

# Particle Swarm Optimization for Simultaneous Tuning of Static Var Compensator and Power System Stabilizer

**Abstract.** In this study, simultaneous coordinated designing of power system stabilizer and static VAR compensator damping controller is investigated. The particle swarm optimization (PSO) is used to search for optimal controller parameters, by incorporating chaos. PSO with chaos is hybridized to form a chaotic PSO, which reasonably combines the population-based evolutionary searching ability of PSO and chaotic searching behavior. The efficiency of the proposed controllers is exhibited through the eigenvalue analysis and nonlinear time-domain simulation. The results of these studies show that the proposed coordinated controllers have an excellent capability in damping interarea oscillations.

**Streszczenie.** Zbadano możliwość równoczesnej kompensacji mocy biernej i stabilizacji system. Wykorzystano algorytm PSO – mrówkowy. Próby systemu wykazały skuteczność i możliwość tłumienia oscylacji. (Wykorzystanie algorytmu mrówkowego do równoczesnej kompensacji mocy biernej i stabilizacji systemu)

**Keywords:** Particle Swarm Optimization, Power System Stabilizer, Static Var Compensator, Chaotic.

**Słowa kluczowe:** algorytm mrówkowy, kompensacja mocy biernej.

## Introduction

Transient and dynamic stability considerations are among the main issues in the reliable and efficient operation of power systems. Electro-mechanical oscillations happen more often than before, and inadequate damping of these oscillations will limit the capacity to transmit power. These oscillations may be very weakly damped in some cases, resulting in mechanical fatigue at the machines and unacceptable power variations across the important transmission lines. Due to this cause, the use of the controllers to provide better damping for these oscillations is of utmost importance [1-3]. Request of power system stabilizers (PSSs) has become the first measure to increase the system damping. In some cases, if the utilization of PSS cannot provide enough damping for inter-area power swing, flexible AC transmission systems based (FACTS) damping controllers are alternative efficient resolutions. FACTS are designed to overcome the limitations of the present mechanically controlled power systems and enhance power system stability by applying reliable and high-speed electronic devices. Usually, the FACTS devices are utilized in power system to supply fast continuous control of power flow in the transmission system by changing the impedance of transmission lines, by controlling voltages at critical buses, or by controlling the phase angles between the ends of transmission lines.

One of the promising FACTS devices is the Static VAR Compensators (SVC) which is a shunt compensation component and it can rapidly regulate its susceptance to supply dynamic reactive compensation and maintain the bus voltage in power system. SVC with damping controller is effective to increase damping of electro-mechanical modes. However, the SVC controllers will likely to react differently with other damping controllers (e.g. PSS) in a power system. The interaction among stabilizers may increase or degrade the damping of the particular modes of rotor oscillation. This problem may happen especially after the clearance of a critical fault, with FACTS devices used in the same area. Interactions between damping controllers can adversely influence the rotor damping of generators and under weakly interconnected system conditions; it can even cause dynamic instability and restrict the operating power range of the generators. To improve overall system performance, many researches focus on the coordination between PSSs and FACTS controllers [4–5].

In this paper, an optimization based tuning algorithm is proposed to coordinate among PSSs and SVC power oscillation damping controllers simultaneously using the chaotic particle swarm optimization (CPSO) technique. PSO

and chaotic methods are combined to improve the global searching capability and premature convergence to local minima. The performance of the simple PSO greatly depends on its parameters, and it often suffers the problem of being trapped in the local optima and has premature convergence. In order to overcome these drawbacks, PSO based on the chaotic sequence is proposed in this study. Chaos is a kind of characteristic for nonlinear systems which have a bounded unstable dynamic behavior and exhibits sensitive dependence on the initial conditions and include infinite unstable periodic motions. It is based on ergodicity, stochastic properties and regularity of the chaos. It is not like some stochastic optimization algorithms that escape from the local minima by accepting some bad solutions according to a certain probability, but CPSO searches on the regularity of the chaotic motion to escape from the local minima. This new approach is used here for simultaneous coordinated design of the PSS and SVC damping controller. The coordinated design problem of PSS and SVC controllers over a wide range of system configurations is formulated as a multi-objective function where the objective is the eigenvalues comprised of the damping factor, and the damping ratio. The effectiveness of the proposed controller is tested on a two-area four-machine power system under different operating. Simulation results show that the proposed method achieves robust performance for damping the low frequency inter-area oscillations under different operating conditions.

## General PSO method

Many real optimization problems can be formulated as the following functional optimization problem.

$$(1) \quad \begin{aligned} & \text{minimize} && f(X), \quad X = [x_1, \dots, x_n], \\ & \text{s.t.} && x_i \in [a_i, b_i], \quad i = 1, 2, \dots, n, \end{aligned}$$

where  $f$  is the objective function, and  $X$  is the decision vector consisting of  $n$  variables.

PSO is a population-based optimization technique proposed firstly for the above unconstrained minimization problem. In a PSO system, multiple candidate solutions coexist and collaborate simultaneously. Each solution called a “particle”, flies in the problem search space looking for the optimal position to land. A particle, as time passes through its quest, adjusts its position according to its own “experience” as well as the experience of neighboring particles. Tracking and memorizing the best position encountered build particle’s experience. For that reason, PSO possesses a memory (i.e. every particle remembers the best position it reached during the past). PSO system

combines local search method (through self experience) with global search method (through neighboring experience), attempting to balance exploration and exploitation [6]. A particle status on the search space is characterized by two factors: its position ( $X_i$ ) and velocity ( $V_i$ ), which are updated by following equations.

$$(2) V_i[t+1] = wV_i[t] + c_1 \text{rand}(\cdot)(P_i - X_i) + c_2 \text{Rand}(\cdot)(P_g - X_i)$$

$$(3) X_i[t+1] = X_i[t] + V_i[t+1]$$

where,  $V_i = [v_{i,1}, v_{i,2}, \dots, v_{i,n}]$  is called the velocity for particle  $i$ , which represents the distance to be traveled by this particle from its current position;  $X_i = [x_{i,1}, x_{i,2}, \dots, x_{i,n}]$  represents the position of particle  $i$ ;  $P_i$  represents the best previous position of particle  $i$  (i.e. local-best position or its experience);  $P_g$  represents the best position among all particles in the population  $X = [X_1, X_2, \dots, X_n]$  (i.e. global-best position);  $\text{Rand}()$  and  $\text{rand}()$  are two independent and uniformly distributed random variables with range  $[0, 1]$ ;  $c_1$  and  $c_2$  are positive constant parameters called acceleration coefficients which control the maximum step size;  $w$  is called the inertia weight that controls the impact of previous velocity of particle on its current one. The inertia weighting function in (3) is usually evaluated utilizing the following equation:

$$(4) w = w_{\max} - (w_{\max} - w_{\min}) \times \text{iter} / \text{iter}_{\max}$$

where  $w_{\max}$  and  $w_{\min}$  are maximum and minimum values of  $w$ ,  $\text{iter}_{\max}$  is the maximum number of iterations and  $\text{iter}$  is the current iteration number.

### Proposed CPSO method

PSO has gained much attention and widespread applications in different fields. However, the performance of the simple PSO greatly depends on its parameters, and it often suffers the problem of being trapped in local optima and hence premature convergence. To enrich the searching behavior and to avoid being trapped into local optimum, chaotic dynamics is incorporated into the PSO. In this study, the well-known logistic equation [7], which exhibits the sensitive dependence on initial conditions, is employed for constructing hybrid PSO. The Logistic equation which used in this paper is described as:

$$(5) \beta_{k+1} = \mu \times \beta_k \times (1 - \beta_k) \quad k = 1, 2, \dots \quad \beta_0 \in (0, 1)$$

where  $\mu$  is the control parameter with a real value between 0 to 4. Although the (5) is deterministic, it exhibits chaotic dynamics when  $\mu = 4$  and  $\beta_0 \notin \{0, 0.25, 0.5, 0.75, 1\}$ . That is, it exhibits the sensitive dependence on initial conditions, which is the basic characteristic of chaos. A minute difference in the initial value of the chaotic variable would result in a considerable difference in its long time behavior. The track of chaotic variable can travel ergodically over the whole search space. In general, the above chaotic variable has special characters, i.e. ergodicity, pseudo-randomness and irregularity. To improve the performance of PSO, this paper introduces a new velocity update equation by applying chaotic sequence for weight parameter,  $w$  in (2). The new weight parameter is defined by multiplying (4) and (5) in order to improve the global searching capability as follows:

$$(6) w_{\text{new}} = w \times \beta$$

Observe that the proposed new weight decreases and oscillates simultaneously for total iteration, whereas the conventional weight decreases monotonously from  $w_{\max}$  to  $w_{\min}$ . As a result, the updated velocity formula will be assigned according to the following equation:

$$(7) V_i[t+1] = w_{\text{new}} V_i[t] + c_1 \text{rand}(\cdot)(P_i - X_i) + c_2 \text{Rand}(\cdot)(P_g - X_i)$$

### Adaptation of CPSO for Coordinated Design

To utilize the developed optimization technique in coordinated tuning of parameters of PSS and SVC to control damping in the power system, the system elements such as generators, excitation system, PSS and SVC must be modeled. It also requires a suitable objective function to obtain satisfactory results.

### Power system model

To demonstrate the application and robustness of CPSO for the damping control design, a four-machine, two-area study system shown in Fig. 1, is simulated. In this system, there are two generation areas and two loads interconnected by transmission lines. Each area has two generators. All the generators are equipped with identical speed governors and turbines, which include exciters, AVR, and PSSs and one SVC is installed at the bus 101. The generators and their controls are assumed to be identical. The system is quite heavily stressed, and it has 400 MW flowing on the tie-lines from area 1 to area 2. The simple model shows the fundamental electromechanical oscillations that are inherent in interconnected power systems. There are three different electro-mechanical modes of oscillation, which includes two local modes of oscillation corresponding to each area, and one inter-area mode. To analyse the LFO in the system, the following cases representing various operating conditions are studied:

Case 1: Base case (all lines in service).

Case 2: Loss of a line between bus 3 and bus 101.

Case 3: Loss of a line between bus 13 and bus 101.

Case 4: Loss of either of these lines.

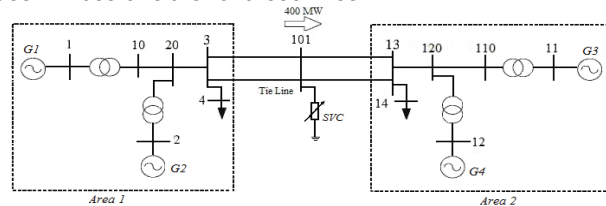


Fig. 1. Multi-machine power system with the SVC

### Power System Stabilizer

The IEEE type-ST1 excitation system is shown in Fig. 2 and can be described as:

$$(8) \rho E_{fd} = (K_A (V_{ref} - v + u_{PSS}) - E_{fd}) / T_A$$

where  $K_A$  and  $T_A$  are the gain and time constant of the excitation system, respectively;  $V_{ref}$  is the reference voltage.

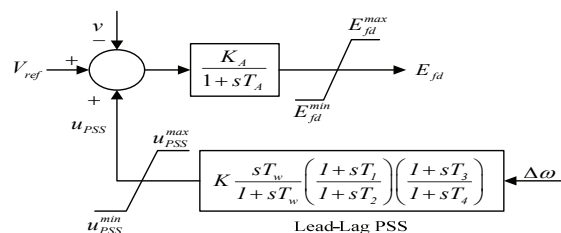


Fig. 2. IEEE Type-ST1 excitation system with PSS

As shown in Fig. 2, a conventional lead-lag PSS is installed in the feedback loop to generate a stabilizing signal  $u_{PSS}$ . The basic function of a PSS is to extend stability limits by modulating generator excitation to provide damping to the oscillations between synchronous machines. Analytically, PSS may be regarded as a transfer function consisting of a PSS gain, wash-out and lead-lag. The lead-lag aims to provide appropriate phase lead to compensate the phase lag between excitation and the generator electrical torque.

### SVC-based stabilizer

In case if PSS cannot provide sufficient damping for inter-area oscillations, FACTS damping controllers are alternative effective solutions. Furthermore, with the deregulation of electricity market, increasing transfer capacities by installing FACTS devices becomes imperative. As, the SVC is the most common FACTS device, the primary application of the SVC is to maintain the busbar voltage at a predefined value. However, there has been a growing trend in using SVCs to aid system stability. The SVC equipped with a voltage regulator may provide synchronizing torque but negligible damping torque. The damping effect of an SVC has the following features [8]: SVC becomes more effective for controlling power swings at higher levels of power transfer; the effectiveness of SVC for power swing damping is dependent on SVC location; it might interact with other SVC and PSS, making other originally stable modes to become unstable. The structure of the SVC based damping controller is shown in Fig. 3. This controller may be considered as a lead-lag compensator. It comprises gain block, signal-washout block and two stages of lead-lag compensator. The parameters of the damping controllers for the purpose of simultaneous coordinated design are obtained using the CPSO algorithm. The susceptance of the SVC,  $B$ , can be expressed as:

$$(9) \quad \rho B = \left( K_s (B_{ref} - u_{SVC}) - B \right) / T_s$$

where  $B_{ref}$  is the reference susceptance of SVC;  $K_s$  and  $T_s$  are the gain and time constant of the SVC. As shown in Fig. 3, a conventional lead-lag controller is installed in the feedback loop to generate the SVC stabilizing signal  $u_{SVC}$ .

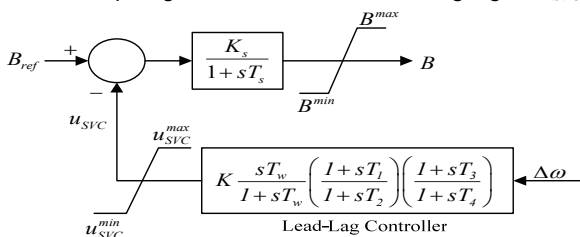


Fig.3. SVC with lead-lag controller

### Linearized model

In this study, each generator is modeled as a two-axis model, which is a six-order model. The dynamical behavior of a power system can be described by a set of differential and algebraic equation. For all operating conditions, the power system can be modeled by a set of nonlinear differential equations as:

$$(10) \quad \dot{x} = f(x, u)$$

where  $x = [\Delta\omega, \delta, \varphi_{fd}, \varphi_{1d}, \varphi_{1q}, \varphi_{fd}, \varphi_{2q}]$  is a vector of the state variables and  $\Delta\omega$  and  $\delta$  are the speed deviation and rotor angle, respectively, and  $\varphi_{fd}, \varphi_{1d}, \varphi_{1q}, \varphi_{fd}$  and  $\varphi_{2q}$  are the contribution to the rotor flux linkage as a result of field winding, one d-axis and two q-axis amortisseur circuits, respectively.  $u = [u_{PSS}, \Delta\beta]$  is the vector of the damping controller outputs signals. In the design of electromechanical mode damping controllers, the linearized incremental model around a nominal operating point is usually employed. Therefore, the system in (10) is linearized around an equilibrium operating point of the power system. Equation (11) describes the linear model of the power system:

$$(11) \quad \begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx + Du \end{aligned}$$

In the frequency domain, the transfer function associated with (11) is given:

$$(12) \quad p(s) = C(sI - A)^{-1} B + D$$

The poles of  $P(s)$  correspond to eigenvalues of matrix  $A$  and only if the system described by (11) is controllable and observable. The controllers are a lead-lag type and can be described as the diagonal matrix  $K(s)$ :

$$(13) \quad u(s) = K(s)e(s)$$

Let  $\lambda_i = \sigma_i \pm j\omega_i$  be the  $i$ th eigenvalue of the closed loop system in Fig. 4. The stability of the linear system is guaranteed if all eigenvalues have negative real parts. The eigenvalues can be real or complex. The imaginary part of the complex eigenvalue ( $\omega$ ) is the radian frequency of the oscillations, and the real part ( $\sigma$ ) is the decrement rate. Then, the damping coefficient ( $\zeta_i$ ) of the  $i$ th eigenvalue is defined as: (14)  $\zeta_i = -\sigma_i / \sqrt{\sigma_i^2 + \omega_i^2}$

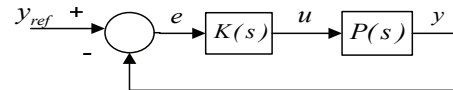


Fig.4. Closed-loop setup

### Objective function

In the proposed method, one must tune the PSS and SVC controller parameters optimally to improve overall system dynamic stability in a robust way under different operating conditions and disturbances. To acquire an optimal combination, this paper employs CPSO to improve optimization synthesis and find the global optimum value of fitness function. For this optimization problem, an eigenvalue based multi objective function reflecting the combination of damping factor and damping ratio is considered as follows [9]:

$$(15) \quad J = \sum_{\sigma_{ij} \geq \sigma_0} (\sigma_0 - \sigma_{ij})^2 + \alpha \sum_{\zeta_{ij} \geq \zeta_0} (\zeta_0 - \zeta_{ij})^2$$

$$(16) \quad F = \sum_{j=1}^{NP} J_j$$

where  $j=1,2,3,\dots, NP$  is the index of system operating conditions considered in this design process,  $i=1,2,\dots, N$ , is the index of eigenvalues in the system,  $\sigma_{ij}$  and  $\zeta_{ij}$  are the damping factor and the damping ratio of the  $i$ th eigenvalue of the  $j$ th operating condition. The value of  $\alpha$ , which is a weight for combining both damping factors and damping ratios, is chosen at 10.  $NP$  is the total number of operating points for which the optimization is carried out. Finally,  $\sigma_0 = -1.5$  and  $\zeta_0 = 0.3$  are the constant value of the expected damping factor and damping ratio, respectively. The design problem can be formulated as the following constrained optimization problem, where the constraints are the PSS and SVC parameters bounds:

$$(17) \quad \begin{aligned} & \text{minimize } F \\ & \text{subject to } K^{min} \leq K \leq K^{max} \\ & T_1^{min} \leq T_1 \leq T_1^{max} \\ & T_2^{min} \leq T_2 \leq T_2^{max} \\ & T_3^{min} \leq T_3 \leq T_3^{max} \\ & T_4^{min} \leq T_4 \leq T_4^{max} \end{aligned}$$

The ranges of the optimized parameters are [0.01, 100] for  $K$ , and [0.01, 1] for  $T_1-T_4$ . The proposed approach employs CPSO to solve this optimization problem and search for the optimal set of PSSs and SVC parameters. Since there are four PSSs and one SVC, twenty five parameters need be optimized. The flowchart of the optimization based coordinated designing is depicted in Fig. 5.

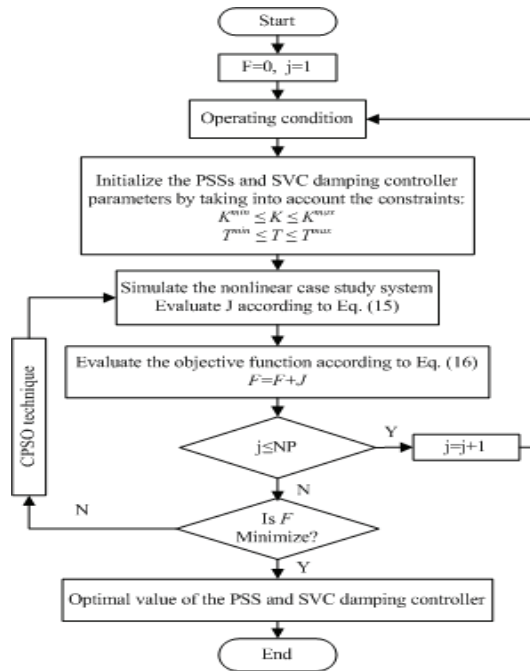


Fig.5. Flowchart of optimization based coordinated designing

### Simulation Results

The proposed controller must be able to work well under all operating conditions, with the improvement for the damping of the critical modes. To acquire an optimal combination, this paper employs the CPSO algorithm to improve the optimization synthesis and find the global optimum value. The optimization procedure following the methods described above was carried out by a specially prepared computer program coded in MATLAB. All the programs were executed on a 2.10 GHz Pentium IV processor with 2GB of RAM. In order to acquire better performance, swarm size,  $iter_{max}$ ,  $c_1$ ,  $c_2$ ,  $w_{min}$ ,  $w_{max}$ ,  $\mu$  and  $f_0$  are chosen as 20, 100, 2, 1, 0.45, 0.95, 4 and 0.54, respectively. It should be noted that the CPSO algorithm is run several times and then optimal set of coordinated controller parameters is selected. To investigate the capability of PSS and SVC controller when applied individually and also through coordinated application, both are designed independently first and then in a coordinated manner. The final values of the optimized parameters for the proposed controllers are given in Table 1.

Table 1. The optimal parameter settings of the proposed controllers

		PSS1	PSS2	PSS3	PSS4	SVC
Uncoordinated design	K	18.61	57.229	13.65	17.37	60.144
	T <sub>1</sub>	0.049	0.05	0.08	0.05	0.152
	T <sub>2</sub>	0.015	0.01	0.015	0.015	0.300
	T <sub>3</sub>	0.08	0.079	0.799	0.08	0.01
	T <sub>4</sub>	0.01	0.015	0.01	0.015	0.310
Coordinated design	K	26.29	65.403	31.32	30.10	136.9
	T <sub>1</sub>	0.011	0.0944	0.042	0.061	0.657
	T <sub>2</sub>	0.01	0.015	0.014	0.01	0.250
	T <sub>3</sub>	0.010	0.1144	0.056	0.150	0.401
	T <sub>4</sub>	0.015	0.01	0.150	0.013	0.300

### Eigenvalue analysis

The principal eigenvalues and the damping ratios obtained for all operating conditions without and with the proposed controllers are given in Table 2. For the system without controller, it can be observed that some of the modes are weakly damped and for some operating conditions the system is unstable. It is clear that the system stability is greatly enhanced with the proposed stabilizers. It

can also be seen that the coordinated design outperforms the individual design at all points considered in the sense that the damping ratios of the electromechanical modes at all points are greatly improved. The results from coordinated design approach show that the minimum damping ratio and the maximum damping factor under all cases are better than the results obtained by the PSS and SVC damping controller individual design. It shows that the use of chaotic sequence in PSO is an effective approach to enhance the global searching capability and improve the performance stability. After the optimized coordinated tuning of PSS/SVC controllers, all the electro-mechanical modes are well damped and the detrimental effects due to PSS/ SVC interactions are suppressed. Movements of the electro-mechanical modes in the whole tuning progress are depicted in Fig. 6.

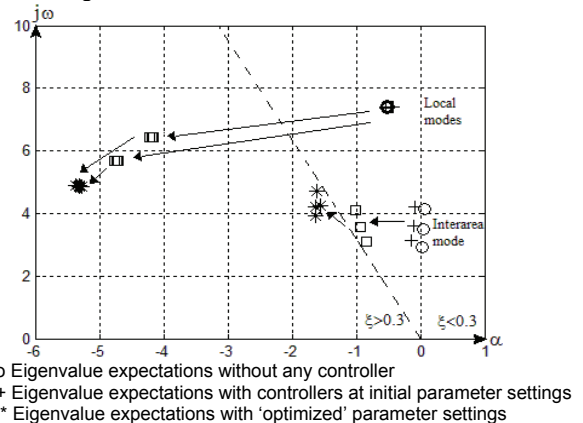


Fig.6. Movements of electro-mechanical modes

### Nonlinear time-domain simulation

The effectiveness and robustness of the performance of the proposed controller under transient conditions is verified by applying a three-phase fault of 200-ms duration at the middle of one of the transmission lines between bus-3 and bus-101. To evaluate the performance of the proposed simultaneous design approach the response with the proposed controllers are compared with the response of the PSS and SVC damping controller individual design. The speed deviations of generator G<sub>1</sub> for all cases are shown in Figs. 7-10, respectively. These time domain simulations are also in well agreement with the results of eigenvalue analysis. It is clear from these figures that, the simultaneous design of the PSS and SVC damping controller by the proposed approach significantly improves the stability performance of the example power system and low frequency oscillations are well damped out. The eigenvalue analysis and non-linear simulation results show the effectiveness and robustness of the proposed controllers to enhance the system stability.

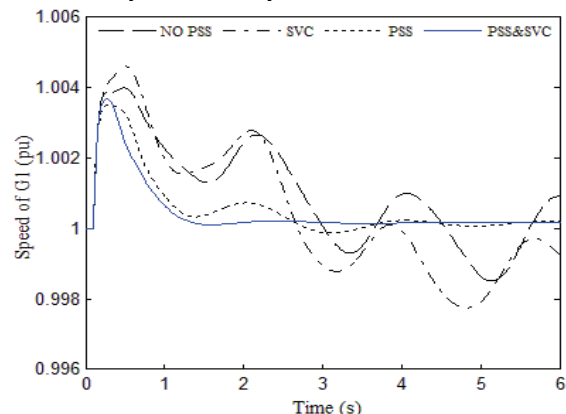


Fig.7. Speed response of G<sub>1</sub> for case1

Table 2. Eigenvalues and damping ratios without and with controller for four cases

	Case 1	Case 2	Case 3	Case 4
No control	0.04438±4.0309i, -0.011 -0.55258±7.302i, 0.0755 -0.55317±7.383i, 0.0747	-0.0231±3.2970i, -0.070 -0.5477±7.2853i, 0.0750 -0.5643±7.3284i, 0.0768	0.0413±3.3227i, -0.0124 -0.572±7.2695i, 0.0784 -0.5412±7.3456i, 0.0735	0.00140±2.5144i, -0.0005 -0.5784±7.2473i, 0.0796 -0.5355±7.2801i, 0.0734
PSS only	-0.9990±4.1114i, 0.2392 -4.7580±5.6849i, 0.6418 -4.2838±6.4564i, 0.5529	-0.9080±3.5542i, 0.2475 -4.7189±5.6972i, 0.6379 -4.2414±6.4584i, 0.5489	-0.9086±3.5554i, 0.2476 -4.7189±5.6970i, 0.6379 -4.2415±6.4585i, 0.5489	-0.8243±3.0854i, 0.2581 -4.6959±5.7069i, 0.6354 -4.2150±6.4592i, 0.5465
SVC only	-0.1022±4.221i, 0.0242 -0.5309±7.392i, 0.0716 -0.4480±7.408i, 0.0604	-0.1241±3.6370i, 0.0341 -0.5356±7.3694i, 0.0725 -0.4260±7.4078i, 0.0574	-0.1238±3.6380i, 0.0340 -0.5356±7.3694i, 0.0725 -0.4263±7.4077i, 0.0575	-0.1429±3.1646i, 0.0451 -0.5356±7.3569i, 0.0726 -0.4071±7.4091i, 0.0549
Coordinated design	-1.6200±4.7161i, 0.3247 -5.3180±4.8677i, 0.7376 -5.3768±4.8939i, 0.7395	-1.6352±4.2179i, 0.3615 -5.2843±4.8641i, 0.7358 -5.3511±4.8994i, 0.7376	-1.5544±4.2311i, 0.3448 -5.2951±4.8897i, 0.7347 -5.3380±4.8655i, 0.7391	-1.6262±3.9128i, 0.3838 -5.2782±4.8651i, 0.7353 -5.3023±4.8952i, 0.7348

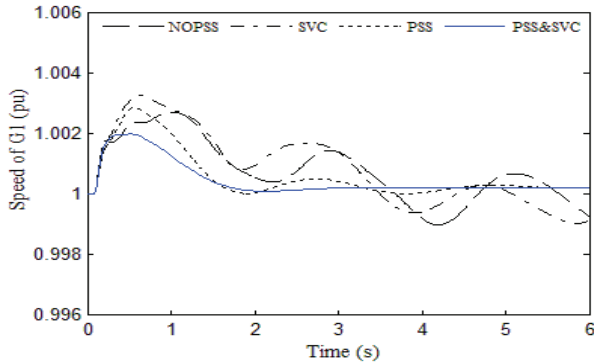


Fig.8. Speed response of  $G_1$  for case2

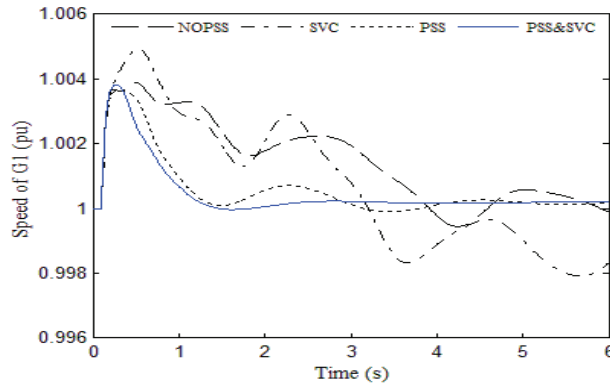


Fig.9. Speed response of  $G_1$  for case3

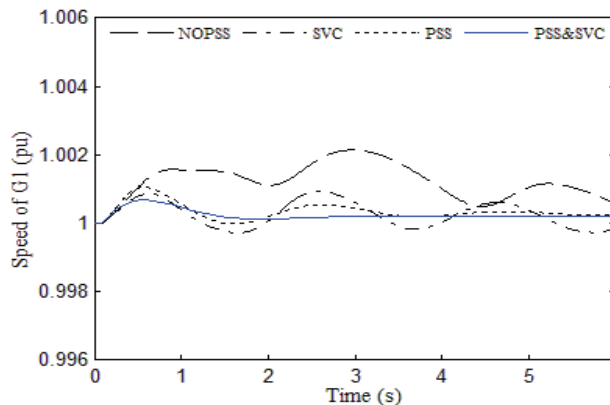


Fig.10. Speed response of  $G_1$  for case4

### Conclusion

This paper presents a chaotic particle swarm optimization for the simultaneous coordinated tuning of the SVC damping controller and PSS in power system. It is done by introducing chaotic into the PSO to improve the global searching capability and escape the premature convergence to local minima. The problem of selecting the PSS and damping controller parameters in order to enhance the damping of the power oscillations for a set of operating conditions is posed to an optimization problem.

For the proposed stabilizer design problem, a multi-objective function where the objective is the aggregation of the two objectives on the damping ratio and damping factor to increase the system damping was developed. Then, the CPSO algorithm has been successfully applied to find the optimal solution of the design problem. The effectiveness of the proposed controller has been tested on a four-machine power system through the simulation studies under different operating conditions. The eigenvalue analysis and nonlinear time-domain simulation results show the effectiveness of the proposed controllers and their ability to provide good damping of low frequency oscillations.

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