An attempt has been made in this paper to investigate the small signal stability problem of a real multimachine power system with the application of Thyristor Controlled Series Compensator (TCSC). Though Power System Stabilizers (PSS) are mandatory requirements for damping of oscillations in the power system, its performance gets affected by changes in network configurations, load variations etc. In order to achieve appreciable damping, installation of TCSC has been suggested here in addition to conventional PSS. However, the performance of any FACTS device highly depends upon its parameters and its placement at suitable locations in the power network. In this paper, a soft computing technique, Particle Swarm Optimization (PSO) has been employed for determining the optimal locations and parameters of the TCSC controller in order to mitigate small signal oscillations. In addition to this, based on critical eigenvalue variations a new indicator being termed as Small Signal Stability Rank (SSSR) has been proposed for assessment of effectiveness of the PSO based TCSC controller for three major contingencies.

Keywords: Particle Swarm Optimization, Small Signal Stability, Small Signal Stability Rank, Thyristor Controlled Series Compensator.

1. INTRODUCTION

The problem of low frequency (0.2-1.0Hz) oscillations is a long-standing issue in electric power systems. These oscillations may sustain and grow up to cause severe system outage if adequate damping is not available. Traditionally, potential benefits of using the PSS to damp these oscillations for enhancing power system stability are well known [1]. With the development of power electronics, Flexible Alternating Current transmission system (FACTS) devices [2] have gathered much attention from the researcher in order to mitigate several power system operation problems. Out of many FACTS devices [3], Thyristor Controlled Series Compensator (TCSC) has been proven to be very robust and effective means [4] for mitigating small signal oscillation problem in long transmission lines of modern power systems.

The power electronic controlled devices such as Static VAR Compensators (SVC), HVDC link and Controllable Series Compensator (CSC) have traditionally been used in transmission networks for many years in order to mitigate small signal stability problem [5, 6]. A supplementary TCSC damping controller has been designed in [7] thereby achieving good damping characteristics by coordinated application of the TCSC and PSS. In [8], the problem electromechanical oscillations has been discussed based on Hopf bifurcation theory, and then compares the application of PSS, SVC, and STATCOM controllers. A new set of controllability indices has been proposed in [9] in order to find the optimal location of FACTS (UPFC, TCSC and SVC) controllers for enhancing damping of small signal oscillations and thus, improving the system stability.

It is a well known fact that the conventional techniques reported in literatures [10, 11] for tuning of power system analysis controllers are time consuming, require heavy computation burden and have slow convergence rate. In recent years, Particle Swarm
Optimization (PSO) technique [12] has appeared as a promising algorithm for handling the optimization problems. PSO can generate high-quality solutions within shorter calculation time and has more stable convergence characteristics than other stochastic methods [13, 14].

The optimal allocation of TCSC has been reported in literatures [15, 16] based on different aspects - optimal power flow (OPF) with lowest cost generation, reactive power planning, maximization of the system loadability etc. However, to date, to the best of authors’ knowledge finding the optimal location and parameters of the TCSC controller based on mitigation of small signal oscillations has not been fully investigate yet. In this paper this problem has been taken into consideration and PSO has been implemented for tuning and optimal allocation of the TCSC controller. Though PSO has been employed in several research papers [17, 18] for the design of optimal FACTS controllers, the applications are mostly limited to the case of single machine infinite bus system or standard test systems only.

In this paper a realistic multimachine power system has been taken as a test case and simulation conducted considering full-order linearized model including all type of network buses. The main objective is to study the impact of TCSC on enhancing power system small signal stability when system is being subjected to disturbances like variation of load, generation drop and transmission line outage and a new indicator, SSSR has been suggested to knowledge better effectiveness of the TCSC controller for these disturbances.

2. SMALL SIGNAL MODELING

2.1 Modeling of PSS and TCSC

The basic theory and the modeling of the PSS have been illustrated in [19]. The state-space equation of a single-stage PSS with gain $K_{PSS}$ can be written as

$$\Delta V_s = -\frac{1}{\tau_2} \Delta V_s + \frac{K_{PSS}}{\tau_2} \Delta v + \frac{K_{PSS} \tau_1}{\tau_2} \Delta \dot{v}$$  \hspace{1cm} (1)

where $\Delta v$ is the normalized speed input and $\Delta V_s$ is the output state of the PSS. $\tau_1$ and $\tau_2$ are the lead and lag time constants.

The basic TCSC module (Fig. 1) consists of a fixed series capacitor bank $C$ in parallel with a Thyristor Controlled Reactor (TCR). This simple model utilizes the concept of a variable series reactance $X_{TCSC}$ [20]. The series reactance, $X_{TCSC}$ is adjusted through appropriate variation of the firing angle ($\alpha$) in order to allow the specified amount of active power flow across the series compensated line.

The transfer function model of a TCSC controller [21] has been shown in Fig. 2. The input signal, ($\Delta v = \Delta \omega/\omega_s$) is the normalized speed deviation, and output signal is the stabilizing signal (i.e. deviation in conduction angle, $\Delta \sigma$). $X_{TCSC}$ is the linearized TCSC reactance. Neglecting the washout stage, the proposed TCSC controller model can be represented by following state equations;

$$\Delta \dot{\alpha} = -\frac{1}{T_2} \Delta \alpha - \frac{K_{TCSC}}{\omega_s} \left( \frac{1}{T_2} \right) \Delta \omega - \frac{K_{TCSC}}{\omega_s} \left( \frac{T_1}{T_2} \right) \Delta \dot{\omega}$$  \hspace{1cm} (2)

$$\Delta \dot{X}_{TCSC} = -\frac{1}{T_{TCSC}} \Delta \alpha - \frac{1}{T_{TCSC}} \Delta X_{TCSC}$$  \hspace{1cm} (3)
2.2 Multimachine linearized-model with PSS and TCSC

The small signal modeling of a multimachine system with IEEE-Type I exciter has been described in [19]. All linearized equations relating to the performance of the machine with exciter, PSS and network power flow are represented by the following state-space equations

$$\Delta \dot{X} = A_1 \Delta X + B_1 \Delta I_g + B_2 \Delta V_g + E_1 \Delta U$$

$$0 = C_1 \Delta X + D_1 \Delta I_g + D_2 \Delta V_g$$

$$0 = C_2 \Delta X + D_3 \Delta I_g + D_4 \Delta V_g + D_5 \Delta V_l$$

$$0 = D_6 \Delta V_g + D_7 \Delta V_l$$

Here equations (4) and (5) represent the linearized differential equations and linearized stator algebraic equations of the machine, while equations (6) and (7) correspond to the linearized network equations pertaining to the generator buses and the load buses. The multimachine linearized model with PSS and TCSC controller has been formulated by adding the state variables corresponding to the PSS ($\nu_s$) and the TCSC controller ($\nu_{TCSC}$) with the equations (4)-(6). The TCSC power flow equation is included in the network equation (7). The TCSC linearized real and reactive power flow equations at the node $s$ and $t$ can be obtained by the following expressions

$$0 = \begin{bmatrix} \frac{\partial P_s}{\partial \nu_s} & \frac{\partial P_s}{\partial \nu_t} & \frac{\partial P_s}{\partial \nu_{TCSC}} \\ \frac{\partial Q_s}{\partial \nu_s} & \frac{\partial Q_s}{\partial \nu_t} & \frac{\partial Q_s}{\partial \nu_{TCSC}} \\ \frac{\partial P_{st}}{\partial \theta_s} & \frac{\partial P_{st}}{\partial \theta_t} & \frac{\partial P_{st}}{\partial \theta_{TCSC}} \\ \frac{\partial Q_{st}}{\partial \theta_s} & \frac{\partial Q_{st}}{\partial \theta_t} & \frac{\partial Q_{st}}{\partial \theta_{TCSC}} \\ \frac{\partial \theta_s}{\partial \nu_s} & \frac{\partial \theta_s}{\partial \nu_t} & \frac{\partial \theta_s}{\partial \nu_{TCSC}} \\ \frac{\partial \theta_t}{\partial \nu_s} & \frac{\partial \theta_t}{\partial \nu_t} & \frac{\partial \theta_t}{\partial \nu_{TCSC}} \end{bmatrix} \begin{bmatrix} \Delta \nu_s \\ \Delta \nu_t \\ \Delta \nu_{TCSC} \end{bmatrix}$$

Here,

$$\nu_{TCSC} = \left[ \begin{array}{c} \Delta \alpha \\ \Delta X_{TCSC} \end{array} \right]^T$$

with the equations (4)-(6). The TCSC power flow equation is included in the network equation (7). The TCSC linearized real and reactive power flow equations at the node $s$ and $t$ can be obtained by the following expressions

$$\begin{bmatrix} \frac{\partial P_s}{\partial \nu_s} & \frac{\partial P_s}{\partial \nu_t} & \frac{\partial P_s}{\partial \nu_{TCSC}} \\ \frac{\partial Q_s}{\partial \nu_s} & \frac{\partial Q_s}{\partial \nu_t} & \frac{\partial Q_s}{\partial \nu_{TCSC}} \\ \frac{\partial P_{st}}{\partial \theta_s} & \frac{\partial P_{st}}{\partial \theta_t} & \frac{\partial P_{st}}{\partial \theta_{TCSC}} \\ \frac{\partial Q_{st}}{\partial \theta_s} & \frac{\partial Q_{st}}{\partial \theta_t} & \frac{\partial Q_{st}}{\partial \theta_{TCSC}} \end{bmatrix} \begin{bmatrix} \Delta \nu_s \\ \Delta \nu_t \\ \Delta \nu_{TCSC} \end{bmatrix}$$

where

$$P_{st} = V_s^2 g_{st} - V_s V_t (g_{st} \cos \theta_{st} + b_{st} \sin \theta_{st})$$

and

$$Q_{st} = -V_s^2 b_{st} - V_s V_t (g_{st} \sin \theta_{st} - b_{st} \cos \theta_{st})$$

Here, $Y_{st}^* = \frac{1}{R_{st} + j(X_{st} - X_{TCSC})} = \frac{R_{st} + j(X_{st} + X_{TCSC})}{R_{st}^2 + (X_{st} + X_{TCSC})^2} = g_{st} - j b_{st}$

The expression for $\frac{\partial g_{st}}{\partial \nu_{TCSC}}$ and $\frac{\partial b_{st}}{\partial \nu_{TCSC}}$ can be obtained from (12).

Eliminating $\Delta I_g$ from the respective equations (4)-(6), the overall system matrix for an $m$-machine system can be obtained as
\[
\begin{align*}
\begin{bmatrix}
A_{TCSC}
\end{bmatrix}_{(8m+2) \times (8m+2)} &= \begin{bmatrix} A' \end{bmatrix} - \begin{bmatrix} B' \end{bmatrix} \begin{bmatrix} D'_1 \end{bmatrix}^{-1} \begin{bmatrix} C' \end{bmatrix} \\
\end{align*}
\]
where \( A' = A_1 - B_1 D_1^{-1} C_1 \), \( B' = \begin{bmatrix} B_2 - B_1 D_1^{-1} D_2 \\ 0 \end{bmatrix} \), \( C' = \begin{bmatrix} K_2 \\ 0 \end{bmatrix} \) and \( D' = \begin{bmatrix} K_1 & D_5 \\ D_6 & D_7 \end{bmatrix} \) with \( K_1 = [D_4 - D_3 D_1^{-1} D_2] \) and \( K_2 = [C_2 - D_3 D_1^{-1} C_1] \). Therefore, linearized state-space model of the multimachine system with PSS and TCSC controller can be expressed as
\[
\begin{align*}
\Delta X &= A_{TCSC} \Delta X + E_1 \Delta U \\
\Delta Y &= C \Delta X
\end{align*}
\]
3. DESCRIPTION OF THE TEST SYSTEM AND BASE CASE STUDY

The power system under consideration is one of the largest power network of Eastern India. It is a 14 area, 24 machine system consisting of 203 buses with 266 branches. It has 108 numbers of 132 kV lines, 30 numbers of 220 kV lines, 15 numbers of 400 kV lines and 6 numbers of 66 kV lines. The whole network includes 35 numbers of 3-windings line transformers and 37 numbers of 2-windings load transformers. Bus #1 is treated as a slack bus. There are 6 numbers of generators having higher capacity (540 MW-600 MW) while 8 numbers of generators are having medium capacity (150 MW-380 MW) and rest 10 numbers are of low capacity (20 MW-90 MW). All machines are assumed to be equipped with IEEE Type –I excitation system and speed-input power system stabilizers to ensure adequate damping of local modes. The proposed system has a total 168 numbers of eigenvalues without PSS and TCSC dynamics for the base case including 78 numbers of complex conjugate oscillation modes. Here 23 numbers of oscillation modes are identified as swing modes [22] among which 11 numbers have the frequency range 0.2-1.0 Hz and are listed in Table 1.

<table>
<thead>
<tr>
<th>#</th>
<th>Swing modes</th>
<th>Frequency (f)</th>
<th>Damping ratio (ζ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-3.0431 ± j6.0689</td>
<td>0.9659</td>
<td>0.4482</td>
</tr>
<tr>
<td>2</td>
<td>-3.3906 ± j5.8905</td>
<td>0.9375</td>
<td>0.4988</td>
</tr>
<tr>
<td>3</td>
<td>-3.3215 ± j5.7429</td>
<td>0.9140</td>
<td>0.5006</td>
</tr>
<tr>
<td>4</td>
<td>-1.0363 ± j4.3800</td>
<td>0.6971</td>
<td>0.2302</td>
</tr>
<tr>
<td>5</td>
<td>-3.4131 ± j5.0370</td>
<td>0.8016</td>
<td>0.5609</td>
</tr>
<tr>
<td>6</td>
<td>-3.2044 ± j4.9464</td>
<td>0.7872</td>
<td>0.5437</td>
</tr>
<tr>
<td>7</td>
<td>-3.8535 ± j4.0865</td>
<td>0.6503</td>
<td>0.6860</td>
</tr>
<tr>
<td>8</td>
<td>-3.2680 ± j4.5548</td>
<td>0.7249</td>
<td>0.5829</td>
</tr>
<tr>
<td>9</td>
<td>-3.3024 ± j4.3813</td>
<td>0.6973</td>
<td>0.6019</td>
</tr>
<tr>
<td>10</td>
<td>-3.3031 ± j4.4201</td>
<td>0.7034</td>
<td>0.5986</td>
</tr>
<tr>
<td>11</td>
<td>-2.9858 ± j2.5168</td>
<td>0.4005</td>
<td>0.7646</td>
</tr>
</tbody>
</table>

It is evident that the damping ratio of the swing mode # 4 is smallest compared to other swing modes and is referred to as the critical swing mode (λ). Therefore, behavior of this mode is of prime concern for the study of the small signal oscillation problem of the system. The mode frequency and right eigenvector analysis suggest that this mode is an inter-area mode involved with almost all machines and in particular it has strong association with machine #20. Therefore, the network branches (line 15, 16, 21, 167, 168, 239 and 240) between two load buses, associated with the machine # 20 are selected here for locating the TCSC module (Fig. 4).
4. FORMULATION OF OPTIMIZATION PROBLEM

4.1 Particle Swarm Optimization (PSO)

PSO begins by initializing a random swarm of \( M \) particles, each having \( R \) unknown parameters to be optimized. At each iteration, the fitness of each particle is evaluated according to the selected fitness function. The algorithm stores and progressively replaces the best fit parameters of each particle (\( p_{best_i}, i=1, 2, 3, \ldots, M \)) as well as a single most fit particle (\( g_{best} \)) as better fit parameters are encountered. The parameters of each particle (\( p_i \)) in the swarm are updated at each iteration (\( n \)) according to the following equations

\[
vel_i(n) = w * vel_i(n-1) + acc_1 * rand_1 * (g_{best} - p_i(n-1)) + acc_2 * rand_2 * (p_{best_i} - p_i(n-1)) \tag{16}
\]

\[
p_i(n) = p_i(n-1) + vel_i(n) \tag{17}
\]

where \( vel_i(n) \) is the velocity vector of particle \( i \). \( acc_1 \), \( acc_2 \) are the acceleration coefficients that pull each particle towards \( g_{best} \) and \( p_{best_i} \) positions respectively and are often set in the range \( \in (0,2) \). \( w \) is the inertia weight of values \( \in (0,1) \). \( rand_1 \) and \( rand_2 \) are two uniformly distributed random numbers in the ranges \( \in (0,1) \). PSO shares many common points with Genetic Algorithm (GA). However, PSO have following advantages over GA [23]:

PSO generates high-quality solutions within shorter calculation time and has more stable and faster convergence characteristics than GA. PSO is simpler in implementation and particles update themselves with the internal velocity. Whereas in GA to update the population for the next generation complex mathematical operators like crossover and mutation is applied. PSO take real numbers as particles. It is not like GA, which needs to change to binary encoding, or special genetic operators.

4.2 Objective Function and Optimization Problem

The problem is to search the optimal location and the parameter set of the TCSC controller using PSO algorithm. The objective is to maximize the damping ratio \( \zeta \) as much as possible. This results in minimization of the critical damping index (CDI) given by

\[
CDI = J = (1 - \zeta_i) \tag{18}
\]

Here, \( \zeta_i = -\sigma_i / \sqrt{\sigma_i^2 + \omega_i^2} \) is the damping ratio of the \( i \)-th critical swing mode. There are four unknown parameters: the TCSC controllers gain \( (K_T^{TCSC}) \), lead time \( (T_1) \), the lag time \( (T_2) \) constants and TCSC location number \( (N_{loc}) \). These parameters are to be optimized by minimizing the objective function \( J \) given by the equation (18). With a change of location and the parameters of the TCSC controller, the damping ratio \( (\zeta) \) as well as \( J \) varies.

The optimization problem can then be formulated as:

- Minimize \( J \)
- S. T. : Inequality constraints

\[
K_{min}^{TCSC} \leq K_T^{TCSC} \leq K_{max}^{TCSC} ; \quad T_{min}^{1} \leq T_1 \leq T_{max}^{1} ; \quad T_{min}^{2} \leq T_2 \leq T_{max}^{2} ;
\]

\[
N_{loc_{min}} \leq N_{loc} \leq N_{loc_{max}}
\]
5. SIMULATION AND RESULT

5.1 Application of PSO

The implementation of the PSO techniques is discussed here with its parameters being shown in Table 2. The particle is defined as a vector which contains the TCSC controller parameters and the location number: $K_{TCSC}$, $T_1$, $T_2$ and $N_{loc}$ as shown in Fig. 3. The values of the TCSC parameters and the location numbers are updated in each generation within this specified range. The objective function corresponding to each particle is evaluated by small signal analysis program of the proposed test system. It is to be noted that TCSC location numbers are updated only for the set of specific branch indexes.

As the network branches (line 15, 16, 21, 167, 168, 239 and 240) between two load buses (Fig. 4) are selected here for locating the TCSC module and therefore, line 15 and line 240 are given as $N_{min}$ and $N_{max}$ respectively. The compensation ($X_{TCSC} / X_{line}$) of the each selected lines were kept to be 60% and therefore $X_L$, $X_C$ and $\alpha$ for the TCSC are chosen according to reactance of the selected lines. The initial value of the firing angle ($\alpha$) of the TCSC is kept within capacitive zone.

Table 2: Parameter values of PSO

<table>
<thead>
<tr>
<th>PSO Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum number of iterations (epochs) to train</td>
<td>50</td>
</tr>
<tr>
<td>Population size</td>
<td>5</td>
</tr>
<tr>
<td>$acc_1$, $acc_2$</td>
<td>2, 2</td>
</tr>
<tr>
<td>Inertia weights ($w_{max}$ and $w_{min}$)</td>
<td>0.9, 0.4</td>
</tr>
<tr>
<td>Minimum error gradient terminates run</td>
<td>$1*e^{-8}$</td>
</tr>
</tbody>
</table>

![Fig. 3: Particle configuration for TCSC](image1)

![Fig. 4: Part of 24 machines, 203 bus system with TCSC](image2)

To optimize equation (18), routines from PSO toolbox [23] are used. The PSO toolbox consists of a main program associated with a bunch of useful sub-programs and routines. In this work the main program pso_Trelea_vectorized.m has been implemented for ‘Common’ type PSO as a generic particle swarm optimizer. To find the optimal value of the objective function ($J$), this main program uses the small signal analysis program as a sub-program. A default plotting routine goplotpso.m is used by the PSO algorithm to plot the best value of the objective function $gbest$ for the specified generation (epochs) limit. The desired optimal outputs are evaluated by the following function in the PSO toolbox environments.

$$[OUT, tr, te] = \text{pso\_Trelea\_vectorized}(\text{functname}, D, \text{mv}, \text{VarRange}, \text{minmax}, \text{PSOparams, plotfcn})$$

where,

$OUT$ : output of the PSO, TCSC controller parameters and the best value of $J$. 

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The PSO algorithm (Appendix A.1) generates the optimal location and the optimal values of the TCSC controller parameters simultaneously by minimizing the objective function $J$ and the output results are represented in Table 3. The convergence rate of objective function $J$ for $gbest$ with the number of generations for 50 has been shown in Fig. 5. In PSO algorithm, the maximum iteration number 50 is adopted for determining termination condition and to stop the simulated evolution. The convergence is guaranteed by observing the value of $J$, which remains unchanged upto 8 decimal places.

Table 3: PSO based TCSC parameters and location

<table>
<thead>
<tr>
<th>PSO based TCSC parameters</th>
<th>PSO based TCSC location</th>
<th>Damping ratio of Critical Swing mode (Base case )</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{TSC} = 2.245$, $T_1 = 1.5$ sec, $T_2 = 0.11$ sec</td>
<td>$N_{loc} =$ line 16 (#154-152)</td>
<td>0.23023 with PSS &amp; TCSC 0.50293 with PSS &amp; PSO based TCSC</td>
</tr>
</tbody>
</table>

Fig. 5: Convergence rate of the objective function towards $gbest$

### 5.2 Small Signal Stability Analysis

To implement the proposed approach, the PSS is installed with all the machines of the network and the PSO based TCSC controller is placed at optimal location (# 152-154) (Fig. 4) in the network. In order to study the small signal stability of the test system simulation is carried out for three independent types of disturbances: (I) load increase at a particular bus (II) reduction of real power generation and (III) outage of transmission line.

**Case I: Load Increase**

In this case the small signal performance of the proposed system has been investigated when real and reactive load of the bus #154 are increased in steps from base load ($P_L = 0.75$ pu and $Q_L = 1.85$ pu). It has been observed that damping ratio of the critical swing mode decreases with increasing load but improved well with installation of PSS. It
has been further observed that the application of both TCSC and PSS controller enhances the damping ratio significantly over the application of PSS only and the effect is different for different values of the TCSC firing angle ($\alpha_0 = 145^\circ$ to $\alpha_0 = 160^\circ$).

**Case II: Generation Drop**

The effect of generation drop on small signal stability of the system has been investigated here by reducing the total generation (15% and 20%) of three machines (Gen #2, #3 and #5) of medium capacity and one machine (Gen #20) of higher capacity. It has been found that the damping ratio and hence the stability of the system reduces with generation drop and improved reasonably after application of PSS. Further enhancement of stability has been achieved with PSS and a TCSC controller when placed in its optimal location (#152-154).

**Case III: Transmission Line Outage**

The study of small signal stability problem of the proposed test system has been extended further when the system is subjected to a contingency like outage of transmission lines #121-152 and #145-149 with ratings 220 kV and 400 kV respectively. The impact of TCSC & PSS control over only PSS control is also evident here. A substantial enhancement of damping has been observed with the variations of TCSC firing angle.

The profiles of damping ratio of the critical swing mode with variation of firing angle for the case of load increase, generation drop and transmission line outage are represented in Fig. 6(a), Fig. 6(b) and Fig. 6(c) respectively.

![Fig. 6 (a): Load increase](image1)

![Fig. 6 (b): Generation drop](image2)

![Fig. 6 (c): Transmission line outage](image3)
It is evident from these plots that PSO based TCSC in addition with PSS is an effective means for damping small signal oscillations against all three cases of power system disturbances. In this stage therefore, it may be required to know the certain case of contingency for which installation of TCSC in addition with PSS is comparatively more effective in mitigating small signal oscillations. In order to investigate this issue authors have proposed a new indicator being termed as Small Signal Stability Rank (SSSR). The computational concept of SSSR has been described in the following section.

6. PERFORMANCE ANALYSIS

6.1 Small Signal Stability Rank (SSSR)

The newly proposed concept of SSSR is based on the change of real part of critical swing mode with and without control at a certain contingency considering base case as a reference. The proposed indicator SSSR for a certain contingency is therefore defined by

$$SSSR = \left( \frac{\text{Real}(\lambda') - \text{Real}(\lambda^0)}{\text{Real}(\lambda)} \right)$$

where $\lambda'$ and $\lambda^0$ are the critical swing modes with and without TCSC control and $\lambda$ is the critical swing mode for the base case. The magnitude of SSSR measures the effect of TCSC on a critical swing mode of interest. The higher value of the SSSR (Table 4) implies more effective control to a contingency. In view of the results obtained in Table 4, it is reasonable to conclude that PSS with PSO based TCSC controllers possess higher rank in mitigation contingencies like load variation and generation drop compared to that for the outage of transmission line.

Table 4: SSSR values with PSS & TCSC control

<table>
<thead>
<tr>
<th>TCSC firing angle</th>
<th>Magnitudes of SSSR</th>
<th>Load increase $P_L=0.90, Q_L=2.15$</th>
<th>Generation drop (15 %)</th>
<th>Line outage (# 121-152)</th>
</tr>
</thead>
<tbody>
<tr>
<td>145°</td>
<td>1.8715</td>
<td>1.4773</td>
<td>0.9212</td>
<td></td>
</tr>
<tr>
<td>147°</td>
<td>2.0250</td>
<td>1.4561</td>
<td>0.9575</td>
<td></td>
</tr>
<tr>
<td>150°</td>
<td>1.9620</td>
<td>2.1117</td>
<td>1.2124</td>
<td></td>
</tr>
<tr>
<td>152°</td>
<td>1.8362</td>
<td>1.9995</td>
<td>1.0447</td>
<td></td>
</tr>
<tr>
<td>155°</td>
<td>2.0434</td>
<td>2.0816</td>
<td>0.9394</td>
<td></td>
</tr>
<tr>
<td>160°</td>
<td>1.7698</td>
<td>2.0208</td>
<td>0.9220</td>
<td></td>
</tr>
</tbody>
</table>

It is to be noted that the proposed concept of SSSR has been described here based on the change of real part of critical swing mode instead of taking the change of imaginary part into account, though the imaginary part also has contribution on the damping ratio. The reason is that the system settling time is particularly depends upon the real part rather than on imaginary part and hence, SSSR has been formulated by considering only the real part of critical swing mode.

6.2 Time domain Response

A comparative study of the small signal performances of the system with PSS and the PSS with TCSC controller has been performed by calculating the angular speed response of machine #20 in face of different type of disturbances. The deviation of angular speed response with and without control has been plotted in Fig. 7 for simulation time 10 sec. It is evident that the TCSC controller is an effective FACT device in mitigating the contingency of transmission line outage particularly in addition to load variation and generation drop.
7. CONCLUSIONS

In this paper the small signal stability problem of a multimachine regional power system has been investigated employing PSS and the PSO based TCSC controller. PSO has been implemented for optimal parameter setting and identification of the optimal site of TCSC controller by minimizing the desired objective function. A new indicator, SSSR has been proposed for assessment of the effectiveness of the PSO based TCSC controller in three major types of power systems disturbances. It has been revealed that simultaneous application of PSS in the generators and the TCSC controllers in transmission side imparted better control effect on small signal stability. It has further been revealed that the combined PSO based TCSC controller with PSS provides better result in mitigating small signal oscillations following load variation and generation drop than transmission line outage. The proposed approach can be applied for other multimachine power systems.

REFERENCES


A.2 Computation of SSSR

For $\alpha = 145^\circ$; Base case $\lambda = -1.0363 \pm j4.380$

Load increase ($P_L=0.90$, $Q_L=2.15$):

$\lambda^* = -1.0145 \pm j4.402$; $\lambda' = -2.954 \pm j5.0804$; $|\text{SSSR}| = \frac{(2.954 - 1.0145)}{1.0363} = 1.8715$

Generation drop (15 %)

$\lambda^* = -0.7175 \pm j4.5671$; $\lambda' = -2.2485 \pm j4.6177$; $|\text{SSSR}| = \frac{(2.2485 - 0.7175)}{1.0363} = 1.4773$

Line Outage (# 121-152)

$\lambda^* = -0.0554 \pm j4.2337$; $\lambda' = -1.0102 \pm j3.2614$; $|\text{SSSR}| = \frac{(1.0102 - 0.0554)}{1.0363} = 0.9212$

A.3 Parameters of PSS and TCSC module

$K_{\text{PSS}} = 10$; $\tau_1|_{\text{PSS}} = 0.4$ sec; $\tau_2|_{\text{PSS}} = 0.15$ sec; $X_L = 0.000526$ pu; $X_C = 0.00526$ pu; $T_{\text{TCSC}} = 17$ ms.