CHAPTER 4

STABILIZATION OF MULTIMACHINE POWER SYSTEM WITH FACTS DEVICES

4.1 INTRODUCTION

In this chapter, the impact of FACTS devices on the small signal stability of a multimachine multi area power system is investigated. During the course of investigation, the efficacy of FACTS controllers in enhancing stability is explored. This chapter also aims to propose an optimal tuning method for FACTS stabilizers to damp out interarea and local modes. The linearized model of the power system is derived with FACTS controllers and the problem is formulated as an optimization problem to maximize the damping ratio of the power system.

The following FACTS controllers are considered for small signal stability enhancement (i) Static Var Compensator (SVC) (ii) Static Compensator (STATCOM) (iii) Thyristor Controlled Series Capacitor (TCSC) (iv) Static Synchronous Series Compensator (SSSC) (v) Unified Power Flow Controller (UPFC).

4.2 BASIC APPROACH FOLLOWED FOR SMALL SIGNAL STABILITY ENHANCEMENT WITH PSS/FACTS CONTROLLER

The basic approach followed for small signal stability enhancement with the FACTS based damping controller is given below.
1. Get the linearized model of the multi-machine power system without the FACTS device around the nominal operating state and compute the damping ratio of the electro mechanical modes. Electromechanical modes, which have a damping ratio less than 0.1, are considered as critical modes. Choose the dominant critical mode. For a typical multi machine power system inter area (0.1-0.5 Hz) and local modes (1-2 Hz) are identified using the frequency range of the electromechanical modes.

2. For the dominant critical mode chosen, select the location of the FACTS controller based on the machines associated with that mode. If it is an inter area mode the location is chosen as one of the tie lines connecting the two areas. If the dominant critical mode is a local mode, the FACTS controller is located in the line emanating from the machine associated to that mode.

3. Compute the stabilizing gain and time constant of the FACTS based damping controller to maximize the damping ratio of the dominant critical mode using the parameter constrained optimization algorithm. The details of this algorithm for multimachine power system is presented in section 4.4.

4. Compute the elements of the linearized model with the FACTS controller using the optimized gain and time constant obtained. Compute the damping ratio of the electromechanical modes. Check whether all the critical modes have a damping ratio greater than 0.1.
5. If still there are critical modes, then choose the next dominant critical mode, proceed to step 2 to optimize the gain and time constant of the damping controller.

6. To ensure robustness of the stabilization process, the above approach is repeated for critical modes (if any) in the linearized model pertaining to overloaded condition.

The following section presents the basic approach for mathematical modeling of power system with FACTS devices for small signal stability enhancement.

4.3 MODELLING OF MULTI MACHINE POWER SYSTEM FOR SMALL SIGNAL STABILITY ENHANCEMENT

The mathematical model of the synchronous machines for multi-machine small signal analysis used in this chapter is the two-axis model of the synchronous machine. The following steps are required to compute the state space model of the multimachine power system with FACTS devices.

1. Formulate the algebraic equations in the network coordinates in the nodal form. While doing this, the machine internal nodes are explicitly included. The loads are represented as constant admittances. These admittances get added to the diagonal elements of the admittance matrix corresponding to the buses to which the loads are connected.

2. The series FACTS devices (TCSC, SSSC) are represented as a single current injection in either nodes of the connected line. However, if the device is a shunt-connected device (SVC, STATCOM) then the injections are confined only to one
node. UPFC is represented as two current injections in one node and one current injection in the other node.

3. Eliminate all the nodes except the generator’s and FACTS nodes. This results in a reduced set of algebraic equations. In these equations, only machine internal nodes and nodes due to FACTS controller are retained.

4. Transform the reduced set of equations obtained at the end of step 3 to individual machine qd coordinates.

5. Linearise the transformed equations at the end of step 4. This will yield appropriate expressions for the incremental changes in algebraic variables in terms of the incremental changes in state variables.

6. Linearise the differential equations for the machine and the controllers. The resulting equations will contain in general, incremental changes in algebraic variables.

7. Eliminate the incremental changes in the algebraic variables from the linearized differential equations obtained in step 6 using the expressions for the incremental changes derived in step 5. The resulting equations will be in the state variable form.

8. Compute the eigenvalues from the system state matrix with the state variables of the synchronous machine \[
\begin{bmatrix}
\delta, \omega, E_d', E_q'
\end{bmatrix}
\] and additional states due to FACTS controllers.
4.3.1 Development of Linearized Model of Multimachine Power System without FACTS controller

The network equation of a typical n machine power system is written as follows when transforming from the system reference to the individual machine d-q coordinates (Anderson and Fouad 1977).

\[
\begin{align*}
\Delta I_1 &= Y_{11}^q I_1^q + Y_{1n}^q I_n^q + \sum_{k=2}^{n} \left( Y_{1k}^q I_k^q + Y_{1k}^d I_k^d \right) - B_1^q E_1^q - B_1^d E_1^d \\
\Delta I_n &= Y_{nn}^q I_n^q + \sum_{k=1}^{n-1} \left( Y_{nk}^q I_k^q + Y_{nk}^d I_k^d \right) - B_n^q E_n^q - B_n^d E_n^d
\end{align*}
\]

(4.1)

where \( \Delta I_1 = \Delta I_{q1} + j \Delta I_{d1} \) is the change in current of machine 1 in d-q coordinates.

\( \Delta I_n = \Delta I_{qn} + j \Delta I_{dn} \) is the change in current of machine n in d-q coordinates.

The following generalized current equations (4.2, 4.3) given in d-q coordinates which is computed from the above matrix equation

\[
\begin{align*}
\Delta I_{qi} &= G_{qi} \Delta E_{qi} - B_{qi} \Delta E_{di} \\
&+ \sum_{k=1}^{n} [(G_{ki} \cos \delta_{kio} - B_{ki} \sin \delta_{kio}) \Delta E_{qk} - (B_{ki} \cos \delta_{kio} + G_{ki} \sin \delta_{kio}) \Delta E_{dk}] \\
&- (G_{ki} \sin \delta_{kio} + B_{ki} \cos \delta_{kio}) \Delta \delta_{ki} E_{qko} + (B_{ki} \sin \delta_{kio} - G_{ki} \cos \delta_{kio}) \Delta \delta_{ki} E_{dko} \\
\Delta I_{di} &= B_{qi} \Delta E_{qi} + G_{qi} \Delta E_{di} \\
&+ \sum_{k=1}^{n} [(G_{ki} \sin \delta_{kio} + B_{ki} \cos \delta_{kio}) \Delta E_{qk} + (G_{ki} \cos \delta_{kio} - B_{ki} \sin \delta_{kio}) \Delta E_{dk}] \\
&+ (G_{ki} \cos \delta_{kio} + B_{ki} \sin \delta_{kio}) \Delta \delta_{ki} E_{qko} - (B_{ki} \cos \delta_{kio} + G_{ki} \sin \delta_{kio}) \Delta \delta_{ki} E_{dko} \\
\end{align*}
\]

(4.2)

(4.3)
Substituting (4.2) and (4.3) in the differential equations of the synchronous machine with exciter in (2.2), (2.4) and torque equation (2.3) yields the system state space matrix with five state variables namely $[E'_d, E'_q, \omega, \delta, E_{FD}]$.

The differential equations describing the dynamic behavior of the synchronous machine with the excitation system are given by the equations as described in chapter two. Equation (2.2) describes the dynamic behavior of the synchronous machine without exciter. Equation (2.4) models the dynamics of the exciter circuit. Equations (2.5) and (2.6) govern the dynamics of the power system stabilizer, which uses speed deviations as the feedback signal.

4.3.2 Development of Linearized Model of Multimachine Power System with FACTS Controller for Small Signal Stability Enhancement

The change in network current with the introduction of SVC in the d-q reference frame is given below which is obtained from the equation (2.21),

\[
\Delta I_{qi} = G_{ki} \Delta E'_{qi} - B_{ki} \Delta E'_{di} \\
+ \sum_{k\neq i,j} [(G_{ki} \cos \delta_{kio} - B_{ki} \sin \delta_{kio}) \Delta E'_{qk} - (B_{ki} \cos \delta_{kio} + G_{ki} \sin \delta_{kio}) \Delta E'_{dk} \\
-(G_{ki} \sin \delta_{kio} + B_{ki} \cos \delta_{kio}) \Delta \delta_{kio} E'_{qko} + (B_{ki} \sin \delta_{kio} - G_{ki} \cos \delta_{kio}) \Delta \delta_{kio} E'_{dko} ] \\
+ \sum_{j \neq i,j} [(G_{ji} \cos \delta_{jio} - B_{ji} \sin \delta_{jio}) \Delta V_{srj} - (B_{ji} \cos \delta_{jio} + G_{ji} \sin \delta_{jio}) \Delta V_{smj} \\
-(G_{ji} \sin \delta_{jio} + B_{ji} \cos \delta_{jio}) \Delta \delta_{jio} V_{sro} + (B_{ji} \sin \delta_{jio} - G_{ji} \cos \delta_{jio}) \Delta \delta_{jio} V_{smj} ]
\] (4.4)
\[ \Delta I_{\text{di}} = B_{ii} \Delta E'_{\text{di}} + G_{ii} \Delta E_{\text{di}} \\
+ \sum_{k \neq i} \left[(G_{ki} \sin \theta_{kio} + B_{ki} \cos \theta_{kio}) \Delta E'_{qk} + (G_{ki} \cos \theta_{kio} - B_{ki} \sin \theta_{kio}) \Delta E'_{dk} \right] \\
+ (G_{ki} \cos \theta_{kio} - B_{ki} \sin \theta_{kio}) \Delta \phi_{kio} + (B_{ki} \cos \theta_{kio} + G_{ki} \sin \theta_{kio}) \Delta E'_{dko} \\
+ \sum_{j} \left[(G_{ji} \sin \theta_{jio} + B_{ji} \cos \theta_{jio}) \Delta E'_{qj} + (G_{ji} \cos \theta_{jio} - B_{ji} \sin \theta_{jio}) \Delta E_{jko} \right] \\
+ (G_{ji} \cos \theta_{jio} - B_{ji} \sin \theta_{jio}) \Delta \phi_{jio} + (B_{ji} \cos \theta_{jio} + G_{ji} \sin \theta_{jio}) \Delta \phi_{jio} \] (4.5)

Substituting (4.4) and (4.5) in the differential equations of the synchronous machine with exciter in (2.2), (2.4) and eliminating the algebraic variables from torque equation of (2.3), the dynamic equations of the SVC for small signal analysis which are given by (2.18-2.20) yields the system state space matrix with the state variables namely

\[ [E'_{d}, E'_{q}, \phi, E_{FD}, B_{L}, X_{w}, X_{le}] \]

Substituting (4.4) and (4.5) in the differential equations of the synchronous machine with exciter in (2.2), (2.4) and eliminating the algebraic variables from torque equation of (2.3), the dynamic equations of the FACTS device yields the system state space matrix of the multimachine power system with the dynamics of FACTS controllers.

The dynamic equations of STATCOM with the damping controller are given by equations (2.25) to (2.31) described in chapter 2.

The differential equations describing the dynamic behavior of TCSC are given by equations (2.34-2.36). The differential equations that govern the dynamics of SSSC in the network are given by equations (2.39-2.45).

The mathematical model of UPFC used for dynamic analysis combines the dynamic equations of SSSC (2.39-2.45) for the series converter and equations (2.25-2.29) for the shunt converter.
The following section presents the mathematical background required for optimal tuning of the damping controller parameters in FACTS stabilizers.

### 4.3.3 Optimal Tuning of FACTS Stabilizer

The damping controller structure used with the FACTS controllers has three controller blocks namely (i) Gain (ii) Washout and a (iii) Lead/Lag filter. The stabilizer gain \( K_{\text{stab}} \) determines the amount of damping introduced by the damping controller. The signal washout block serves as a high pass filter, with the time constant high enough to allow oscillations in the stabilizing signal to pass unchanged. Without it steady changes in the stabilizing signal would modify the FACTS controller output. From the viewpoint of the washout function, the value of \( T_w \) is not critical and fixed in the range of 1 to 20 seconds. Hence, the stabilizing gain \( K_{\text{stab}} \) and the lead lag filter time constant \( T_1 \) are chosen as critical parameters to be optimized. The optimization problem for tuning the parameters of FACTS stabilizers is formulated below.

Statement of the problem:

\[
\begin{align*}
\text{Maximize} & \quad f(K_{\text{stab}}, T_1) = \zeta(K_{\text{stab}}, T_1) \\
\text{subject to constraints} & \quad K_{\text{min}} \leq K_{\text{stab}} \leq K_{\text{max}} \\
& \quad T_{\text{min}_1} \leq T_1 \leq T_{\text{max}_1}
\end{align*}
\]

where \( \zeta \) is the damping ratio of the critical electromechanical mode.
The induced torque due to FACTS stabilizer \( j \) is related to the speed perturbation of generator \( i \), \((\Delta \omega_i)\) by a complex induced torque coefficient \( D_{ij}^h \), defined by

\[
\Delta T_{e_{ij}}(\lambda_h) = D_{ij}^h \Delta \omega_i(\lambda_h)
\]

(4.9)

where

\[
D_{ij}^h = \frac{\Delta T_{e_{ij}}(\lambda_h)}{\Delta \omega_i(\lambda_h)}
\]

(4.10)

and

\[
D_{ij}^h(s) = \frac{\Delta T_{e_{ij}}(s)}{\Delta \omega_i(s)} = \frac{\Delta T_{e_{ij}}(s)}{\Delta U_s(s)} \frac{\Delta U_s(s)}{\Delta \lambda_i(s)} \frac{\Delta \lambda_i(s)}{\Delta \omega_i(s)}
\]

(4.11)

\[
G(s) = \frac{\Delta T_{e_{ij}}(s)}{\Delta U_s(s)} \quad \text{and} \quad H(s) = \frac{\Delta U_s(s)}{\Delta \lambda_i(s)}
\]

(4.12)

\( G(s) \) is the transfer function between reference input of FACTS device and the electrical torque output of generator \((\Delta T_{e_{ij}})\) in the forward path.

\[
G(s) = C_q^* [sI - A]^{-1} B
\]

(4.13)

\( H(s) \) is the transfer function of the FACTS based stabilizer between the stabilizing signal and the FACTS device input. \( C_q^* \) is the state output vector corresponding to the electric torque output of machine \( i \).

If only the \( h \)th complex mode of rotor oscillation \( \lambda_h \) is excited then the relationship between the speed perturbation on any machine and any system output is given by
\[
\frac{\Delta y_1(s)}{\Delta \omega_i(s)} = \frac{C_{q^*} \Phi_{*h}}{\Phi_{ih}}
\]  
(4.14)

\[
D_{ij}^h = G(s) H(s) (C_{q^*} \Phi_{*h} / \Phi_{ih})
\]  
(4.15)

Equating \(D_{ij}^h\) with the coefficient of the damping term in the second order system equation \((Ms^2 + (D + D_{ij}^h)s + K_1) = 0\) and neglecting system damping

\[
D_{ij}^h = 2\zeta_h M_1
\]  
(4.16)

The damping ratio of the critical electromechanical mode can be written in terms of the FACTS stabilizer gain as given below.

\[
\zeta_i = \frac{K_{stab} \sqrt{(1 + \omega_h^2 T_1) |G(s)|_s = j\omega_h M_1 (C_{q^*})}}{\sqrt{(1 + \omega_h^2 T_2) (2\omega_h M_1) (\Phi_{ih})}}
\]  
(4.17)

4.4 NUMERICAL EXAMPLE

The multimachine system taken up for small signal stability study with PSS and FACTS based damping controllers is the 4-generator two-area system shown in Figure 4.1 (Kundur 1994). Each area consists of two generating units, each having a rating of 900 MVA and 20 KV. The system is operating with area 1 exporting 400 MW to area 2. The shunt connected FACTS devices are located at bus 7 in the network. The series devices are located between buses 7 and 8 nearer to bus 7. For series devices the real power flow between buses 7-8 is taken as the stabilizing signal. For shunt devices, the bus voltage deviation (bus 7) is taken as the stabilizing signal.
4.4.1 Eigenvalue Analysis

Table 4.1 summarizes the eigenvalues of the system state matrix and the electromechanical modes of the system. From the table it is clear that there are three electro mechanical modes [(9, 10), (11, 12) and (13, 14)] which have a damping ratio less than 0.1. The interarea mode corresponds to mode (13, 14) and the damping ratio of this critical mode is 0.0371.

The induced torque is computed for the most critical mode which is associated to machine G3. Since the inter area mode is the most critical mode (ζ=0.0371) the FACTS stabilizers are located in the one of the two identical tie lines connecting the two areas.

Table 4.1 Eigenvalue analysis of the two-area system

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Eigenvalues</th>
<th>Damping ratio (ζ)</th>
<th>Frequency (Hz)</th>
<th>Nature of oscillatory mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-100</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>-100</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>-99.9</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>-99.9</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>-19.9</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>-19.9</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>-20</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>
To enhance the damping of the electromechanical modes power system stabilizers are connected to excitation system one in machine G1 and other in machine G3. Table 4.2 displays the participation factors of the electromechanical modes of the two area system.

Table 4.2 Participation of the generators in the Electro mechanical modes of the two- area test system.

<table>
<thead>
<tr>
<th>Eigenvalues</th>
<th>G1</th>
<th>G2</th>
<th>G3</th>
<th>G4</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.54288 ± 6.529i</td>
<td>0.0097</td>
<td>0.0217</td>
<td>0.4692</td>
<td>0.5052</td>
</tr>
<tr>
<td>-0.51649 ± 6.6352i</td>
<td>0.4666</td>
<td>0.5056</td>
<td>0.0245</td>
<td>0.0088</td>
</tr>
<tr>
<td>-0.12107 ± 3.257i</td>
<td>0.2642</td>
<td>0.1795</td>
<td>0.3048</td>
<td>0.2539</td>
</tr>
</tbody>
</table>

From table 4.2 it can be observed that the first electromechanical mode is a local mode associated with machines G3 and G4. The second swing mode is associated with machines G1 and G2. In contrast, mode -0.12107 ± 3.257i is an inter-area mode since the participation is distributed among all generators. Table 4.3 displays the eigenvalue analysis results with FACTS devices.

Table 4.3 tabulates the results of the eigenvalue analysis of the two-area system with PSS connected in G1 and G3. The eigenvalue analysis of the two-area system is given below without the FACTS controller, with PSS connected to each area (Generators G1 and G3) and with FACTS devices placed one at a time.
Table 4.3 Eigenvalue Analysis of the Two Area System with PSS/FACTS -Base Case

<table>
<thead>
<tr>
<th>S. No</th>
<th>Without Damping Controllers</th>
<th>Without PSS</th>
<th>With PSS</th>
<th>With SVC</th>
<th>With STATCOM</th>
<th>With TCSC</th>
<th>With SSSC</th>
<th>With UPFC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(-0.54288 \pm 6.529i) (\epsilon = 0.0829) (f=1.05Hz)</td>
<td>-1.477 (\pm 9.4174i) (\epsilon = 0.155)</td>
<td>-1.6588 (\pm 9.2666i) (\epsilon = 0.1762)</td>
<td>-2.4467 (\pm 9.3496i) (\epsilon = 0.2532)</td>
<td>-1.255 (\pm 5.391i) (\epsilon = 0.2268)</td>
<td>-1.835 (\pm 6.0282i) (\epsilon = 0.2914)</td>
<td>-2.16 (\pm 6.1978i) (\epsilon = 0.3291)</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>(-0.51649 \pm 6.6352i) (\epsilon = 0.0782) (f=1.06Hz)</td>
<td>-0.82186 (\pm 7.713i) (\epsilon = 0.1059)</td>
<td>-1.112 (\pm 7.728i) (\epsilon = 0.1424)</td>
<td>-3.321 (\pm 8.5579i) (\epsilon = 0.3617)</td>
<td>-3.408 (\pm 10.7407i) (\epsilon = 0.3024)</td>
<td>-4.8934 (\pm 7.1969i) (\epsilon = 0.5623)</td>
<td>-5.327 (\pm 7.464i) (\epsilon = 0.574)</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>(-0.12107 \pm 3.257i) (\epsilon = 0.0381) (f=0.519 Hz) Intarea Mode</td>
<td>-0.1206 (\pm 1.1724i) (\epsilon = 0.1024)</td>
<td>-1.56455 (\pm 5.036i) (\epsilon = 0.2966)</td>
<td>-1.244 (\pm 5.202i) (\epsilon = 0.2324)</td>
<td>-0.9387 (\pm 5.285i) (\epsilon = 0.1749)</td>
<td>-1.636 (\pm 4.919i) (\epsilon = 0.3156)</td>
<td>-1.892 (\pm 2.948i) (\epsilon = 0.5402)</td>
<td></td>
</tr>
</tbody>
</table>

From Table 4.3 it can be observed that the damping ratio of local modes have improved from the base case value to 0.155 and 0.1059 with power system stabilizers in machines G1 and the damping ratio of the interarea mode is 0.1024. With SVC in the network, the damping ratio improves to 0.2966 for the inter area mode and 0.1762, 0.1424 for the two local modes. With STATCOM the damping ratio of the interarea mode improves to 0.2324. Also, the damping ratios of both the local modes are enhanced to 0.2532 and 0.3617. With TCSC in the tie line the damping ratio of the interarea mode improves to 0.1749. The damping ratios of the local modes have increased to 0.2268 and 0.3024. The damping ratio of the interarea mode improves to 0.3156 with SSSC in the network, whereas the local modes improve to 0.2914 and 0.5623. The damping ratio of the interarea modes is 0.5402 with UPFC in the network, whereas the local modes enhance to 0.3291 and 0.574.

Comparing the series connected FACTS devices it can be observed that the UPFC and SSSC give the best damping effort to damp out both
interarea and local modes effectively. Among shunt connected devices STATCOM provides the best damping effort compared to the SVC. Table 4.4 displays the eigenvalue analysis results of the two area system with the total system load increased by 20%. It can be observed that with the increase in system load the damping ratio of the electromechanical modes are stable higher than 0.1 with tuned FACTS controllers in the network.

**Table 4.4 Eigenvalue Analysis of the Two Area System with PSS/FACTS -Increased Loading**

<table>
<thead>
<tr>
<th>S.No</th>
<th>Without Damping Controllers</th>
<th>With PSS</th>
<th>With SVC</th>
<th>With STATCOM</th>
<th>With TCSC</th>
<th>With SSSC</th>
<th>With UPFC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.5428 ± 6.529i</td>
<td>-16.588 ± 9.417i</td>
<td>-1.2603 ± 7.44198i</td>
<td>-3.2799 ± 10.0659i</td>
<td>-1.2403 ± 5.6022i</td>
<td>-0.1696 ± 0.6295i</td>
<td>-1.6851 ± 6.292i</td>
</tr>
<tr>
<td></td>
<td>ζ=0.0829 f=1.04Hz</td>
<td>ζ=0.1736</td>
<td>ζ=0.1669</td>
<td>ζ=0.3082</td>
<td>ζ=0.2158</td>
<td>ζ=0.2586</td>
<td>ζ=0.2576</td>
</tr>
<tr>
<td>2</td>
<td>-0.5164 ± 6.635i</td>
<td>-0.7717 ± 10.962i</td>
<td>-1.07445 ± 7.751i</td>
<td>-4.02259 ± 8.4448i</td>
<td>-3.215 ± 11.2346i</td>
<td>-0.4901 ± 0.7163i</td>
<td>-4.90477 ± 7.182i</td>
</tr>
<tr>
<td></td>
<td>ζ=0.0776 f=1.05Hz</td>
<td>ζ=0.1373</td>
<td>ζ=0.4294</td>
<td>ζ=0.275</td>
<td>ζ=0.5626</td>
<td>ζ=0.5639</td>
<td>ζ=0.5639</td>
</tr>
<tr>
<td>3</td>
<td>-0.12064 ± 3.257i</td>
<td>-0.11687 ± 1.2064i</td>
<td>-1.849 ± 2.978i</td>
<td>-1.3119 ± 5.413i</td>
<td>-0.73138 ± 5.308i</td>
<td>-0.16588 ± 0.4901i</td>
<td>-1.6625 ± 4.9575i</td>
</tr>
<tr>
<td></td>
<td>ζ= 0.0371 f=0.518Hz Interarea Mode</td>
<td>ζ=0.0961</td>
<td>ζ=0.5268</td>
<td>ζ=0.2366</td>
<td>ζ=0.1361</td>
<td>ζ=0.3173</td>
<td>ζ=0.3177</td>
</tr>
</tbody>
</table>

To verify the effectiveness of the FACTS based stabilizers to damp out multiple interarea modes the 10 Machine, 39 bus New England system is taken for small signal analysis (Figure 4.2). All the synchronous machines are modeled using two axis model.
Linearized analysis of the New England system is carried out around the operating state given in Padiyar.K.R (2004). Table 4.5 reveals 9 electro mechanical modes of the system out of which the last three modes are interarea modes. The shunt connected FACTS devices are located at bus 13 which is a connecting bus in the tie line. The series connected FACTS devices are located in the line 13 -14.
Table 4.5 Eigenvalue Analysis of New England System–Effect of FACTS stabilizers

<table>
<thead>
<tr>
<th>S.No</th>
<th>Without Damping Controllers</th>
<th>With SVC</th>
<th>With STATCOM</th>
<th>With TCSC</th>
<th>With SSSC</th>
<th>With UPFC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.3925 ± 7.369i</td>
<td>-0.79798 ± 7.0398i</td>
<td>-1.1272 ± 7.1372i</td>
<td>-1.15552 ± 7.4889i</td>
<td>-1.15866 ± 6.8012i</td>
<td>-1.34706 ± 7.6396i</td>
</tr>
<tr>
<td></td>
<td>ζ = 0.05318 f = 1.17 Hz</td>
<td>ζ = 0.13783</td>
<td>ζ = 0.15601</td>
<td>ζ = 0.15249</td>
<td>ζ = 0.16794</td>
<td>ζ = 0.17365</td>
</tr>
<tr>
<td>2</td>
<td>-0.31714 ± 6.54062i</td>
<td>-0.79128 ± 6.20464i</td>
<td>-0.90746 ± 6.21406i</td>
<td>-0.85094 ± 6.2643i</td>
<td>-0.97026 ± 6.00682i</td>
<td>-1.02992 ± 6.27372i</td>
</tr>
<tr>
<td></td>
<td>ζ = 0.04843 f = 1.041 Hz</td>
<td>ζ = 0.12651</td>
<td>ζ = 0.14450</td>
<td>ζ = 0.1346</td>
<td>ζ = 0.15946</td>
<td>ζ = 0.16199</td>
</tr>
<tr>
<td>3</td>
<td>-0.30458 ± 6.95196i</td>
<td>-1.32194 ± 6.11358i</td>
<td>-1.15866 ± 6.03822i</td>
<td>-1.45622 ± 5.95016i</td>
<td>-1.48522 ± 5.69282i</td>
<td>-1.69246 ± 6.26116i</td>
</tr>
<tr>
<td></td>
<td>ζ = 0.04377 f = 1.077 Hz</td>
<td>ζ = 0.21601</td>
<td>ζ = 0.16732</td>
<td>ζ = 0.23456</td>
<td>ζ = 0.25244</td>
<td>ζ = 0.26095</td>
</tr>
<tr>
<td>4</td>
<td>-0.25434 ± 6.27372i</td>
<td>-0.91374 ± 5.80272i</td>
<td>-0.9891 ± 5.82744i</td>
<td>-0.95456 ± 5.79016i</td>
<td>-0.9924 ± 5.55466i</td>
<td>-1.00794 ± 5.8875i</td>
</tr>
<tr>
<td></td>
<td>ζ = 0.04051 f = 0.999 Hz</td>
<td>ζ = 0.15555</td>
<td>ζ = 0.16732</td>
<td>ζ = 0.16266</td>
<td>ζ = 0.17585</td>
<td>ζ = 0.16874</td>
</tr>
<tr>
<td>5</td>
<td>-0.52124 ± 5.31916i</td>
<td>-0.080384 ± 5.59862i</td>
<td>-0.77558 ± 5.23438i</td>
<td>-0.77244 ± 5.55466i</td>
<td>-0.79128 ± 5.33172i</td>
<td>-0.85094 ± 5.63316i</td>
</tr>
<tr>
<td></td>
<td>ζ = 0.09753 f = 0.847 Hz</td>
<td>ζ = 0.14212</td>
<td>ζ = 0.14657</td>
<td>ζ = 0.13774</td>
<td>ζ = 0.1468</td>
<td>ζ = 0.14936</td>
</tr>
<tr>
<td>6</td>
<td>-0.6908 ± 5.08366i</td>
<td>-0.067824 ± 5.14644i</td>
<td>-0.81296 ± 5.10564i</td>
<td>-0.7065 ± 5.06482i</td>
<td>-0.75674 ± 5.0711i</td>
<td>-0.75674 ± 5.15</td>
</tr>
<tr>
<td></td>
<td>ζ = 0.01359 f = 0.8095 Hz</td>
<td>ζ = 0.13066</td>
<td>ζ = 0.1573</td>
<td>ζ = 0.13815</td>
<td>ζ = 0.14759</td>
<td>ζ = 0.14522</td>
</tr>
<tr>
<td>7</td>
<td>-0.1099 ± 4.86836i</td>
<td>-1.09272 ± 4.76966i</td>
<td>-1.14296 ± 4.82304i</td>
<td>-1.17122 ± 4.81048i</td>
<td>-1.07702 ± 4.31122i</td>
<td>-1.17122 ± 4.8042i</td>
</tr>
<tr>
<td></td>
<td>ζ = 0.0226 f = 0.7745 Hz</td>
<td>ζ = 0.22331</td>
<td>ζ = 0.23059</td>
<td>ζ = 0.23656</td>
<td>ζ = 0.24237</td>
<td>ζ = 0.23671</td>
</tr>
<tr>
<td>8</td>
<td>-0.08792 ± 4.64092i</td>
<td>-0.55264 ± 4.43682i</td>
<td>-0.56206 ± 4.67546i</td>
<td>-0.56834 ± 4.59068i</td>
<td>-0.56206 ± 4.16678i</td>
<td>-0.6060 ± 4.39914i</td>
</tr>
<tr>
<td></td>
<td>ζ = 0.01894 f = 0.739 Hz</td>
<td>ζ = 0.1236</td>
<td>ζ = 0.11936</td>
<td>ζ = 0.12287</td>
<td>ζ = 0.13368</td>
<td>ζ = 0.13647</td>
</tr>
<tr>
<td>9</td>
<td>-0.05338 ± 3.6267i</td>
<td>-0.46786 ± 3.54506i</td>
<td>-0.46158 ± 3.15256i</td>
<td>-0.48984 ± 3.51994i</td>
<td>-0.46472 ± 3.23106i</td>
<td>-0.078186 ± 4.62522i</td>
</tr>
<tr>
<td></td>
<td>ζ = 0.01472 f = 0.5775 Hz</td>
<td>ζ = 0.13084</td>
<td>ζ = 0.14487</td>
<td>ζ = 0.13783</td>
<td>ζ = 0.14236</td>
<td>ζ = 0.16668</td>
</tr>
</tbody>
</table>

From the results, it is evident among shunt-connected devices STATCOM provides the best damping effect. UPFC provides the best damping effect among series connected FACTS devices compared to TCSC.
and SSSC. It should be noted that the damping effect of UPFC is superior to all the FACTS devices discussed.

### 4.5 DYNAMIC SIMULATION OF THE TWO-AREA SYSTEM FOR A THREE-PHASE FAULT

To examine the performance and robustness of the FACTS controller in the system, following a major disturbance transient stability simulations are conducted. A three-phase fault is applied on line 7-8 on the two-area system at 1 second in the second line, which is cleared in 1.1 seconds. Fig 4.3 shows the rotor angle response of the generators G1-G4 when a three-phase fault is applied in one of the lines.

![Figure 4.3 Rotor angle response of synchronous generators without damping controllers](image)

Figure 4.3 Rotor angle response of synchronous generators without damping controllers
It can be observed that the rotor angles of all the synchronous generators oscillate around their steady state value without FACTS controllers in the network

4.5.1 Dynamic Simulation of the Two-area system – Effect of Shunt Connected FACTS Devices

Figure 4.4 shows the rotor angle response of the two-area system with SVC connected to bus 8 in the system.

Figure 4.4 Rotor angle response of synchronous generators – Effect of SVC
From Figure 4.4 it can be observed that the rotor angle oscillations are damped out after a 4 seconds with the inclusion of SVC in the network. It is observed that the system is dynamically stable.

Figure 4.5 shows the rotor angle response of the synchronous generators with STATCOM in the network. It is observed that the settling time is 3 seconds.

Figure 4.5  Rotor angle responses of synchronous generators –Effect of STATCOM

Figure 4.5 shows the rotor angle response of the synchronous generators with STATCOM in the network. It is observed that the settling time is 3 seconds.
4.5.2 Dynamic Simulation of the Two-area System – Effect of Series Connected FACTS Devices

Figure 4.6 shows the rotor angle response of the synchronous generators with TCSC in the network.

![Rotor angle response of synchronous generators – Effect of TCSC](image)

Figure 4.6  Rotor angle response of synchronous generators – Effect of TCSC

From the figure it can be observed that that the system is stable with a settling time of 4 seconds. Figure 4.7 shows the rotor angle response of the synchronous generator with SSSC in the network.
The system is stable with a settling time of 2 seconds with SSSC in the network. Figure 4.8 shows the rotor angle response of the generators with UPFC in the network.

Figure 4.7 Rotor angle response of synchronous generators- Effect of SSSC
It can be observed that there are no significant overshoots in the rotor angle response of the generators and the settling time is very low.

4.6 CONCLUSION

This chapter has investigated the effectiveness of FACTS controllers in damping both interarea and local oscillations in a two-area 4-machine power system. It is demonstrated that both interarea and local oscillations, can be effectively damped using series/shunt connected FACTS controllers by properly placing them in selected tie lines/nodes of the system. This section has developed a generalized multimachine small signal stability
model with FACTS controllers. A nonlinear parameter constrained optimization model is proposed to tune the damping controller parameters (gain and time constant). The tuning methodology adopted for the single machine infinite bus system is extended to the multimachine power system to optimize the gain and time constant of the damping controller.

It is observed that among shunt connected devices, STATCOM provides a better damping performance compared to SVC. Among series connected FACTS devices SSSC is very effective to enhance the small signal stability of the system. With UPFC the system damping ratio is higher compared to the other FACTS devices.