Power System Damping Enhancement via Coordinated Design of PSS & TCSC in Multimachine Power System

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***Abstract* — the main objective of this paper is to investigate the enhancement of power system stability via coordinated design of Thyristor Controlled Series Compensation (TCSC) and Power System Stabilizers (PSSs) in multimachine power system. The design problem of the proposed controllers is formulated as an optimization problem. Using the developed linearized power system model, the particle swarm optimization (PSO) algorithm is employed to search for optimal controllers' parameters settings that maximize the minimum damping ratio of all system eigenvalues. The proposed controller is evaluated on a multimachine power system. The nonlinear simulation results and eigenvalue analysis show the effectiveness of the proposed controller in damping power system oscillations.**

***Index Terms* — FACTS, TCSC, PSS, Particle Swarm Optimization (PSO), Power Oscillation Damping (POD), Multimachine Power System**

I. INTRODUCTION

Power systems are experiencing low frequency oscillations due to disturbances. These oscillations may sustain and grow to cause system separation if no adequate damping is available [1]. In order to damp power system oscillation and increase system oscillation stability, the installation of power system stabilizer (PSS) is both economical and effective [2-5].

To date, most major electric power system plants in many countries are equipped with PSS. However, 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 and losing system stability under severe disturbances.

Recently appeared FACTS-based stabilizers such as Static Var Compensator (SVC), Thyristor controlled Series Compensation (TCSC), and Thyristor Controlled Phase Shifter (TCPS) offer an alternative way in damping power system oscillations. Although, the damping duty of a FACTS controller often is not its primary function, the capability of FACTS-based stabilizers to increase power system oscillation damping characteristics has been explored in many aspects [6-19].

Several approaches based on modern control theory have been applied to TCSC controller design [9-17]. The effectiveness of the series compensation devices on power system stability enhancement in SMIB system has been presented in [9]. Chen at al. [10] presented a state feedback controller for TCSC by using a pole placement technique. Cang and Chow [11] developed a time optimal control strategy for the TCSC where a performance index of time was minimized. A fuzzy logic controller for a TCSC was proposed in [12]. Heuristic optimization techniques have been implemented to search for the optimum TCSC based stabilizer parameters for the purpose of enhancing SMIB system stability [13]. In addition, different control scheme for a TCSC were proposed such as variable structure controller [14-15], bilinear generalized predictive controller [16], and H∞-based controller [17].

A little work has been devoted in the literature to study the coordination control of excitation and FACTS stabilizers. Hiyama et al [18] presented a coordinated fuzzy logic-based scheme for PSS and switched series capacitor modules to enhance overall power system stability. Robust coordinated design of excitation and TCSC-based stabilizers using genetic algorithm in SMIB also has been presented. Pourbeik and Gibbard [19] presented a two-stage method for the simultaneous coordination of PSSs and FACTS-based lead-lag controllers in multimachine power systems by using the concept of induced damping and synchronizing torque coefficients.

In this paper, a comprehensive assessment of the effects of the coordinated design of PSS and TCSC-based stabilizer on power system stability enhancement has been carried out in multimachine power system. The controller design problem is transformed into an optimization problem where the particle swarm optimization (PSO) is employed to search for the optimal settings of stabilizer parameters. The location of PSS selected based on Participation Factor (PF) analysis while Modal Analysis technique is employed to find the TCSC location. The eigenvalue analysis and nonlinear simulation results are carried out to demonstrate the effectiveness of the proposed stabilizers to enhance system stability.

II. PROBLEM STATEMENT

A. Power System Model

A power system can be modeled by a set of nonlinear differential equations as:

$$\dot{X} = f(X, U) \tag{1}$$

Where X is the vector of the state variables and U is the vector of input variables. In this study

$X = [\delta, \omega, E_q^{'}, E_{fd}]^T$ and U are the PSS and SVC output signals.

In this study, each generator will be presented by the third-order model comprising of the electromechanical swing equation end the generator internal voltage equation.

$$\dot{\delta}_i = \omega_b(\omega_i - 1) \quad (2)$$

$$\dot{\omega}_i = (T_{mi} - T_{ei} - D_i(\omega_i - 1)) / M_i \quad (3)$$

$$\dot{E}_{qi}^{'} = (E_{fdi} - (x_{di} - x_{di}^{'})i_{di} - E_{qi}^{'}) / T_{doi}^{'} \quad (4)$$

$$T_{ei} = v_{qi} i_{qi} + v_{di} i_{di} \quad (5)$$

Where, T_m and T_e are input and output power of the generator respectively; M and D are the inertia constant and damping coefficient respectively; δ and ω are rotor angle and speed respectively; E_{fd} is the field voltage; $T_{do}^{'}$ is the open circuit field time constant, x_d and $x_d^{'}$ are the d-axis reactance and d-axis transient reactance of the generator respectively.

B. Power System Stabilizers (PSS)

A PSS can be viewed as an additional block of a generator excitation control or Automatic Voltage Regulator (AVR), added to improve the overall power system dynamic performance, and especially control electromechanical oscillations. This is a very effective method of enhancing small-signal stability performance on a power system network

PSS involves a transfer function consisting of an amplification block, a wash out block and two lead-lag blocks. The lead-lag blocks provide the appropriate phase-lead characteristic to compensate the phase lag between the exciter input and the generator electrical torque. The structure of the used PSS is illustrated in Fig. 1.

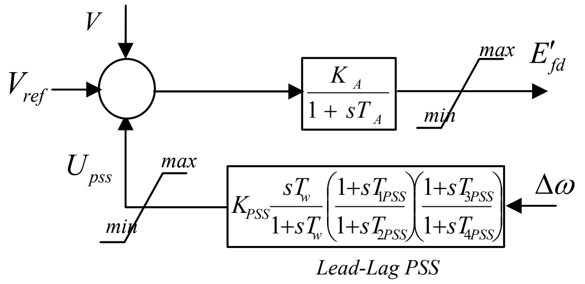

Fig. 1: IEEE type-ST1 excitation system with PSS

The IEEE Type-ST1 can be described as

$$\dot{E}_{fd} = \left(K_A\left(V_{ref} - v + u_{PSS}\right) - E_{fd}\right)/T_A \quad (6)$$

Where, K_A and T_A are the gain and time constant of the excitation system respectively; V_{ref} is the reference voltage. As shown in Fig. 1, a conventional lead-lag PSS is installed in the feedback loop to generate a stabilizing signal u_{PSS}.

C. Thyristor Controlled Series Compensation (TCSC)

Fig. 2 illustrates the block diagram of TCSC with a lead-lag compensator. The reactance of X_{TCSC} can be expressed as

$$\dot{X}_{TCSC} = \frac{1}{T_S}\left[K_S\left(X_{ref} + U_{CSC}\right) - X_{TCSC}\right] \quad (7)$$

Where:

X_{ref} is the reference reactance of TCSC; Ks and Ts are the gain and time constant of the device respectively. As shown in Fig. 3 a conventional lead-lag controller is installed in the feedback loop to generate the compensation stabilizer signal U_{TCSC}

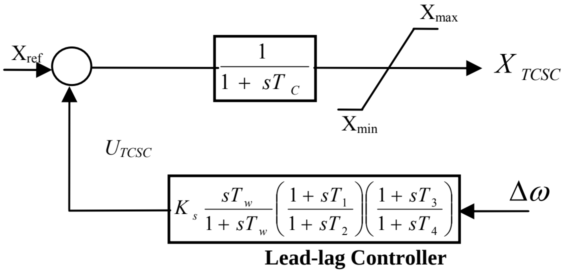

Fig.2: TCSC with Lead-Lag Controller

The TSSC has the same block diagram as TCSC except that the minimum limit of the compensation is zero i.e. $X_{min}= 0$.

D. Linearized System Model

In the design of electromechanical mode damping controllers, the linearized incremental model around a nominal operation point is employed.

Linearized the system model yield the following state equation

$$\dot{X} = AX + HU \quad (8)$$

Here, the state vector X is $\left[\Delta\delta, \Delta\omega, \Delta E_q', \Delta E_{fd}\right]^T$

And the control vector U is $\left[\Delta X_{CSC}, \Delta U_{PSS}\right]$.

III. Proposed Design Approach

In this section the proposed approach is illustrated as follows; the location of the reactive power compensation device TCSC and PSSs are identified in multimachine system by using modal analysis method and participation factor technique respectively. Then, the PSO is proposed in this paper to search for optimal parameters setting.

A. Problem Formulation

To increase the system damping to the electromechanical model, the objective function J defined below is proposed.

$$J = \max\left\{\begin{matrix}\zeta : \zeta \text{ is the } \min \text{elctromechanical} \\ \text{mode damping ratio}\end{matrix}\right\} \quad (9)$$

This objective function will identify the minimum value of damping ratio among electromechanical modes of all loading condition considered in the design process. The design problem can be formulated as the following optimization problem format.

Maximize J

Subject to

$K_{TCSC}^{min} \le K_{TCSC} \le K_{TCSC}^{max}$

$K_{PSS}^{min} \le K_{PSS} \le K_{PSS}^{max}$

$T_{TCSC1}^{min} \le T_{TCSC1} \le T_{TCSC1}^{max}$,

$T_{TCSC3}^{min} \le T_{TCSC3} \le T_{TCSC3}^{max}$

$T_{PSS1}^{min} \le T_{PSS1} \le T_{PSS1}^{max}$,

$T_{PSS}^{min} \le T_{PSS3} \le T_{PSS3}^{max}$

The minimum and maximum value of the controller gain is set as 0.1 and 100 respectively. The maximum values of T_1 and T_3 are set to 1.0s. PSO has been employed to solve the above optimization problem.

B. Particle Swarm Optimization (PSO) Algorithm

Like evolutionary algorithms, PSO technique conducts search using a population of particles. Each particle represents a candidate solution to the problem. In PSO System, particles change their positions by flying around in a multi dimensional search space until a relatively unchanging position has been encountered, or until computational limitations are exceeded. In social science context, a PSO system combines a social-only model and a cognition-only model [20]. The social-only component suggests that individuals ignore their own experience and adjust their behavior according to the successful beliefs of individuals in the neighborhood. On the other hand, the cognition-only component treats individuals as isolated beings. The advantages of PSO over other traditional optimization techniques can be summarized as follows: -

- PSO is a population-based search algorithm i.e., PSO has implicit parallelism. This property ensures PSO to be less susceptible to getting trapped on local minima.
- PSO uses objective function information to guide the search in the problem space. Therefore, PSO can easily deal with non-differentiable objective functions.
- PSO uses probabilistic transition rules, not deterministic rules. Hence, P80 is a kind of stochastic optimization algorithm that can search a complicated and uncertain area. This makes PSO more flexible and robust than conventional methods.
- Unlike GA and other heuristic algorithms, PSO has the flexibility to control the balance between the global and local exploration of the search space.

IV. SIMULATION RESULT

A. Test System

The system considered in this paper is the two-area power system. The system one-line diagram is shown in Fig.3. The details system data including the dynamic generators model and exciter data used along with load flow result are given in the Appendix.

The system consists of two identical areas. Each includes two 900 MVA generating units equipped with fast static exciters. All four generating units are represented by the same dynamic model. The power transfer from Area 2 to Area 1 over a single tie line is considered.

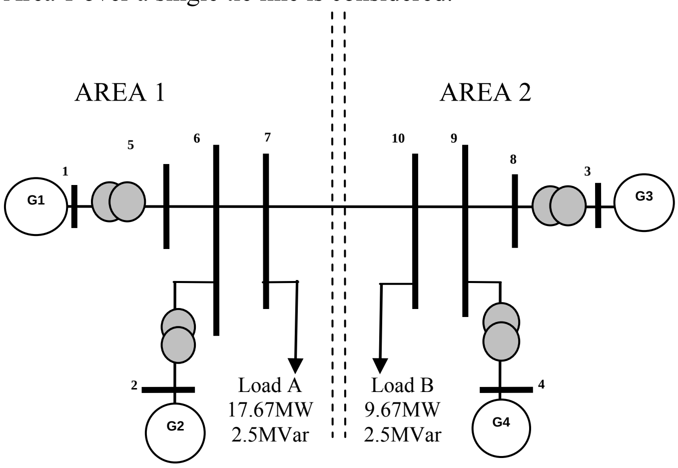

Fig. 3: Two-area 4-machin power system.

B. System Analysis and Controllers Locations

From the open loop system eigenvalue and participation factor analysis shown in Table 1, the system exhibits three electromechanical modes:

- An inter-area mode, with a frequency of 0.5098 Hz, in which the generating units in one area oscillate against those in the other area.
- Local mode, in area 1, with a frequency of 1.1125 Hz. In this mode the machines in Area 1 oscillate against each other.
- Local mode, in area 2, with a frequency of 1.0941 Hz. In this mode the machines in Area 2 oscillate against each other.

The frequencies, damping ratios, and participation factors (PF) for these three electromechanical modes are given in the table.

The table shows that the two generating units in each area have close participation factor in the inter-area mode. The same is also true for the two local modes. This is to be expected, since all units are identical, and units in each area are electrically close. The table also shows that the units in Area 1 (the receiving end) have higher participation factor than the units in Area 2 (sending end) to the inter-area mode. It can also be seen that, the inter-area mode has negative damping ratio at this operating condition.

Table 1: System Eigenvalue and Participation Factor Analysis

Eigenvalues	***Freq.***	***Mode***	***Damping Ratio***	***Machines Participation Factor***			
				G1	**G2**	**G3**	**G4**
-0.660 ±6.9904i	1.1125	Local	0.094	0.7544	1	0.0015	0.0088
-0.7375 ±6.8742i	1.0941	Local	0.1067	0.0133	0.0016	0.8438	1
0.0279 ± 3.2030i	0.5098	Inter-Area	-0.0087	1	0.7869	0.3891	0.2432

The first electromechanical mode has a very low damping ratio equal to (0.094) in which Generator no. 1 & 2 have the significant participation factors of that mode. Therefore, PSSs are located at machine number 1 and 2 in addition to machine 4 since it has the significant PF of the inter-area mode.
The TCSC is to be installed at the tie-line. This location is satisfied the primary function of TCSC as will as the practical experience.

C. Controller Design

All stabilizers PSS's & TCSC are simultaneously tuned by PSO searching for the optimum controllers parameter settings that maximize the minimum damping ratio of all the system complex eigenvalues.
The convergence rate of the objective function when PSS's and TCSC-based controllers are designed individually and in a coordinated manner is shown in Fig. 4. It is clear that the coordinated design of PSS's and TCSC-based stabilizer improves greatly the system damping compared to their individual application. The final settings of the optimized parameters for the proposed stabilizers are given in Table 2.

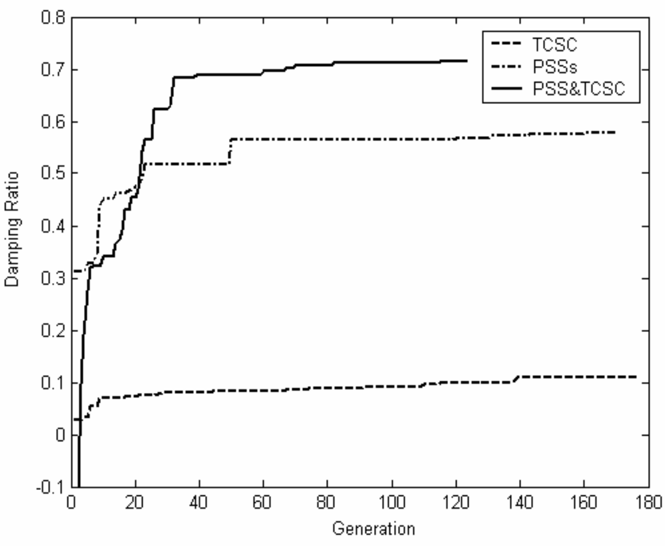

Fig. 4: The convergence rate of the objective function when PSS's and TCSC-based controllers are designed individually and in a coordinated manner

Table 2: Optimal parameter settings of PSS and TCSC, coordinated design for 4-machine system

Parameters	***Coordinated Design***			
	PSS1	***PSS2***	***PSS4***	***TCSC***
K	100	100	49.2614	1.064
T_1	0.0783	0.0702	0.1354	5.0
T_2	0.01	0.01	0.01	0.021
T_3	------	------	------	0.01
T_4	------	------	------	5.0

D. Eigenvalue Analysis

The system eigenvalues with the proposed PSS's and TCSC-based stabilizers when applied individually and by means of coordinated design is given in Table 3. The bold rows of this table represent the EM modes eigenvalues and their damping ratios and frequency. It is evident that, using the proposed coordinated stabilizers design, the damping ratio of the EM mode eigenvalue is greatly enhanced. Hence, it can be concluded that this improves the system stability.

Table 3: System eigenvalues with the proposed stabilizer

PSSs	***TCSC***	***TCSC & PSSs***
-3.9219±5.7975i 0.5603*, 0.922**	**-0.749±6.8431i 0.108*, 1.09****	**-4.423±6.07504i 0.59*, 0.97****
-3.4337±5.4358i 0.534*, 0.8651**	**-0.509±4.3648i 0.115*, 0.69****	**-6.16589±5.0236i 0.783*, 0.8****
-1.7682±1.6360i 0.734*, 0.2604**	-0.597±5.0238i	**-2.390±3.2546i 0.59*, 0.526****
-2.6113±3.0188i	-1.614±4.9672i	-1.9658±2.7841i
-7.7989±11.9581i -12.372±17.9649i -17.3096±0.1076i -21.5036±1.8633i -92.0013,-89.364 -81.0185,-76.811 -11.898, -7.4442, -6.2647, -4.9271, -0.2024, -0.2122	-89.067,-89.41 -79.4 -76.692,-23.969 -21.044,-16.712 -13.890,-13.650 -7.5208,-6.4332 -5.4079, -4.908 -0.2000	-6.4785±9.132i -13.00±15.812i -22.269±4.7965i -100,-100,-0.2, -100, -128.36, -82.485,-100 -20.009,-17.72, -15.80, -12.841, -9.4599,-6.023, -5.3289,-2.619

* damping ration, ** frequency (Hz)

E. Nonlinear Time Domain Simulation

Figs. 5-6 show the speed deviations and the rotors angle responses, for a 6-cycle 3θ fault at bus 7 while using the proposed PSSs and TCSC coordinated design.

The simulation results obtained clearly indicate that the proposed coordinated PSS-TCSC design enhances the system stability. These results confirm the conclusion drawn from eigenvalue analysis results.

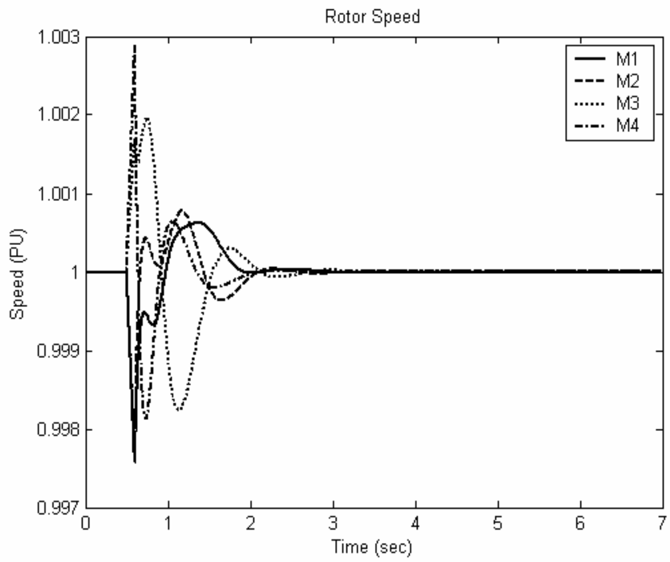

Fig 5: Speed response for 6-cycle fault with PSS & TCSC, coordinated design

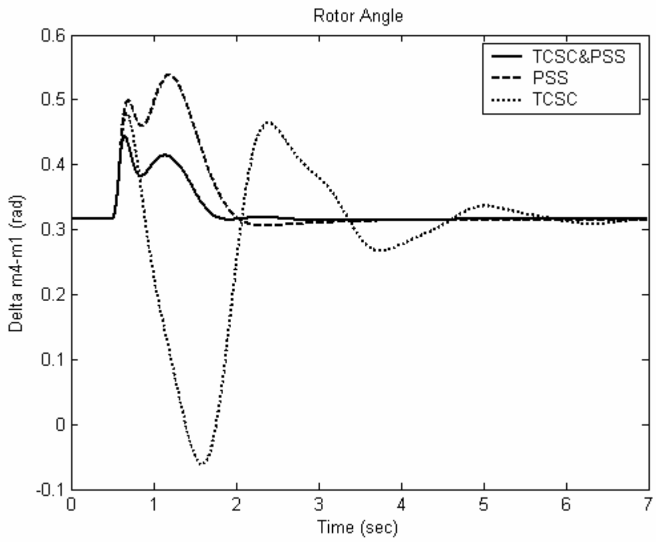

Fig 6: Rotor angle response for 6-cycle fault with PSS & TCSC, individual and coordinated design

V. Conclusion

In this study, a coordination design of TCSC and PSS stabilizers is proposed. The tuning parameters of the proposed stabilizer were optimized using PSO. The proposed stabilizer have been applied and tested on a weakly connected multimachine power system under severe disturbance. The eigenvalues analysis and the nonlinear time domain simulation results show the effectiveness of the proposed stabilizer and its ability to provide good damping of low frequency oscillation and improve greatly the system voltage profile.

VI. Acknowledgment

The first author would like to acknowledge the support of Saudi Electricity Company-ERB**.**

The second author would like to acknowledge the support of King Fahd University of petroleum & Minerals.

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Appendix A

4-Machine Power System Data:

Table 4: 4-machine System bus data in per unit value.

Bus no.	*Type*	*Voltage*	*Angle*	*Load*		*Generation*	
				P	**Q**	**P**	**Q**
1	1	1.03	0	0	0	0	0
2	2	1.01	0	0	0	7	0
3	2	1.03	0	0	0	7	0
4	2	1.01	0	0	0	7	0
5	3	1	0	0	0	0	0
6	3	1	0	0	0	0	0
7	3	1	0	17.67	2.5	0	0
8	3	1	0	0	0	0	0
9	3	1	0	0	0	0	0
10	3	1	0	9.67	1	0	0

Table 5: 4-machine System line data in per unit.

Line no.	*From*	*To*	*R*	*X*	*B*
1	1	5	0	0.0167	0
2	2	6	0	0.0167	0
3	3	8	0	0.0167	0
4	4	9	0	0.0167	0
5	5	6	0.0025	0.025	0.021875
6	8	9	0.0025	0.025	0.021875
7	6	7	0.001	0.01	0.00875
8	9	10	0.001	0.01	0.00875

Table 6: Machine Data

M	*H*	X_d	X_d'	X_q	X_q'	T_d'	T_q'	KA	TA	D
1	55.575	0.2	0.033	0.19	0.016	8	0.4	200	0.01	0
2	55.575	0.2	0.033	0.19	0.016	8	0.4	200	0.01	0
3	58.5	0.2	0.033	0.19	0.016	8	0.4	200	0.01	0
4	58.5	0.2	0.033	0.19	0.016	8	0.4	200	0.01	0

Table 7: Load flow result of the 4-machine system

Bus no.	*Voltage*	*Angle (degree)*	*Load*		*Generation*	
			P	**Q**	**P**	**Q**
1	1.03	0	0	0	7.2532	2.8008
2	1.01	-10.65	0	0	7	4.4762
3	1.03	27.292	0	0	7	1.7721
4	1.01	17.548	0	0	7	2.155
5	0.99159	-6.8112	0	0	0	0
6	0.94312	-17.7	0	0	0	0
7	0.89954	-27.012	17.67	2.5	0	0
8	1.0077	20.825	0	0	0	0
9	0.98122	10.774	0	0	0	0
10	0.96662	2.4251	9.67	1	0	0