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Dynamic Stability Enhancement for Multi-Machine Power System by Coordinated Design of PSS and SSSC

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Abstract - Damping of inter-area power system oscillation is detrimental to the goals of maximum power transfer and optimal power system security. In this paper, individual and coordinated optimization of parameters for both static series synchronous compensator (SSSC) based damping controller and power system stabilizer (PSS) to enhance the power system damping are presented. A lead-lag stabilizer is used to demonstrate this technique. An optimization method based on simulated annealing (SA) algorithm is used for optimal parameters design of the SSSC stabilizer and PSS to improve the dynamic stability of the power system. Eigenvalue analysis is carried out to assess the effectiveness of the proposed stabilizers on enhancing the electromechanical mode stability. The effect of SSSC based stabilizers on damping inter-area oscillations for a small disturbance are studied and compared with PSS. Obtained results include eigenvalue analysis and non-linear time simulation for two area multi-machine power systems.

Index Terms - Dynamic stability, Simulated annealing, SSSC, PSS, Inter-area oscillation.

I. Introduction

Since the development of interconnection of large electric power systems, there have been system oscillations at very low frequencies in order of [0.2-3] Hz. Once started, the oscillation would continue for a while and then disappear, or continue to grow, causing system separation [1]. There are two electromechanical modes of oscillations have been reported [2]:Local mode, with a frequency 0.8-3 Hz, which is related to oscillation in a group of generators in the same area and Inter-area mode, with frequency 0.2-0.8 Hz, in which the units in one area oscillate against those in other area. Conventionally, PSS is used for damping of power system oscillations. But, the use of PSSs only may not be effective in providing sufficient damping for inter-area oscillations, particularly with increasing transmission line loading over a long distance [3]. Also, PSSs suffer a drawback of being liable to cause great variations in the voltage profile and they may even result in leading power factor operation [4].

Nowadays, series power electronics-based FACTS controllers have become one of the best alternative means to improve power oscillation damping. The SSSC, in comparison to other FACTS devices, is more effective for damping mechanical oscillations [5, 6]. Panda has used PSO, GA and their variants for optimal tuning parameters of lead-lag controller to improve the damping capability of SSSC [7-11]. In [12], a robust design of SSSC-based leag -lag stabilizer was presented as a quadratic mathematical programming problem to damp the inter-area oscillations. In [13], a method for the simultaneous coordinated tuning of a SSSC-based stabilizer and a PSS for multi-machine power system was presented by quadratic mathematic programming. In this method, the gain and phase of the stabilizer were calculated simultaneously. In [14], a Neuro-fuzzy Inference System (ANFIS) based SSSC controller for stability improvement has been tested on 3-machine 9-bus power system.

In this paper, individual and coordinated optimization of parameters for both SSSC based damping controller and PSS to enhance the power system damping are presented. An integral time absolute error of the speed signals corresponding to the local and inter-area modes of oscillations is taken as the objective function which solved by SA algorithm. Comparison between individual and coordinated design of both controllers has been done. The simulation results include eigenvalue analysis and non-linear simulations are obtained.

II. Power System Modelling

A. Synchronous generator model

The dynamic model of the synchronous machine can be represented by three state variables: $\delta,\ \omega,\ E'_q$. So, each generator represented by three order model as follows [1]:

$$\dot{\delta}_i = \omega_i - \omega_s \tag{1}$$

$$M_i\dot{\omega}_i = T_{Mi} - T_{ei} - D_i(\omega_i - \omega_s) \tag{2}$$

$$T'_{doi}\dot{E}'_{qi} = -E'_{qi} - \left(x_{di} - x'_{di}\right)I_{di} + E_{fdi} \tag{3}$$

The electromagnetic torque equation is,

$$T_{ei} = E'_{qi}I_{di} + \left(x_{qi} - x'_{di}\right)I_{di}I_{qi} \tag{4}$$

where, i=1, 2…,m. m is number of synchronous Generator

B. Excitation system

The excitation system can be represented by IEEE type–ST1 system as shown in Fig. 1 [1], and is described by the following equation:

$$\dot{E}_{fdi} = -\frac{1}{T_{Ai}}E_{fdi} + \frac{K_{Ai}}{T_{Ai}}\left(V_{refi} - V_i + u_{pssi}\right) \tag{5}$$

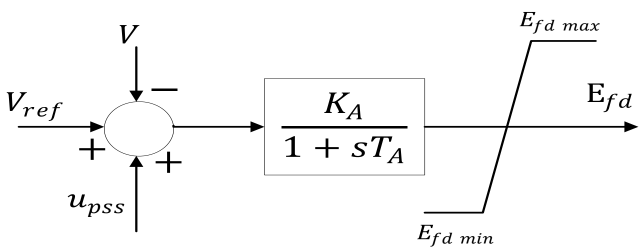

Fig. 1 IEEE type–ST1 excitation system block diagram

C. Stator algebraic equations

The stator algebraic equations are [1]:

$$E'_{qi} - V_i\cos(\delta_i - \theta_i) - x'_{di}I_{di} = 0 \tag{6}$$

$$V_i\sin(\delta_i - \theta_i) - x_{qi}I_{qi} = 0 \tag{7}$$

where,*i=1,…,m*

D. network equations

The network equation can be written in the power balance form as in section (7.3.1) in reference [1].

III. Linearization of overall system model

Lineralize the above equations we can get the overall lineralized equations as follows [1]:

$$\Delta\dot{X} = A_1\Delta X + B_1\Delta I_g + B_2\Delta V_g + E\Delta U \tag{8}$$

$$0 = C_1\Delta X + D_1\Delta I_g + D_2\Delta V_g \tag{9}$$

$$0 = C_2\Delta X + D_3\Delta I_g + D_4\Delta V_g + D_5\Delta V_L \tag{10}$$

$$0 = C_6\Delta V_g + D_7\Delta V_L \tag{11}$$

By getting ΔI_g from equation. 9 and substituting in equation. 8 and 10 we have:

$$\Delta\dot{X} = K_1\Delta X + K_2\Delta V_g + E\Delta U \tag{12}$$

$$0 = K_2\Delta X + K_4\Delta V_g + D_5\Delta V_L \tag{13}$$

$$0 = C_6\Delta V_g + D_7\Delta V_L \tag{14}$$

Equations. 12 to 14 can be put in compact matrix form as follows,

$$\begin{bmatrix}\Delta\dot{X}\\ 0\end{bmatrix} = \begin{bmatrix}A & B\\ C & D\end{bmatrix}\begin{bmatrix}\Delta X\\ \Delta V_L\end{bmatrix} + \begin{bmatrix}E\\ 0\end{bmatrix} \tag{15}$$

where,

$$\Delta V_L = [\Delta V_G\ \Delta V_L]^T,\ \Delta X = \left[\Delta\delta,\ \Delta\omega,\ \Delta E'_q,\ \Delta E_{fd}\right]^T$$

So,

$$\Delta\dot{X} = A_{sys}\Delta X + B\ \Delta U \tag{16}$$

where,

$$A_{sys} = A - BD^{-1}C$$

IV. Dynamic Model of SSSC

The SSSC device has been placed in series with transmission line to control power flow and consequently enhancing system dynamic stability [15]. The structure of the SSSC with controller is presented in Fig. 2. It is assumed that, in multi-machine power system, a SSSC is installed on the transmission line between nodes m and k.

The SSSC consists of a series coupling transformer (SCT) with a leakage reactance x_s, a three-phase GTO based voltage source converter (VSC) and DC capacitor. The SSSC can be described as [15]:

$$\overrightarrow{\mathrm{I_{km}}} = \mathrm{I_{kmd}} + \mathrm{j}\ \mathrm{I_{kmq}} = \mathrm{I_{km}}\angle\varphi \tag{17}$$

$$\overrightarrow{\mathrm{V_{ser}}} = \mathrm{mkV_{DC}}(\cos\psi + \mathrm{j}\sin\psi) = \mathrm{mkV_{DC}}\angle\psi \tag{18}$$

$$\varphi + \psi = \pm 90 \tag{19}$$

The following differential equation applies to the DC circuit:

$$\frac{\mathrm{dV_{DC}}}{\mathrm{dt}} = \frac{\mathrm{mk}}{\mathrm{C_{DC}}}\left(\cos\psi\,\mathrm{I_{kmd}} + \sin\psi\,\mathrm{I_{kmq}}\right) \tag{20}$$

where, k is the constant ratio between inverter AC and DC voltage. Signal m is the amplitude modulation ratio of the pulse width modulation (PWM) based VSC. Also, signal ψ is the phase of the injected voltage whereas, it is kept in quadrature with the line current (inverter losses are ignored).

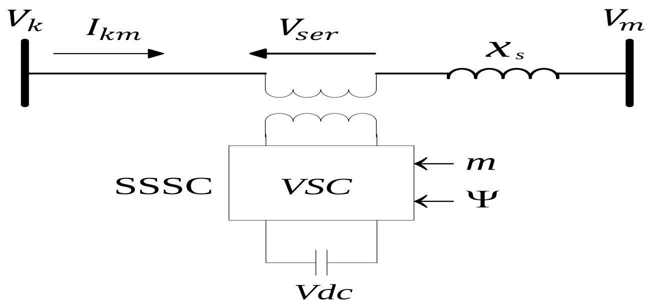

Fig. 2 SSSC dynamic model

V. Mathematical model of multi-machine power system with SSSC

To include SSSC into multi-machine system, equation 15 and 20 are putted in compact form using the same notations of equation. 15, so that the final open loop state space model can be in the form:

$$\Delta\dot{X} = A\Delta X + B\Delta u \tag{21}$$

where,

$$\Delta X_i = \left[\Delta\delta_i,\ \Delta\omega_i,\ \Delta E'_{qi},\ \Delta E_{fdi}, \Delta V_{dc}\right]^T, u = [\Delta m\ \ \Delta\psi]$$

VI. Power System Stabilizer

A conventional lead-lag PSS is installed in the feedback loop to generate a supplementary stabilizing signal U_{pss}, as shown in Fig. 3. The PSS input is the deviation of machine speed.

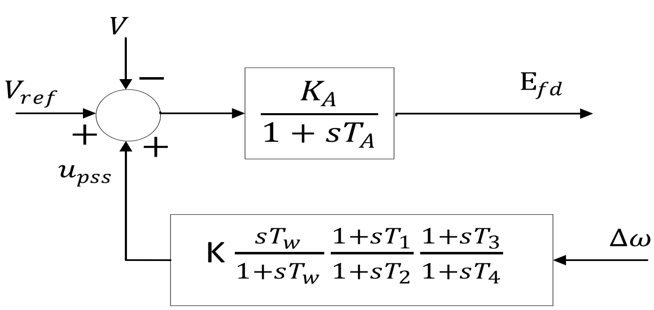

Fig. 3 IEEE type-STI excitation system with PSS.

VII. SSSC Controller

The SSSC control scheme has two loops, which are designed for controlling the DC voltage V_{dc} to maintain the DC link voltage at their pre-specified value and control the active power flow in the AC side to damp system oscillations. Fig. 4 depicts the DC voltage control and the power damping scillations.

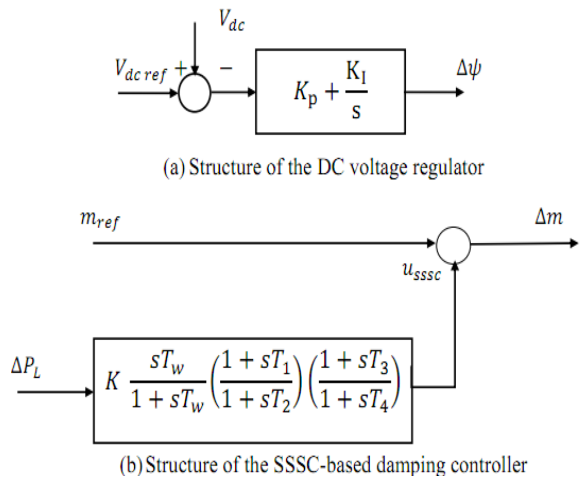

Fig.4 SSSC damping controller.

where, $K_p$and K_I are the PI controller gains,

K,T_1,T_2,T_3 *and* T_4 are the lead lag controller parameters.

VIII. The Studied System

The system considered in this section is the two-area power system. The one-line diagram is shown in Fig. 5. The detailed system data including the dynamic generators models and exciters used along with load flow results are given in reference [2].

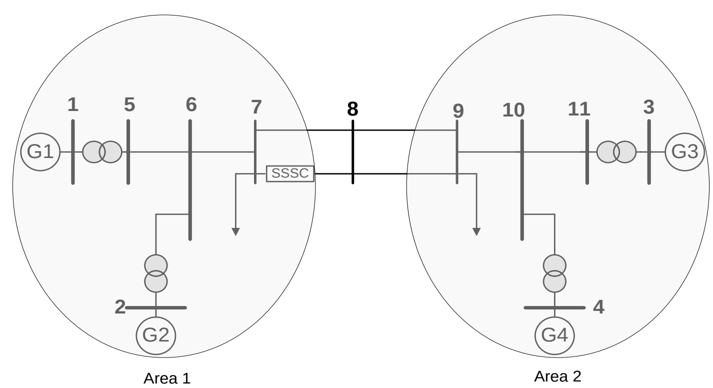

Fig. 5 Two area system.

A. Objective function

An integral time absolute error of the speed signals corresponding to the local and inter-area modes of oscillations is taken as the objective function. The objective function is expressed as:

$$J = \int_{t=0}^{t=t_{sim}} (\sum|\Delta\omega_l| + \sum|\Delta\omega_i|) \quad (22)$$

where,
$\Delta\omega_l$ represents the local mode $(\Delta\omega_{12}, \Delta\omega_{34})$.
$\Delta\omega_i$ represents the inter-area mode $(\Delta\omega_{13}, \Delta\omega_{14})$, t_{sim} is the simulation time range.

The SA algorithm has been applied to search for the optimal parameter settings of the controller so that this objective functions is optimized [15].

B. System analysis

The open-loop eigenvalues can be calculated using the state matrix of equation 15. Using participation factor analysis, the inter-area modes and local modes can be identified. Table 1 shows the frequencies and damping ratios of these modes.

Table 1. Two-area system eigenvalues analysis

Eigenvalues	**Freq(HZ)**	**Mode**	**Damping ratio**	**Dominant states**
-0.1964 ± 6.4875i	1.0334	Local	0.0303	$\Delta\delta$ and $\Delta\omega$ of G_1 and G_2
-0.2276 ± 6.6576i	1.0605	Local	0.0342	$\Delta\delta$ and $\Delta\omega$ of G_3 and G_4
0.0405 ± 3.5812i	0.5701	Inter - area	-0.01133	$\Delta\delta$ and $\Delta\omega$ of G_1, $G_2 G_3$ and G_4

The first electromechanical mode has a very low damping ratio equal to (0.0303) in which generators 1 and 2 have the significant participation factors of that mode. Therefore, PSS's are located at generators 1 and 2 in addition to machine 3 since it has the significant PF of the inter-area mode.

C. Individual design

All PSS's and SSSC-based stabilizers are tuned individually by SA algorithm, searching for the optimum controller's parameters settings that minimize the objective function. The final settings of the optimized parameters for the applied stabilizers are shown in Table 2.

Table 2. Optimal parameters settings of individual design for PSS's and SSSC for two-area system.

Parameters	PSS's			SSSC
	PSS1	PSS2	PSS3	
K	2.199	1.541	2.881	4.01
T_1	0.873	1.851	1.605	0.0488
T_2	0.081	0.029	0.090	0.001
T_3	1.977	1.075	1.765	0.3501
T_4	0.067	0.876	0.960	1.0975
K_P	----	----	----	-0.06
K_I	----	----	----	-0.03

D. Coordinated design [SSSC and PSS's]

All PSS's and SSSC-based stabilizer are simultaneously tuned by SA algorithm, searching for the optimal controller's parameters settings that minimize the objective function. The final settings of the optimized parameters for the applied stabilizers are shown in Table 3.

Table 3. Optimal parameters settings for coordinated design for PSS's and SSSC.

Parameters	Coordinated Design			
	PSS1	PSS2	PSS3	SSSC
K	3.489	6.716	8.891	5.06
T_1	0.628	1.981	1.912	0.6064
T_2	0.910	1.265	0.473	0.0013
T_3	1.996	1.422	1.982	0.6856
T_4	0.111	0.482	0.724	0.23
K_P	----	----	----	-0.075
K_I	----	----	----	-0.06

The system eigenvalues with PSS's and SSSC–based stabilizer when each controller applied individually and coordinated are given in Table 4.

Table 4. System eigenvalues with individual and coordinated design of PSS's and SSSC.

Eigenvalues with PSS's	Eigenvalues with SSSC	Eigenvalues with PSS's and SSSC
$-2.2344 \pm 6.5896i$ (0.32)	$-0.20 \pm 6.42i$ (0.0308)	$-3.1645 \pm 5.94i$ (0.47)
$-1.99806 \pm 5.6417i$ (0.334)	$-0.21 \pm 6.63i$ (0.0319)	$-8.2032 \pm 3.623i$ (0.9)
$-0.4444 \pm 3.1309i$ (0.141)	$-0.56 \pm 2.90i$ (0.2)	$-3.61 \pm 5.98i$ (0.517)

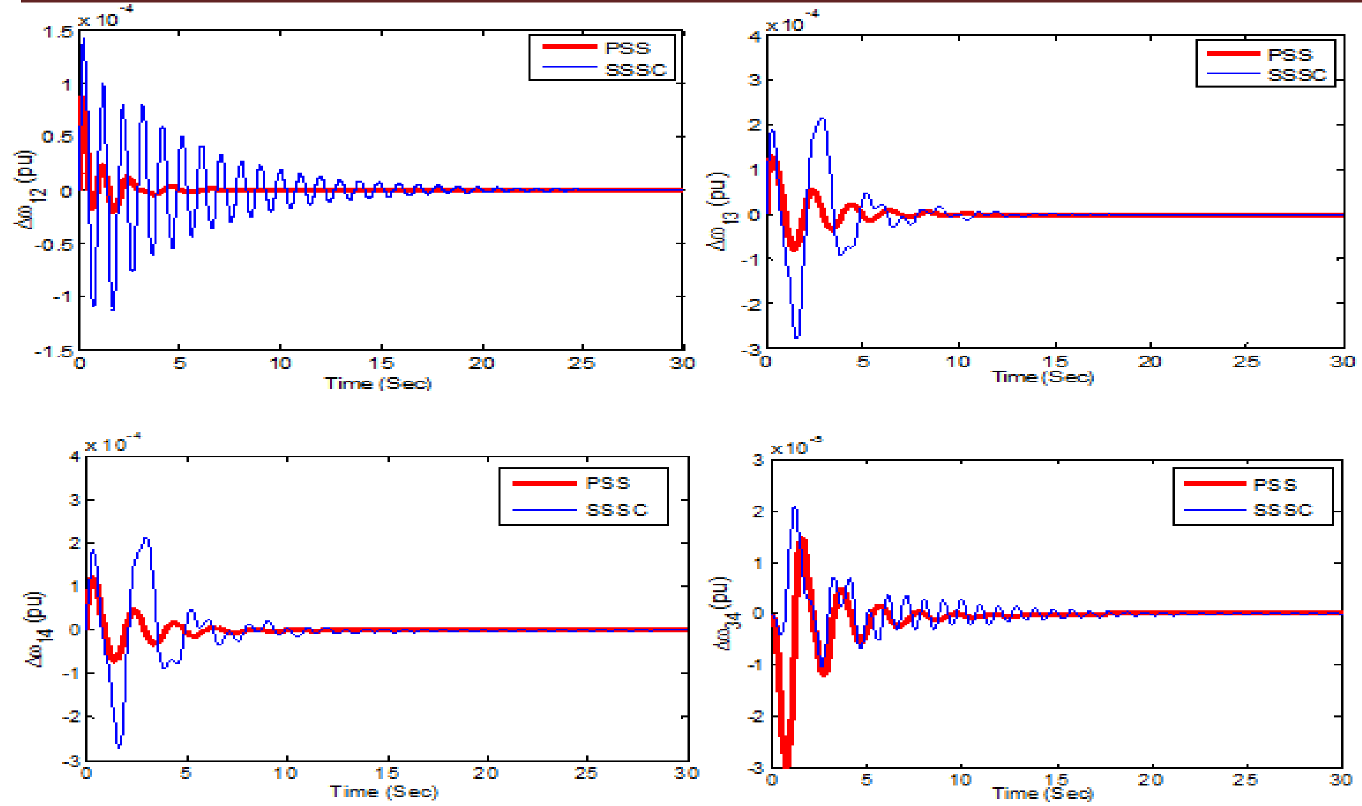

Fig. 6 The speed deviation responses for local and inter-area modes with each applied stabilizers, individual control

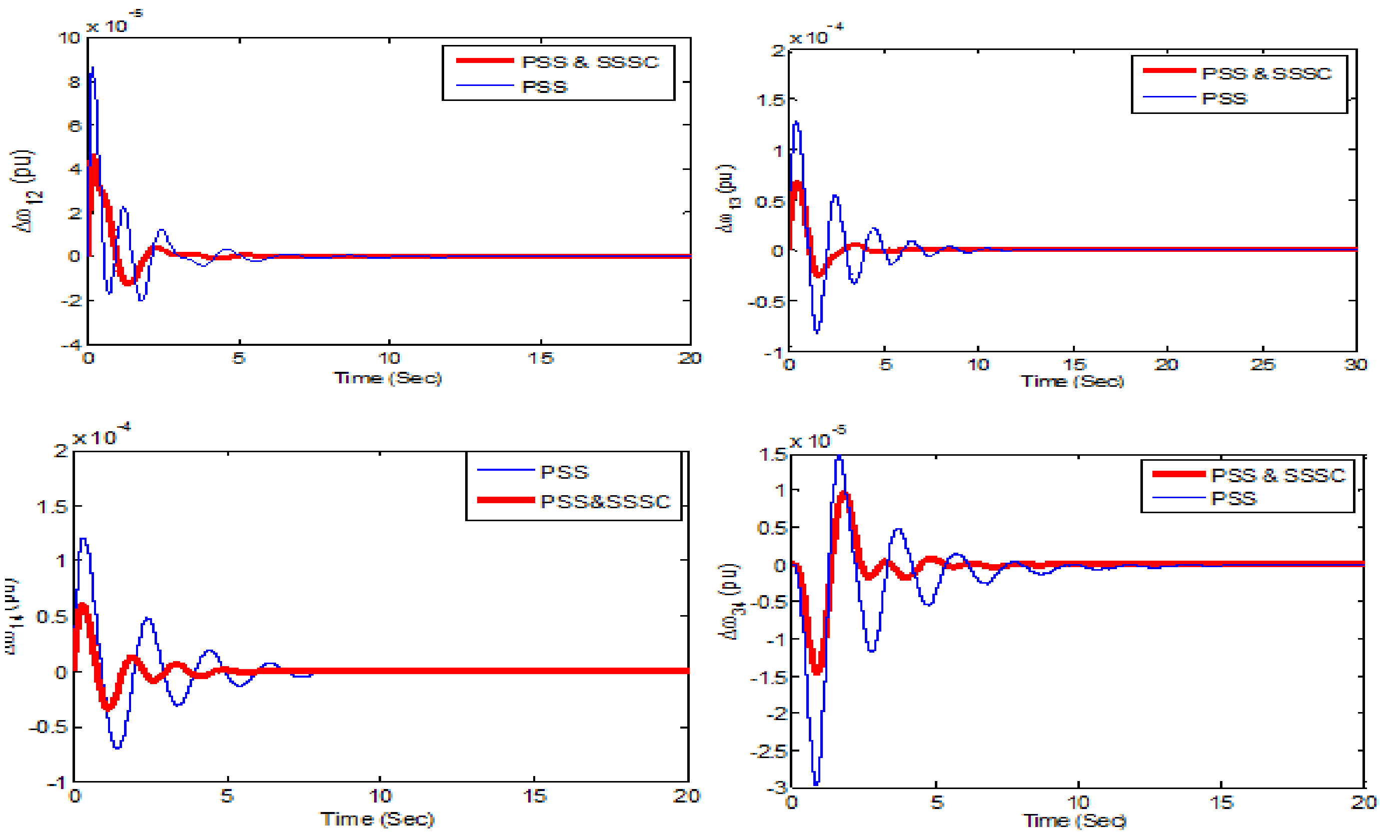

Fig 7. The speed deviation responses for local and inter-area modes using PSS's individual, and coordinated with SSSC

Figure 6. combined the speed deviation responses for local and inter-area modes with each applied stabilizers, individual control for a 10% increase in mechanical power input of machine #1.

Figure 7. combined the speed deviation responses for local and inter-area modes using PSS's individual, and coordinated with SSSC for a 10% increase in mechanical power input of machine #1.

IX. Conclusion

This paper presents a method of individual and coordinated optimization of parameters for both SSSC based damping controller and PSS to enhance the power system damping, especially for interconnected power system to damp inter-area power oscillation between two-area connected through a weak transmission line. From obtained eigenvalues analysis, we note that PSS only can't give the sufficient damping for this system. So, we used SSSC FACTS device based damping controller with PSS to improve system stability which is noted in figure 6. It can be concluded that, the local and inter-area modes of oscillations of power system can be effectively damped by using the proposed SSSC controller.

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