and can be used in conjunction with efficient techniques for the analysis of large sparse linear system models.

Study experience with a complex longitudinal system indicates that the application of high levels of series compensation might result in SSR problems for several major thermal and nuclear turbine-generator units under extreme operating conditions. The possibility of unstable subsynchronous oscillations in major generators appears from these studies, mainly related to the use of increased level of series compensation, the ac system strength, as well as the lack of voltage support.
SVCs can affect torsional damping through the control system response. This mechanism is rather complicated and depends on several factors such as the electrical distance between the SVC and the turbine-generator unit, the relative strength of the connecting system, and the SVC control characteristics and operating point. The inception of an SVC in a series capacitive-compensation transmission system poses additional problems that must be further investigated. System studies have shown that an SVC embedded in a complex series capacitor-compensated transmission system can affect torsional characteristics of remote generators. Major interacting factors affecting the torsional interaction include the level of series compensation, the SVC operating point and control setting, and system loading. Other aspects such as the use of modulation controls and the impact of multiple FACTS devices are to be addressed in future studies. Detailed nonlinear simulations are now being conducted to gain further insight on the nature of torsional interaction and the validity of the results.

References


