Synchronising and Damping Effects of TCPS and TCSC Based Coordinated Damping Controllers: Single Machine Infinite Bus

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Abstract — **This paper proposes a new design for the coordination control of the low frequency oscillation damping issues of single machine infinite bus power system (SMIB). The controller gains of a linearized power system are optimized using genetic algorithm (GA) to achieve an eigen value based objective function. Here SMIB is employed with TCPS and TCSC based controllers. Their effectiveness in suppressing power system oscillations is investigated by eigenvalue analysis, time domain simulations and synchronising and damping power contributed in the system. The conclusions have been drawn here, based on theoretical analysis so as to provide an insight and better understanding of damping effect of different schemes. Finally, six different control schemes for power oscillations damping of test power system are employed and the results are compared in terms of damping ratio and time-domain analysis.**

Keywords —Eigen values, Facts controllers, Genetic Algorithm, Coordination, Power System Stabilizer, Synchronising and damping power

I. INTRODUCTION

Power system is prone to experience stability problems. The limiting factor is not first swing stability but the damping of system oscillations. Power systems are subjected to low frequency disturbances that might cause loss of synchronism and an eventual breakdown of entire system. The oscillations, which are typically in the frequency range of 0.2 to 3.0 Hz [11], might be excited by the disturbances in the system or, in some cases, might even build up spontaneously. In order to damp these oscillations power system stabilizer (PSS) has been used conventionally [4].

But, with advent of FACTS technology enhancement of oscillation damping and system stability has been explored as potential application [3]-[5]. Series compensation devices like Thyristor Controlled Series Compensator help in controlling power flow and series-shunt compensator helps in increasing system stability. However, to enhance power system oscillation damping simultaneous application of PSS and Facts based controllers are needed. Research on the same has been investigated as coordinated PSS and Facts based controllers [1],[2],[4],[6]. Genetic Algorithm has been as an optimization tool in different fields. Genetic Algorithm based application to optimize different controller parameters of PSS have been reported in [2],[6].Also, coordinated control tuning of PSS and Facts based controllers have been reported in [2],[6],[8]-[10]. The eigen value based coordinated control design to damp electromechanical oscillations is discussed in [2].In [6] the authors have discussed global tuning of coordinated PSS and FACTS devices using non-linear optimization algorithm.

The present work deals with simultaneous coordinated tuning of TCPS and TCSC controllers to enhance the power system oscillation damping. Here, the control parameters of coordinated controllers are optimized by eigen value based objective function using GA. The proposed controllers are used independently and in coordination with each other. Their effectiveness in suppressing power system oscillations is investigated by eigenvalue analysis, time-domain simulations and Synchronizing and Damping Power contributing to the power system. The conclusions have been drawn here, based on theoretical analysis so as to provide an insight and better understanding of synchronizing and damping effect of different schemes.

This paper is organized is as follows, in section II, the mathematical modeling of power system with different schemes is presented which also contains linearization of test system. In section III, the synchronizing and damping power components contributed by different schemes is calculated. In section IV, the objective function used is described. In section V, a brief introduction of GA and its optimization procedure are discussed. In section VI, the simulation results are formulated followed by conclusions.

II. SYSTEM MODEL WITH CONTROLLERS

A. Single Machine Infinite Bus Modeling

In this paper, a single machine infinite bus (SMIB) power system is considered for analysis. The SMIB system is equipped with TCPS and TCSC are installed at generator terminals as shown in Fig 1. The controller shown in figure is coordinated controller which gives appropriate signals to the stabilizers at a time. The generator taken, taking field circuit into account [17], this also contains swing equation and q-axis generator internal voltage equation. The dynamic equation [3],[4],[11] are shown in Eq. (1)-(2).

$$\frac{d}{dt}\delta = w_o \Delta w$$
$$\frac{d}{dt}\Delta w = \left(P_m - P_e - D\Delta w\right)/2H$$
$$\frac{d}{dt}E_q^{'} = \left(-E_q + E_{fd}\right)/T_{do}^{'}$$
$$\frac{d}{dt}E_{fd} = \frac{K_A}{1+sT_A}\left(V_{to} - V_t\right)$$

(1)

Where,

$$Pe = \frac{Eq' V_b \sin\delta}{X'_{d\Sigma}} - \frac{V_b^2 \left(Xq - Xd'\right)\sin 2\delta}{2X'_{d\Sigma} X_{q\Sigma}}$$

$$Eq = \frac{X_{d\Sigma} Eq'}{X'_{d\Sigma}} - \frac{\left(Xq - Xd'\right) V_b \cos\delta}{X'_{d\Sigma}}$$

$$Vt_d = \frac{X_q V_b \sin\delta}{X_{q\Sigma}}$$

$$Vt_q = \frac{X_{tl} Eq'}{X'_{d\Sigma}} + \frac{X'_d V_b \cos\delta}{X'_{d\Sigma}}$$

$$Vt = \sqrt{Vt_d^{\,2} + Vt_q^{\,2}}$$

$$X'_{d\Sigma} = X'_d + X_{tl}$$

$$X_{q\Sigma} = X_q + X_{tl}$$

$$X_{d\Sigma} = X_d + X_{tl}$$

(2)

X_{tl} is impedance of transmission line.

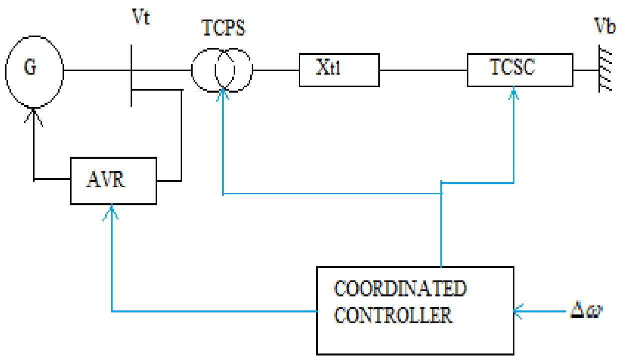


Fig. 1 SMIB under study

B. Exciter system Modelling

Here, IEEE-ST1 type excitation system is considered shown in Fig 2.

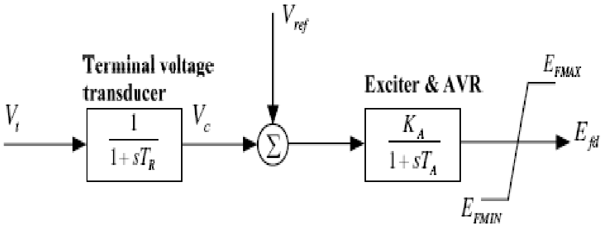


Fig. 2 IEEE ST1 type Excitation

C.TCPS and TCSC controller modelling

The design of TCPS and TCSC based controllers are based on conventional lead-lag type. The TCPS based controller consists of washout block, single stage lead-lag block and gain block [6].The TCSC based controller consists of an additional a first order lag block [3] with time constant ranging from 15 to 20 milliseconds. In stability studies it is not necessary to model the gate pulses [3]. The input signal to the controllers used as speed deviation of the generator.

The controller structures for TCPS and TCSC are shown in Fig.3 and 4.The lead-lag block is used to provide phase-lead characteristics to provide required phase lag. The wash out block serves as a high-pass filter with time constant in the range of 1 to 20 seconds.

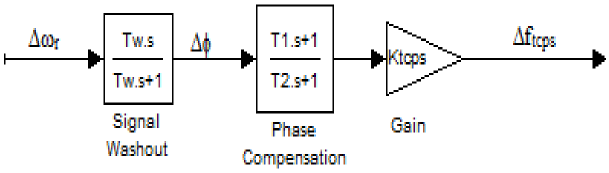


Fig. 3 Structure of TCPS based Controller

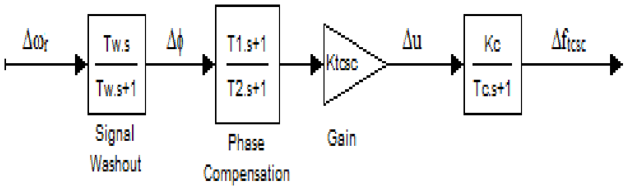


Fig. 4 Structure of TCSC based Controller

The non-linear equations of Eq. (2) for the power system with both TCPS and TCSC FACTS devices can be modified as [17]:

$$Pe = \frac{Eq' V_b \sin\left(\delta + \Delta f_{ps} F_0\right)}{X'_{d\Sigma}} - \frac{V_b^2 \left(Xq - Xd'\right)\sin 2\left(\delta + \Delta f_{ps} F_0\right)}{2X'_{d\Sigma} X_{q\Sigma}}$$

$$Eq = \frac{X_{d\Sigma} Eq'}{X'_{d\Sigma}} - \frac{\left(Xq - Xd'\right) V_b \cos\left(\delta + \Delta f_{ps} F_0\right)}{X'_{d\Sigma}}$$

$$Vt_d = \frac{X_q V_b \sin\left(\delta + \Delta f_{ps} F_0\right)}{X_{q\Sigma}}$$

$$Vt_q = \frac{X_{tl} Eq'}{X'_{d\Sigma}} + \frac{X'_d V_b \cos\left(\delta + \Delta f_{ps} F_0\right)}{X'_{d\Sigma}}$$

$$Vt = \sqrt{Vt_d^{\,2} + Vt_q^{\,2}}$$

$$X'_{d\Sigma} = X'_d + X_{tl}$$

$$X_{q\Sigma} = X_q + X_{tl}$$

$$X_{d\Sigma} = X_d + X_{tl}$$

$$X_{tl} = X_{tl} - \Delta f_{tcsc} X_{tcsc}$$

(3)

D. Linearized power system model

The non-linear Eq. (1)-(2) can be linearized about an operating point to have a linear model.

$$\frac{d}{dt}\Delta\delta = w_o \Delta w$$

$$\frac{d}{dt}\Delta w=\left[\Delta P_m-K_1\Delta\delta-K_2\Delta Eq^{'}-D\Delta w\right]/2H$$
$$\frac{d}{dt}\Delta E_q^{'}=\left(-K_4\Delta\delta-K_3\Delta Eq^{'}+\Delta E_{fd}\right)/T_{do}^{'}$$
$$\frac{d}{dt}\Delta E_{fd}=\left[-\Delta E_{fd}-K_A\left(K_5\Delta\delta+K_6\Delta Eq^{'}\right)\right]/T_A$$

(4)

Where,

$$K_1=\frac{\partial Pe}{\partial\delta},K_2=\frac{\partial Pe}{\partial Eq^{'}},K_3=\frac{\partial Eq}{\partial Eq^{'}}$$
$$K_4=\frac{\partial Eq}{\partial\delta},K_5=\frac{\partial Vt}{\partial\delta},K_6=\frac{\partial Vt}{\partial Eq^{'}}$$

The values of K constants are given in appendix.
From Eq. (4) the state space representation of the system is given by:

$$\frac{d}{dt}\Delta x=A\Delta x+B\Delta u$$

$$\frac{d}{dt}\begin{bmatrix}\Delta\delta\\ \Delta\omega_r\\ \Delta E_{fd}\\ \Delta Eq`\end{bmatrix}=\begin{bmatrix}0 & w_o & 0 & 0\\ \frac{-K_1}{2H} & \frac{-D}{2H} & 0 & \frac{-K_2}{2H}\\ \frac{-K_AK_5}{T_A} & 0 & \frac{-1}{T_A} & \frac{-K_AK_6}{T_A}\\ \frac{-K_4}{Td_o`} & 0 & \frac{1}{Td_o`} & \frac{-K_3}{Td_o`}\end{bmatrix}\begin{bmatrix}\Delta\delta\\ \Delta\omega_r\\ \Delta E_{fd}\\ \Delta Eq`\end{bmatrix}+\begin{bmatrix}0\\ \frac{1}{2H}\\ 0\\ 0\end{bmatrix}\left[\Delta P_m\right]$$

(5)

With constant mechanical power input ΔP_m=0.
For TCPS based controller, using perturbed values, we have from Fig.(3)

$$\Delta\phi=\frac{sT_w}{1+sT_w}\Delta\omega_r$$
$$\frac{d}{dt}(\Delta\phi)=\frac{\left[\Delta P_m-K_1\Delta\delta-D\Delta\omega_r-K_2\Delta Eq'-K_p\Delta f_{tcps}\right]}{2H}-\frac{1}{T_w}\Delta\phi$$
$$\frac{d}{dt}\left(\Delta f_{tcps}\right)=\frac{K_{tcps}T_1}{T_2}\left[\frac{d}{dt}\Delta\phi\right]+\frac{K_{tcps}}{T_2}\Delta\phi-\frac{1}{T_2}\Delta f_{tcps}$$

(6)

For TCSC based controller, using perturbed values, we have From Fig.(4)

$$\Delta\phi=\frac{sT_w}{1+sT_w}\Delta\omega_r$$
$$\frac{d}{dt}(\Delta\phi)=\frac{\left[\Delta P_m-K_1\Delta\delta-D\Delta\omega_r-K_2\Delta Eq'-K_p\Delta f_{tcsc}\right]}{2H}-\frac{1}{T_w}\Delta\phi$$
$$\frac{d}{dt}\left(\Delta u\right)=\frac{K_{tcsc}T_1}{T_2}\left[\frac{d}{dt}\Delta\phi\right]+\frac{K_{tcsc}}{T_2}\Delta\phi-\frac{1}{T_2}\Delta u$$
$$\frac{d}{dt}\left(\Delta f_{tcsc}\right)=\frac{K_c}{T_c}\Delta u-\frac{1}{T_c}\Delta f_{tcsc}$$

(7)

The linearized equations of power system with coordinated TCPS and TCSC facts devices can be obtained from Eq. (5), (6) and (7) as:

$$\frac{d}{dt}\Delta\delta=w_o\Delta w$$
$$\frac{d}{dt}\Delta w=\left[\Delta P_m-K_1\Delta\delta-K_2\Delta Eq^{'}-D\Delta w-K_p^{tcsc}\Delta f_{tcsc}-K_p^{tcps}\Delta f_{tcps}\right]/2H$$
$$\frac{d}{dt}\Delta E_q^{'}=\left(-K_4\Delta\delta-K_3\Delta Eq^{'}-K_q^{tcsc}\Delta f_{tcsc}-K_q^{tcps}\Delta f_{tcps}+\Delta E_{fd}\right)/T_{do}^{'}$$
$$\frac{d}{dt}\Delta E_{fd}=\left[-\Delta E_{fd}-K_A\left(K_5\Delta\delta+K_6\Delta Eq^{'}+K_v^{tcsc}\Delta f_{tcsc}+K_v^{tcps}\Delta f_{tcps}\right)\right]/T_A$$

(8)

The state space representation of the system with coordinated FACTS devices, the Eq. (5) can be modified as:

$$\frac{d}{dt}\Delta x=A\Delta x+B\Delta u$$

$$\frac{d}{dt}\begin{bmatrix}\Delta\delta\\ \Delta\omega_r\\ \Delta E_{fd}\\ \Delta Eq`\\ \Delta\phi\\ \Delta u\\ \Delta f_{tcsc}\\ \Delta\phi_{tcps}\\ \Delta f_{tcps}\end{bmatrix}=\begin{bmatrix}0 & w_o & 0 & 0 & 0 & 0 & 0 & 0 & 0\\ A_{11} & A_{12} & 0 & A_{13} & 0 & 0 & A_{14} & 0 & A_{15}\\ A_{21} & 0 & A_{22} & A_{23} & 0 & 0 & A_{24} & 0 & A_{25}\\ A_{31} & 0 & A_{32} & A_{33} & 0 & 0 & A_{34} & 0 & A_{35}\\ A_{41} & A_{42} & 0 & A_{43} & A_{44} & 0 & A_{45} & 0 & A_{46}\\ A_{51} & A_{52} & 0 & A_{53} & A_{54} & A_{55} & A_{56} & 0 & A_{57}\\ 0 & 0 & 0 & 0 & 0 & A_{61} & A_{62} & 0 & 0\\ A_{71} & A_{72} & 0 & A_{73} & 0 & 0 & A_{74} & A_{75} & A_{76}\\ A_{81} & A_{82} & 0 & A_{83} & 0 & 0 & A_{84} & A_{85} & A_{86}\end{bmatrix}\begin{bmatrix}\Delta\delta\\ \Delta\omega_r\\ \Delta E_{fd}\\ \Delta Eq`\\ \Delta\phi\\ \Delta u\\ \Delta f_{tcsc}\\ \Delta\phi_{tcps}\\ \Delta f_{tcps}\end{bmatrix}+\begin{bmatrix}0\\ B_1\\ 0\\ 0\\ B_2\\ B_3\\ 0\\ B_4\\ B_5\end{bmatrix}\Delta P_m$$

(9)

Where, A_{ij} and B_i values are formed using Eq. (6)-(8).

III. SYNCHRONISING AND DAMPING POWER

With electrical power systems, the change in electrical power of a synchronous machine, following a small disturbance can be resolved into two components [4],[10].

$$\Delta Pe=K_S\Delta\delta+K_D\Delta\omega_r$$

(10)

Lack of sufficient synchronizing power results in instability through a periodic drift in rotor angle (K_S = pu power / rad).
Lack of sufficient damping power results in oscillatory instability (K_D = pu power / pu speed deviation).
For a generator connected radially to a large power system, in the presence of automatic voltage regulator, the instability is due to the lack of sufficient damping power. This results in instability through an oscillatory mode.
When TCPS and TCSC are acting in coordination than

$$\Delta Eq`_{|TCPS\_TCSC} = -\left[\frac{K_q^{tcps}\left(1+sT_A\right)+K_A K_v^{tcps}}{\left(K_3+sTdo`\right)\left(1+sT_A\right)+K_A K_6}\right]\Delta f^{TCPS} -\left[\frac{K_q^{tcsc}\left(1+sT_A\right)+K_A K_v^{tcsc}}{\left(K_3+sTdo`\right)\left(1+sT_A\right)+K_A K_6}\right]\Delta f^{TCSC}$$

(11)
And,

$$\Delta Pe_{|TCPS\_TCSC} = K_p^{tcps}\Delta f^{TCPS} + K_p^{tcsc}\Delta f^{TCSC} -K_2\left(\left[\frac{K_q^{tcps}\left(1+sT_A\right)+K_A K_v^{tcps}}{\left(K_3+sTdo`\right)\left(1+sT_A\right)+K_A K_6}\right]\Delta f^{TCPS} + \left[\frac{K_q^{tcsc}\left(1+sT_A\right)+K_A K_v^{tcsc}}{\left(K_3+sTdo`\right)\left(1+sT_A\right)+K_A K_6}\right]\Delta f^{TCSC}\right)$$

(12)
Rearranging Eq. (12) in terms of rotor speed deviation,

$$\Delta Pe_{|TCPS\_TCSC} = \begin{bmatrix} K_p^{tcps}.G_1(s) + K_p^{tcsc}.G_2(s) \\ -K_2\left(G_3(s).G_1(s)+G_4(s).G_2(s)\right)\end{bmatrix}\Delta w_r$$

(13)
Where $G_i(s)$ values for particular oscillatory eigen values are given in appendix.

IV. OBJECTIVE FUNCTION

The mathematical expression describing a relationship of the parameters is called an Objective function. In this paper, an eigen value based objective function consisting of coordinated controller parameters [2] is considered. As the main objective is to enhance power system oscillation damping, maximize-tion of the damping ratio (ξ) of poorly damped eigen values of the power system is considered.
Hence, the Objective function J is given by:

$$J = \min\left(\sum_{i=1}^{n}\left(1-\xi_i\right)\right)$$

(14)

Where, $\xi_i = \dfrac{-\sigma_i}{\sqrt{\sigma_i^{\,2}+\omega_i^{\,2}}}$

Subjected to:

$$K^{\min} \le K \le K^{\max}$$
$$T_1^{\min} \le T_1 \le T_1^{\max}$$
$$T_2^{\min} \le T_2 \le T_2^{\max}$$

Where, K and T represent controller gains and time constants of lead-lag blocks respectively.

V. GENETIC ALGORITHM

Genetic Algorithm (GA) is a search heuristic that mimics the process of natural evolution [13].Genetic Algorithms belong to the larger class of evolutionary algorithms (EA), which generate solutions to optimization problems using techniques by natural evolution, such as inheritance, mutation, and crossover. The objective function assigns each individual a corresponding number called its fitness. The fitness of each chromosome is assessed and a survival of the fittest strategy is applied.
Here, GA is used for optimizing the control variables of coordinated FACTS controllers. All variables are optimized by minimizing the objective function given by Eq. (14).
The GA parameters used in optimization are given in Table I

TABLE I.
GA Parameters

Parameters	Type / Value
Population Size	20
Maximum Generation	500
Selection Function	Roulette
Convergence Criterion	Maximum generation
Crossover	Heuristic

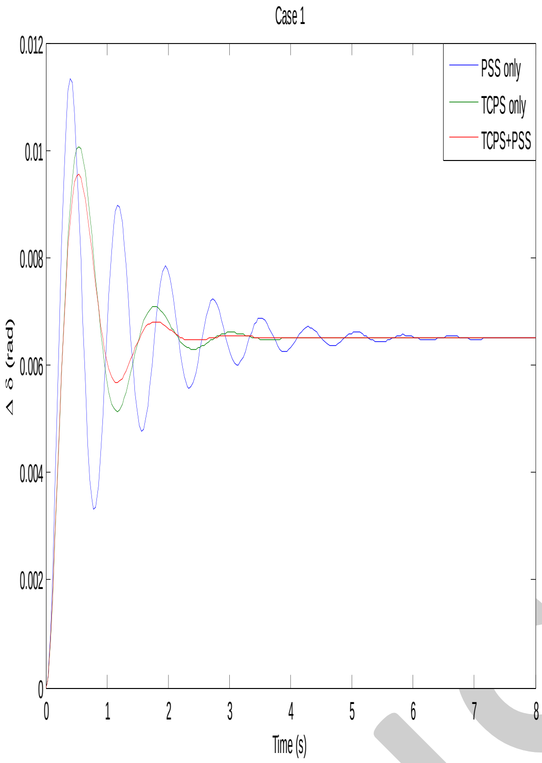
VI. SIMULATION RESULTS

The dynamic performance of the test system is analyzed about an operating condition given in appendix. The system Eigen values of two controllers are optimized by GA with minimizing the objective function. The optimal values of different control variables are given in appendix. Six different control schemes are employed to analyze the performance of coordinate controller. The system is tested with PSS, TCPS, TCSC, PSS & TCPS, PSS & TCSC and TCPS & TCSC.
The Eigen values of electromechanical mode for six different control schemes are given below in Table II. The time-domain simulation is carried out using MATLAB software package for an operating condition following a 1 % step perturbation in mechanical power. The simulation results are given in Fig. (5) to (7)

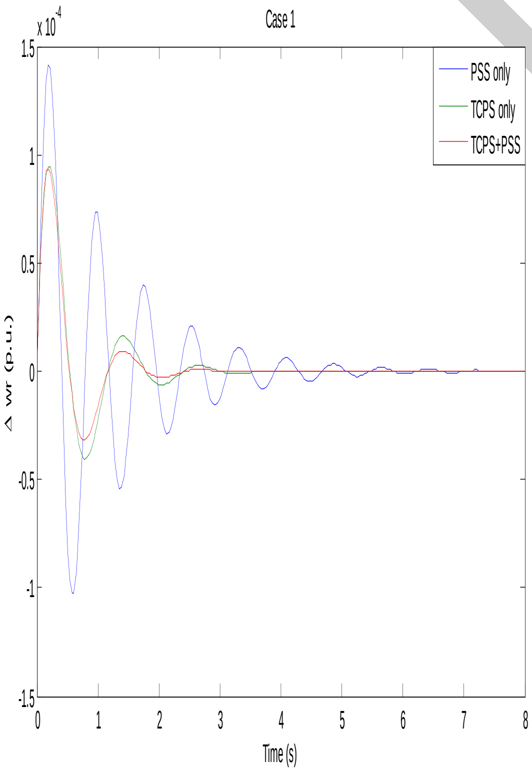
TABLE II

Comparision of Eigen Values

Control Scheme	Eigen Value	Damping ratio (ξ)
PSS only	$-0.8054 \pm i\ 8.0808$	0.0991
TCPS only	$-1.4823 \pm i\ 5.0575$	0.2812
TCPS with PSS	$-1.9035 \pm i\ 4.9881$	0.3565



(a)



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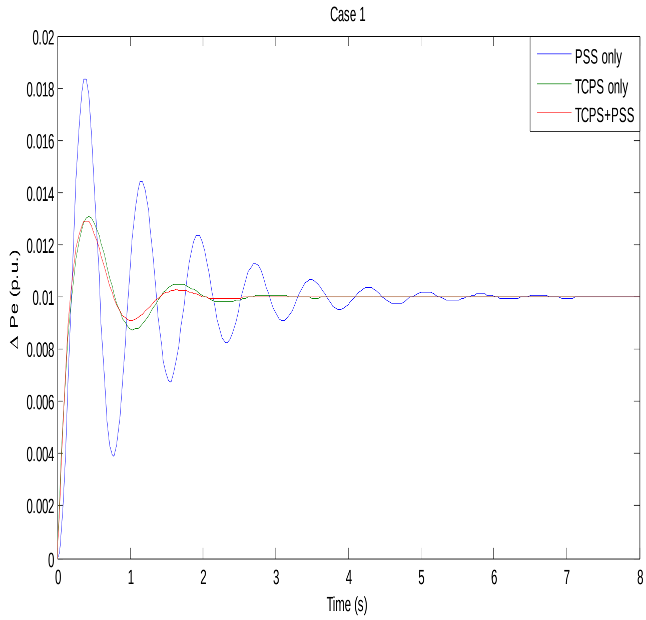


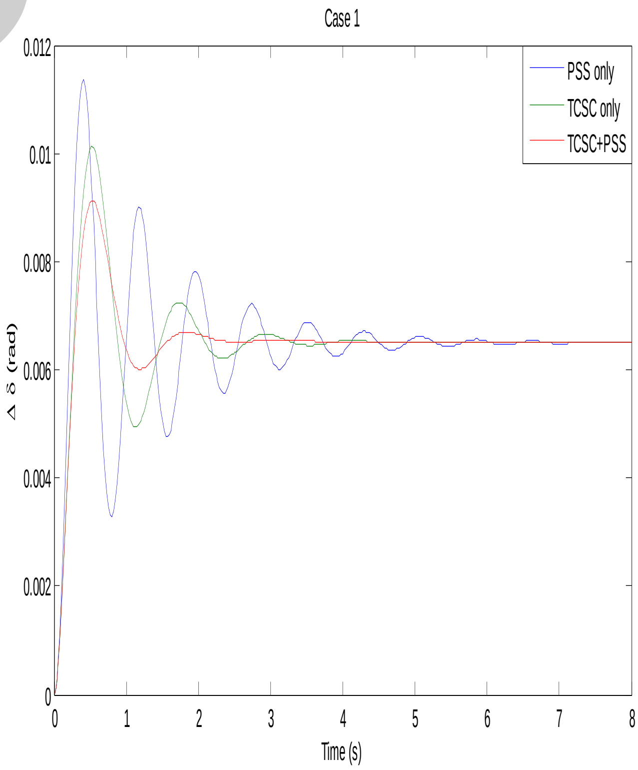
(c)

Fig. 5 Comparative System dynamic response (a) Rotor angle (b) Rotor speed variation (c) Active power deviation.

TABLE III

Comparision of Eigen Values

Control Scheme	Eigen Value	Damping ratio (ξ)
PSS only	$-0.8054 \pm i\ 8.0808$	0.0991
TCSC only	$-1.3396 \pm i\ 5.2283$	0.2482
TCSC with PSS	$-2.2446 \pm i\ 4.786$	0.4246



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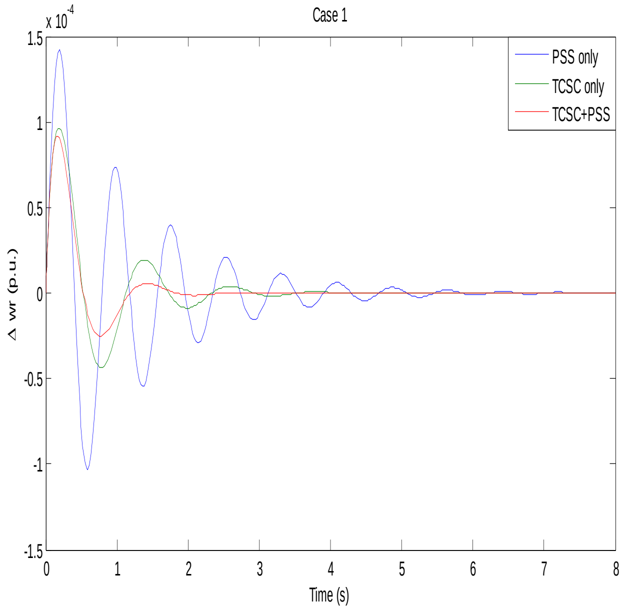

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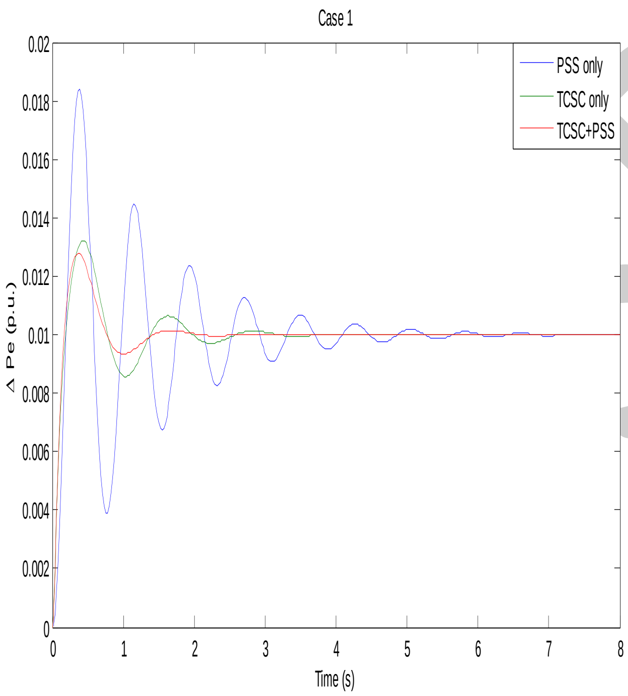


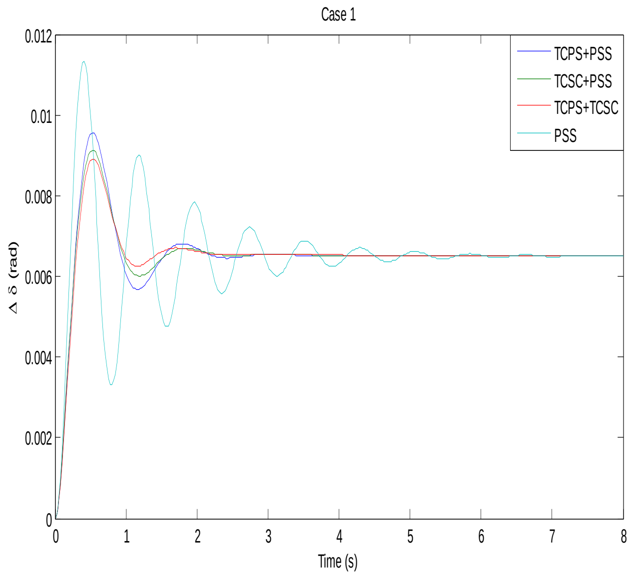
(c)

Fig. 6 Comparative System dynamic response (a) Rotor angle (b) Rotor speed variation (c) Active power deviation.

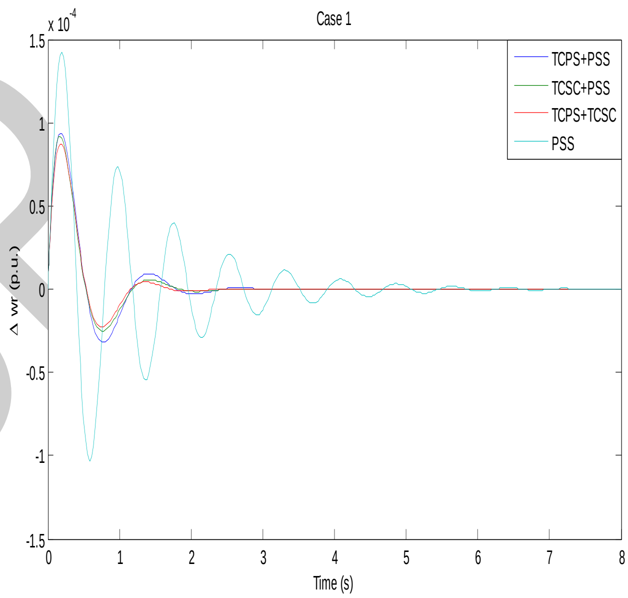
TABLE IV

Comparision of Eigen Values

Control Scheme	Eigen Value	Damping ratio (ξ)
PSS	-0.8054 ± i 8.0808	0.0991
TCPS with PSS	-1.9035 ± i 4.9881	0.3565
TCSC with PSS	- 2.2446 ± i 4.786	0.4246
TCPS with TCSC	-2.5004 ± i 5.2964	0.4269



(a)



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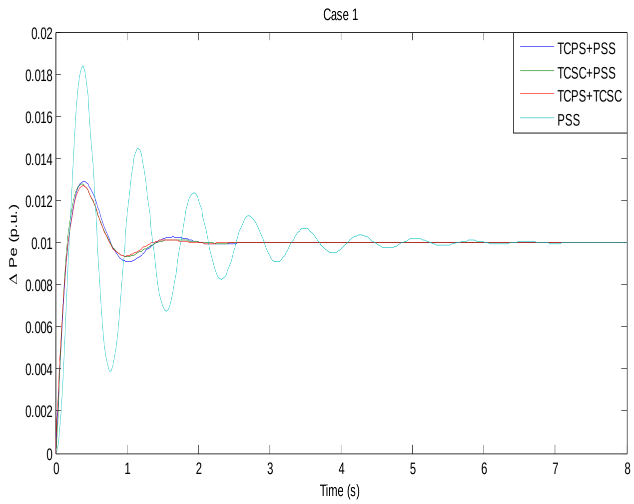

(c)

Fig. 7 Comparative System dynamic response (a) Rotor angle (b) Rotor speed variation (c) Active power deviation.

TABLE V

Synchronising and Damping Power Components for Different Schemes at their Respective Oscillatory Mode.

Control Scheme	Eigen Value	K_S	K_D
No Scheme	$0.0431 \pm i\,7.481$	1.5214	- 0.7367
PSS	$-0.8054 \pm i\,8.0808$	1.7927	13.7567
TCPS only	$-1.4823 \pm i\,5.0575$	0.755	25.3175
TCSC only	$-1.3396 \pm i\,5.2283$	0.7918	22.8799
TCPS with PSS	$-1.9035 \pm i\,4.9881$	0.7748	32.5112
TCSC with PSS	$-2.2446 \pm i\,4.786$	0.7596	38.3379
TCPS with TCSC	$-2.5004 \pm i\,5.2964$	0.9325	42.7056

The simulations results show that the test system dynamic performance and the damping are enhanced by simultaneous tuning of two FACTS based controllers. The damping ratios of poorly damped electromechanical modes are improved using tuning with GA based optimization.

VI. CONCLUSION

In this paper, genetically optimized coordinated control of thyristor controlled series compensator (TCSC) and a thyristor controlled phase shifter (TCPS) based controller is discussed. An objective function is minimized using GA for finding optimal control parameters of coordinated controller. Six different control schemes are employed on the test system to investigate the performance of proposed controller. The time domain simulation is carried out in MATLAB software. The small signal stability analysis of the test system is discussed using proposed coordinate controller. The damping in the system is enhanced by simultaneous employment of two FACTS based controllers.

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REFERENCES

[1] C. F. Lu, C. H. Hsu, C.F. Juang, "Coordinated Control of Flexible AC Transmission System Devices Using an Evolutionary Fuzzy Lead-Lag Controller With Advanced Continuous Ant Colony Optimization", *IEEE Transactions on Power Systems*, vol. 28, no. 1, 2013.

[2] R. Narne, P.C.Panda, J.. P. Therattil, "Genetic Algorithm Based Simultaneous Coordination of PSS and FACTS Controllers for Power Oscillations Damping", *IEEE ICSET* 2012, Nepal.

[3] K.R.Padiyar, (2013)"FACTS Controllers in Power Transmission and Distribution", , *New Age International Limited*, Publishers.

[4] P. Kundur, "Power System Stability and Control", *Tata McGraw-Hill*.

[5] M. A. Abido, "Power System Stability Enhancement Using Facts Controllers: A Review", *The Arabian Journal for Science and Engineering*, vol. 34, 2009.

[6] L. J. Cai and I. Erlich, "Simultaneous Coordinated Tuning of PSS and FACTS Damping Controllers in Large Power Systems", *IEEE Transactions on Power Systems*, vol. 20, no. 1, February 2005.

[7] S. C. Lee, S. Moon, "Hybrid Linearization of a Power System with FACTS devices for a Small Signal Study: Concept and Application", *Electrical Power Systems Research* 64(2003), pp. 27-34.

[8] S.M. A. Elazim, E.S. Ali, "Coordinated design of PSS and SVC via Bacteria Foraging Optimization Algorithm in a multi machine Power system", *Electrical Power and Energy Systems* 41(2012), pp. 44-53.

[9] X. Lei, E. N. Lerch, and D. Povh, "Optimization and Coordination of Damping Controls for Improving System Dynamic Performance", *IEEE Transactions on Power Systems*, vol. 16, no. 3, 2001.

[10] J.J. Sanchez-Gasca, "Coordinated Control of Two Facts Devices for Damping Inter Area Oscillations", *IEEE Transactions on Power Systems*, vol. 13, no. 2, 1998.

[11] H.F.Wang, M.Li, F.J.Swift, "Facts-based Stabilizer Designed by the Phase Compensation Method Part 1:Single-Machine Infinite-Bus Power Systems", *4th International Conference on Advance in Power System Control, Operation and Management*, APSCOM-97,Hong-Kong,Nov-1997.

[12] Q.Wang, P. Spronck, R. Tracht, "An overview of Genetic Algorithms applied to control Engineering Problems", *IEEE ICMLC* Nov 2003.

[13] R. Rojas, "Genetic Algorithms" , *Neural Networks, Springer*, 1996.

[14] N. G. Hingorani, L. Gyugyi, (2000) "Understanding FACTS Concepts and Technology of Flexible AC Transmission Systems", *IEEE Power Engineering Society, Sponsor*.

[15] A. Chipperfield, P. Fleming, H. Pohlheim, C. Fonseca, "Genetic Algorithm TOOLBOX for Use with MATLAB", *Mathworks.in*.

[16] A. M. Liapunov, "The general problem of the stability of motion", 1892.

[17] H.F..Wang, F.J.Swift," A Unified Model for the Analysis of FACTS Devices in Damping Power System Oscillations Part I: Single-machine Infinite-bus Power Systems", *IEEE Transactions on Power Delivery*, vol. 12, no. 2, April 1997.

APPINDEX

The data of single machine infinite bus system

Synchronous generator: (Base Power 100 MVA)

X_d (p.u)	X'_d (p. u)	T'_{do} (seconds)	X_q (p. u)	H	f_o (Hz)
1.445	0.316	5.26	0.959	4.27	50

IEEE Type-1 Excitation System

K_A	T_A (seconds)
100	0.01

PSS: T_w =2 seconds

TCPS: T_w =2 seconds, F_o =1.0

TCSC: T_w =2 seconds, X_{TCSC} = 1.0 p.u

System operating condition:

	CASE 1
P (p. u)	0.736
V_{bo} (p. u)	0.92
V_{to} (p. u)	1.0522
δ_o (deg)	29.85
E'_{qo} (p. u)	1.2713
V_{to} (p. u)	1.0522
V_{tdo} (p. u)	0.3789
V_{tqo} (p. u)	0.9814

$G_i(s)$ expressions are:

$$G_1(s)=\left[K_{TCPS}\left(\frac{sT_w}{1+sT_w}\right)\left(\frac{1+sT_1^{tcps}}{1+sT_2^{tcps}}\right)\right]$$

$$G_2(s)=\left[K_{TCSC}\left(\frac{sT_w}{1+sT_w}\right)\left(\frac{1+sT_1^{t\mathrm{csc}}}{1+sT_2^{t\mathrm{csc}}}\right)\left(\frac{k_c}{1+sT_c}\right)\right]$$

$$G_3(s)=\left[\frac{K_q^{tc\,ps}\left(1+sT_A\right)+K_A K_v^{tc\,ps}}{\left(K_3+sTdo`\right)\left(1+sT_A\right)+K_A K_6}\right]$$

$$G_4(s)=\left[\frac{K_q^{t\mathrm{csc}}\left(1+sT_A\right)+K_A K_v^{t\mathrm{csc}}}{\left(K_3+sTdo`\right)\left(1+sT_A\right)+K_A K_6}\right]$$

BIOGRAPHIES

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