Damping Improvement of Multiple Damping Controllers by Using Optimal Coordinated Design Based on PSS and FACTS-POD in a Multi-Machine Power System

Ali Nasser Hussain   Ayad Fadhil Mijbas
Electrical Techniques Dept. /Technical Institute-Suwaira/Middle Technical University
alinasser 1974@yahoo.com

Abstract

The aim of this study is to present a comprehensive comparison and assessment of the damping function improvement of power system oscillation for the multiple damping controllers using the simultaneously coordinated design based on Power System Stabilizer (PSS) and Flexible AC Transmission System (FACTS) devices. FACTS devices can help in the enhancing the stability of the power system by adding supplementary damping controller to the control channel of the FACTS input to implement the task of Power Oscillation Damping (FACT− POD) controller. Simultaneous coordination can be performed in different ways. First, the dual coordinated designs between PSS and FACTS− POD controller or between different FACTS− POD controllers are arranged in a multiple FACTS devices without PSS. Second, the simultaneous coordination has been extended to triple coordinated design among PSS and different FACTS− POD controllers. The parameters of the damping controllers have been tuned in the individual controllers and coordinated designs by using a Chaotic Particle Swarm Optimization (CPSO) algorithm that optimized the given eigenvalue-based objective function. The simulation results for a multi-machine power system show that the dual coordinated design provide satisfactory damping performance over the individual control responses. Furthermore, the triple coordinated design has been shown to be more effective in damping oscillations than the dual damping controllers.

Key word: Damping Improvement, Damping controllers, power system

الملخص

الهدف من هذه الدراسة هو لتقديم مقارنة شاملة وتقييم لتحسين وظيفة التخميد لذبذبات نظام القدرة لمسيطرات إخماد متعددة باستخدام تصميم منسقة متزامنة استنادا على مثبت نظام القدرة (PSS) واجهزة الأنظمة المرنة لنقل التيار المتردد (FACTS). أجهزة FACTS يمكن أن تساعد في تحسين استقرار نظام القدرة بواسطة إضافة مسيطر أخماد تكميلي الى مدخل قناة السيطرة لأجهزة FACTS لتنفيذ مهمة مسيطر اخماد ذبذبات القدرة (POD− FACT). التنسيق المتزامن يمكن تشكيلة بطرق مختلفة. أولاً، تصاميم التنسيق الثنائية بين PSS و المسيطرات POD− FACTS أو بين مسيطرات مختلفة من POD− FACTS تكون مرتبة في أجهزة FACTS متعددة بدون PSS. ثانيا، التنسيق المتزامن قد وسع الى تصميم التنسيق الثلاثي بين PSS و مسيطرات POD− FACTS مختلفة. قيم مكونات مسيطرات الاخماد قد تم ضبطها في المسيطرات الفردية والتصاميم المنسقة باستخدام خوارزمية أمثلية سرب الجسيمات الفوضوية (CPSO) التي أمثلت القيم الذتية استنادا الى دالة هدف معينة. اظهرت نتائج المحاكاة لنظام قدرة متعدد المكائن ان تصاميم التنسيق الثنائية تقدم أداء تخميد مرضية أكثر من استجابات السيطرة الفردية. وعلاوة على ذلك، أظهر تصميم المنسقة الثلاثية أكثر فعالية في تخميد الذبذبات من مسيطرات التخميد المزدوجة.

الكلمات المفتاحية: التخميد التحسين، التخميد التحكم ، نظام الطاقة

1. Introduction

Low Frequency Oscillations (LFO) in a power system limits the ability of power transmission and sometimes these oscillations may sustain and grow in magnitude to cause the system separation and loss power supply to custom loads if no adequate damping of the system is available (Kundur, 1994; Yu, 1983).

The installation of a Power System Stabilizer (PSS) appears as a simple and inexpensive technique for many years to produce an amount of damping torque, which has increased the stability of the power system. However, their performance deteriorated when the system parameters and operating conditions varied widely (Abdel-Magid & Abido, 2004).

Flexible AC Transmission Systems (FACTS) devices have been an effective technology that meets these requirements. It expressively alters the way transmission systems are developed and controlled along with the enhancements in asset utilization, system flexibility, and system stability (Sadiković,2006). Thyristor Controlled Series Compensator (TCSC) is one of the important members of the FACTS devices that is increasingly applied to the utilities in modern power systems with long transmission lines. It has many advantages in the operation and control of power systems such as scheduling power flow, providing voltage support, decreasing net loss, limiting short circuit current, damping the low frequency oscillation and improving transient stability (Panda & Padhy, 2007). The Static VAR Compensator (SVC) is another type of FACTS devices connected in shunt with the transmission line. The basic function of it is to regulate the voltage at a specified bus through a suitable adjustment of the equivalent line reactance (Karpagam & Devaraj,2009). Beside these primary functions, it can also provide appropriate damping effect to the tie interconnected modern power systems oscillation through its supplementary controller. To improve the damping function of the general power system performance, possible interactions among multiple damping stabilizers are considered but the uncoordinated design of these controllers may cause destabilizing interaction on the damping of system oscillations. Therefore, the simultaneously coordinated design of multiple damping stabilizers is a necessity to gain the benefits of multiple stabilizers, which will enhance the system stability and prevent the drawbacks accompanied with their operation (Lu *et. al*., 2013). One approach for achieving the required performance is to make the coordinated design of the controller as a constrained optimization problem. Hence, the use of optimization techniques must be efficient and quick, and it must ensure the security of dynamic system in case of critical events. Many artificial intelligence techniques have been used to provide the desired coordinated design and robustness of multiple damping controllers, including the application of artificial neural networks (Farahani,2013), genetic algorithms (Abdel-Magid & Abido, 2004), fuzzy logic control (Mukherjee & Ghoshal,2007). Recently, the particle swarm optimization (PSO) technique has appeared as a useful tool for engineering global optimization to solve the coordinated design problem of multiple power system stabilizers (Hemmati *et. al*., 2011; Shayeghi *et. al*., 2010).

However, when the system parameters to be optimized are large and highly correlated, the efficiency of these intelligence techniques is degraded to get the global optimum solution and the search process takes a lot of time as well (Ghoshal *et. al*., 2010).

In this research, we present the results of our comprehensive comparison and assessment of the damping function of multiple damping controllers using different coordinated designs in order to identify the design that provided the most effective damping performance. The three alternative designs we evaluated are listed below:

1. Individual controllers: PSS, TCSC− POD and SVC− POD.
2. Dual-coordinated design between PSS and any one of FACTS− POD controller (PSS & TCSC− POD), (PSS & SVC− POD) or between FACTS− POD controllers themselves without PSS: (TCSC− POD & SVC− POD).
3. Triple-coordinated design among PSS and two FACTS− POD controllers: (PSS & TCSC− POD & SVC− POD).

The enhanced technique of chaotic particle swarm optimization (CPSO) is proposed by combining the PSO algorithm and chaotic sequence techniques. The parameters of the PSS and FACTS damping controllers in both schemes, the individual and the coordinated design, are tuned using CPSO technique based on eigenvalue objective function, which is formulated by maximizing the minimum damping ratio of all complex eigenvalues and to add the robustness. Then, the effectiveness of the optimized control schemes, individual and the simultaneous coordinated designs have been verified through the time domain simulations under severe disturbances. The simulation results show that the dual coordinated design of the multiple damping controllers has high ability in damping oscillations compared to the individual damping controllers. Furthermore, the-triple coordinated design demonstrates the superiority over the dual coordinated design for enhancing greatly the stability of the power system.

2. Power system Model

For stability valuation, suitable and sufficient mathematical models are required to represent the power system. These models must be computationally accurate, efficient and be able to describe the main dynamic characteristics of the power system.

2.1. Nonlinear Model of Multi-machine Power system

The power system can be described by a set of nonlinear differential equations. Model of third order for *i*th machine is widely used to be suitably accurate to study the phenomenon of LFO and power system stability (Abido & Abdel-Magid, 2002).

$$s\delta_i = \omega_b(\omega_i - 1) \tag{1}$$

$$s\omega_i = \left[P_{m_i} - P_{e_i} - D_i(\omega_i - 1)\right] / M_i \tag{2}$$

$$sE'_{qi} = \left[E_{fdi} - E'_{qi} - (x_{di} - x'_{di})i_{di}\right] / T'_{doi} \tag{3}$$

$$P_{ei} = E'_{qi} i_{qi} + (x_{qi} - x'_{di}) i_{di} i_{qi} \tag{4}$$

where s is the first derivative with respect to time, ω_b is the synchronous speed; δ and ω are the angle and speed of the generator rotor respectively; P_m and P_e are the mechanical input and electrical output power of the generator respectively; M and D are the machine inertia and damping coefficient respectively; E_{fd}, E_q and E'_q are field voltage, internal voltage and transient internal voltage of the generator respectively; T'_{do} is the open-circuit field time constant; i_d and i_q are stator currents in d - and q - axis circuits respectively; x_d and x_q are d - and q - axis synchronous reactances respectively; x'_d is the d -axis transient reactance.

Excitation system of the generator can be described by a st order model (IEEE type – ST1), as shown in Figure 1 (Yu,1983).

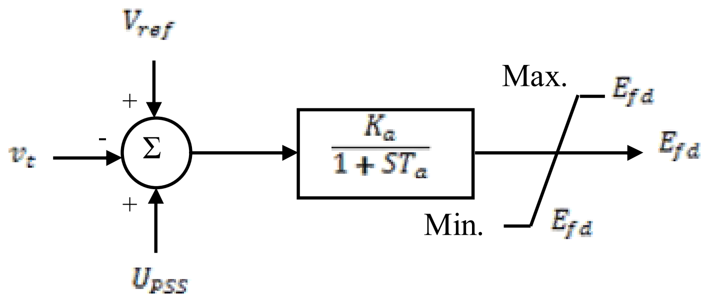


Figure 1: Block diagram of excitation system.

$$sE_{fdi} = {[K_{ai}(V_{refi} - v_{ti} + U_{PSSi}) - E_{fdi}]}/{T_{ai}}$$
(5)
$$v_{ti} = \left(v_{td}^2 + v_{tq}^2\right)^{1/2}$$
(6)
$$v_{td} = x_q i_q \,, \; v_{tq} = E_q' - x_d' i_d$$
(7)

Where v_t and V_{ref} are the terminal and reference voltages of generator respectively, K_a and T_a are the gain and time constant of excitation system respectively; v_{td} and v_{tq} are the terminal voltage in d - and q - axis respectively; U_{PSS} is the PSS output signal at the machine.

2.2. Multi-Machine Power System Equipped with FACTS Devices

The admittance matrix of multi-machine model power system is assumed to be constant. When the FACTS device is added to the power system, this assumption is no longer valid. The admittance matrix will be a function of the FACTS device control signal. We assume for n-machines power system a FACTS device will be installed at node K for SVC device and between nodes *R* and *K* for TCSC device. In order to obtain a systematic expression for $\mathbf{Y}_{ij}$ which includes the effect of the FACTS-damping controllers, the following procedure is carried out:

1. From the load-flow data, convert the loads as a constant admittance in the admittance matrix.
2. Form $Y_{\mathbf{aug}}$ by modifying the admittance matrix to include the transient reactance x_d' of the machines.
3. Reduce the $Y_{\mathbf{aug}}$ by deleting all buses except the internal generator and FACTS device nodes to form Y_{FACTS}.

   If n is the number of machines, the Y_{FACTS} matrix size will be:
   - $(n+1)\times(n+1)$ in case of SVC is installed; and
   - $(n+2)\times(n+2)$ in case of TCSC is installed.
4. Y_{RR} sub matrix shown below contains nodes associated with FACTS-damping controller.

$$Y_{FACTS} = \begin{bmatrix} Y_{NN} & Y_{NR} \\ Y_{RN} & Y_{RR} \end{bmatrix}$$
(8)

- For SVC-damping controller Y_{RR} is $[1\times 1]$ matrix and the output signal B_{SVC} is modeled as:
  $Y_{RR} = y_{kk} - jB_{SVC}$, where y_{kk} is the self-admittance at node K.
- For TCSC-damping controller Y_{RR} is $[2\times 2]$ matrix and the output signal X_{TCSC} is modeled as:

$$Y_{FACTS} = \begin{bmatrix} y_{kk} + \dfrac{jx_{TCSC}}{ZKR(ZKR - jx_{TCSC})} & y_{kk} + \dfrac{jx_{TCSC}}{ZKR(ZKR - jx_{TCSC})} \\ y_{Rk} + \dfrac{jx_{TCSC}}{ZKR(ZKR - jx_{TCSC})} & y_{RR} + \dfrac{jx_{TCSC}}{ZKR(ZKR - jx_{TCSC})} \end{bmatrix} \qquad (9)$$

5. Y_{FACTS} is further reduced to

$$Y = Y_{NN} - Y_{NR}{Y_{RR}}^{-1}Y_{RN} \qquad (10)$$

2.3. Linearized Model of Power System Equipped with SVC and TCSC Devices

The equations describing the generators can be written as

$$sX = f(X, U) \tag{11}$$

where $X = [\delta \quad \omega \quad E_q' \quad E_{fd}\ ]^{\mathrm{T}}$, U is the output signal of the supplementary damping controller $(PSS, FACTS-POD)$. Therefore, the state equation of a power system with n generators and m damping controllers can be written as:

$$s\Delta X = A\Delta X + B\Delta U \tag{12}$$

where A is the system state matrix and equals $\left[A = \partial f/\partial X\right]^{4n\times 4}$ while B is the control matrix and equals $\left[B = \partial f/\partial U\right]^{4n\times m}$. Both matrices A and B are calculated at a specific operating point. ΔX is the state vector and equals $[\Delta X]^{4n\times 1}$ while ΔU is the input vector and equals $[\Delta U]^{m\times 1}$. Now, The linearized power system model for n generator is obtained by linearizing the nonlinear equations at nominal operating point taking into account the output control signal of FACTS− POD controller (ΔU_F), which can be ΔX_{TCSC}, ΔB_{SVC} or combinations of them. The following model is obtained:

$$s\Delta\delta_n = \omega_b \Delta\omega_n \tag{13}$$

$$s\Delta\omega_n = M_n^{-1}(-K_1\Delta\delta_n - D_n\Delta\omega_n - K_2\Delta E_{qn}' - K_p I_n \Delta U_{Fm}) \tag{14}$$

$$[K_3 + sT_{don}']\Delta E_{qn}' = [\Delta E_{fdn} - K_4\Delta\delta_n - K_q I_n \Delta U_{Fm}] \tag{15}$$

$$(1 + sT_{an})\Delta E_{fdn} = -K_{an}[K_5\Delta\delta_n + K_6\Delta E_{qn}' + \Delta U_{PSSm} + K_v I_n \Delta U_{Fm}] \tag{16}$$

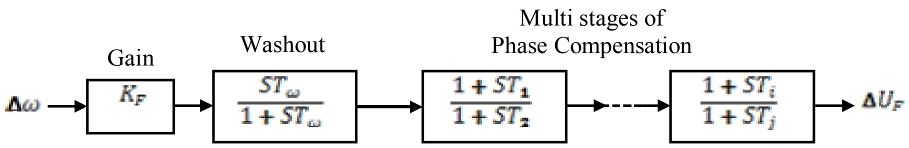
where the linearization constants $K_1 - K_6$, K_p, K_q, K_v are functions of the system parameters and the initial operating conditions.

3. Intelligent Supplementary Damping Controllers

In order to overcome the problem of low frequency oscillation, a supplementary damping control action is inserted to the excitation unit of the generator in the form of PSS or FACTS device as POD controller. In this study, we have proposed a supplementary damping controller (lead− lag type) as a part of the main control channel of the FACTS devices to implement the task of power oscillation damping controller. The main control action of the FACTS device channel can be modulated in order to generate the suitable damping torque.

3.1. Structure of the FACTS− Power Oscillation Damping Controller

The FACTS− POD controller has a structure similar to that of the PSS. Figure 2 illustrates a block diagram of a FACTS− POD controller. This controller comprises three main blocks, namely, the gain block, the washout filter block and one or multi stages (lead-lag) phase compensator blocks. It provides an appropriate damping electrical torque signal in phase with the speed deviation in order to increase the damping performance of



power system oscillations. The main function of the washout filter block serves as a high-pass filter to remove the dc offset from the FACTS− POD output and to prevent steady− state errors in the generator terminal voltage. From this perspective, the washout time constant (T_ω) must have a value in the range of 1 to 20 seconds distinct to the eigenvalue modes of electromechanical oscillations (Kundur, 1994). In this study, the time constants of the FACTS− POD controller T_ω, T_2 and T_j have been the pre-specified values of 10s, 0.1s and 0.1s respectively while the other parameters such as K_F, T_1 and T_i need to be determined optimally. The generator speed deviation $\Delta\omega$ is applied to the FACTS− POD as an input signal and ΔU_F as the output damping control action.

Figure 2: The FACTS− POD controller.

3.2. Optimal Design of the Supplementary Damping Controllers PSS or FACTS QUOTE − − − lag) is represented mathematically by the following equation:

$$U(s) = G(s)Y(s) \tag{17}$$

where $G(s)$ is the transfer function of the supplementary damping controller, $Y(s)$ is the measurement signal and $U(s)$ is the output signal of the supplementary damping controller, which will provide additional damping by moving the electromechanical mode to the left hand side of the vertical line in the complex s− plane. Equation (17) can be expressed in state− space form as:

$$s\Delta X_C = A_C\Delta X_C + B_C\Delta U_C \tag{18}$$

where ΔX_C is the state vector of the supplementary damping controller. In the state− space representation, the general equation that is described the linearized model of the power system equipped with any type of FACTS devices, extracted around a certain operating point is expressed as follows:

$$s\Delta X = A\Delta X + B\Delta U \tag{19}$$

Now, by combining equation (18) with equation (19), we obtain a closed− loop system.

$$s\Delta X_{Cl} = A_{Cl}\Delta X_{Cl} \tag{20}$$

$$\Delta X_{Cl} = [\Delta X \quad \Delta X_C\ ]^T \tag{21}$$

$$\zeta_i = -[real(\lambda_i)/|\lambda_i|] \tag{22}$$

$$J = min(\zeta_i) \tag{23}$$

where A_{Cl}, ΔX_{Cl}, are the transition matrix and state vector of the closed loop system respectively, λ_i is the i− th eigenvalue mode of the closed loop transition matrix A_{Cl} and ζ_i is the damping coefficient of the i− th eigenvalue. It is clear that the objective function (J) will identify the minimum value of the damping coefficient among all system modes.

The optimization technique is applied to maximize the objective function J in order to achieve the appropriate damping for all modes including the eigenvalue of the electromechanical modes, by moving the dominant poles to the optimal location in the left complex s− plane, which enhances the system damping characteristics, and maximum J is searched for in the typical ranges of supplementary damping controller parameters.

$K_m^{Min} \leq K_m \leq K_m^{Max}$, $T_{mh}^{Min} \leq T_{mh} \leq T_{mh}^{Max}$

$m = \mathbf{PSS, FAC{\square}S - POD}$ and $h = 1, 3, 5, \dots i$

In the present study, the typical ranges of the optimized parameters are

$K_m = [0.01 - 100]$, $T_{mh} = [0.001 - 1]$ sec.

4. Optimization Process

The problem of the optimal tuning parameters for individual design or multiple damping controllers in the coordinating design, which would ensure a maximum damping performance of the power system at different loading conditions and disturbances, was solved via a PSO algorithm. The PSO is a member of large group of swarm intelligence techniques that emerged to be a promising tool for handling optimization problems. It is a population-based, stochastic-optimization technique that was inspired by the social behavior of flock school fish or swarms of birds (Kennedy & Eberhart, 1995).

4.1. Standard PSO Algorithm

In the PSO algorithm, each candidate solution to the optimization problem is represented randomly as a "particle" in the specified D-dimension space, and each group of particles comprises a "population". The location coordinates for each particle in a hyperspace is stored in a special memory called $(Pbest)$, which is associated to the fittest solution in ever experiences. In addition, the location coordinates related to the best value obtained so far among all the particles in the population is stored in a memory called $(Gbest)$. The $Pbest$ and $Gbest$ values are updated at every iteration of the PSO algorithm, and each particle changes its velocity toward them randomly. These concepts are expressed in the following formulas (Babaei & Hosseinnezhad, 2010):

$$v_i^{k+1} = wv_i^k + c_1r_1(Pbest_i - x_i^k) + c_2r_2(Gbest - x_i^k) \quad (24)$$

$$x_i^{k+1} = x_i^k + v_i^{k+1}, \mathrm{i} = 1,2,\dots,n \quad (25)$$

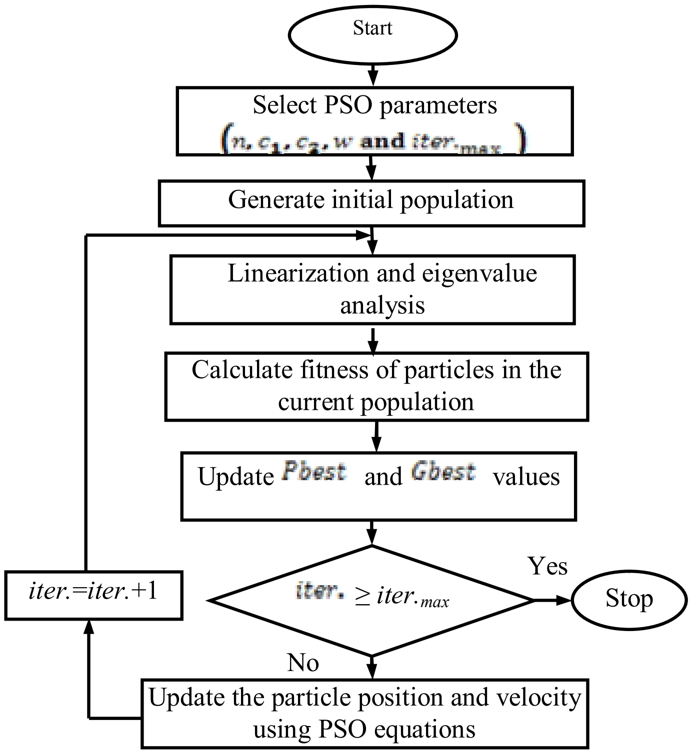


Figure 3: Flowchart of the PSO algorithm for the tuning parameters of an individual and multiple damping controllers.

Where v is the particle velocity, x is the particle position, k is the number of iterations, w is the inertia weight factor, c_1 and c_2 are the cognitive and asocial acceleration factors, respectively, n is the number of particles, and r_1 and r_2 are the uniformly-distributed random numbers in the range (0, 1). Figure 3 shows the flow chart of the PSO algorithm.

4.2. Chaotic Particle Swarm Optimization (CPSO)

Although the standard version of the PSO algorithm has attractive performance and many superior advantages, it is sometimes easy to be trapped into the local minima near optimal solutions especially when the optimization problem is relatively complex, and the convergence rate is decreased significantly in the final steps of searching. In order to enhance the quality of the PSO, the PSO algorithm and chaotic sequence techniques are blended to form a Chaotic Particle Swarm Optimization (CPSO). The chaos greatly helps the hybrid algorithm CPSO to escape from the local optima due to the special behavior and high ability. The logistic sequence equation adopted for constructing the hybrid CPSO algorithm is described as (Eslami *et. al.*, 2012):

$$\beta^{k+1} = \mu\beta^{k}(1-\beta^{k}), \qquad 0 \le \beta^{0} \le 1 \tag{26}$$

where μ is the control parameter with a real value between 0.0 to 4.0, K is the number of the iterations. The performance of the system represented by equation (26) is significantly related with the variation of the parameter μ. The value of β determines whether β stabilizes at a constant area, oscillates within restricted bounds, or behaves chaotically in an unpredictable form. Although the equation (26) is deterministic, it exhibits chaotic dynamics when $\mu = 4.0$ and $\beta^{0} \notin \{0, 0.25, 0.5, 0.75, 1\}$. It exhibits the sensitive dependence on initial conditions, which is the basic characteristic of chaos. The inertia weight factor in the standard formula (24) is evaluated by using the LDW equation (Shi & Eberhart, 1998):

$$W=W_{max}-[(W_{max}-W_{min})/K_{max}]K \tag{27}$$

where W_{max} and W_{min} are the maximum and minimum values of W, W_{max} is the maximum number of iterations and K is the current iteration number. The new inertia weight factor W_{new} is defined by multiplying the W in equation (27) and logistic sequence equation (26) as follows:

$$W_{new} = W \times \beta^{k+1} \tag{28}$$

To improve the performance of the standard PSO, this study introduces a new velocity update by incorporating a logistic sequence equation for inertia weight factor. Finally, by substituting equation (28) with equation (24), the following velocity updated equation for the proposed CPSO is obtained:

$$V_i^{k+1} = W_{new}V_i^{k} + c_1 r_1 (Pbest_i - X_i^{k}) + c_2 r_2 (Gbest - X_i^{k}) \tag{29}$$

We have observe the CPSO inertia weight decreases and oscillates simultaneously from $W_{\max}$ to $W_{\min}$, whereas the conventional weight decreases monotonously. The final choice of the control parameters CPSO algorithm that is considered the optimal choice in this study: n , $iter_{\max}$, c_1, c_2 , $W_{\min}$, $W_{\max}$, μ and β^0 are chosen as 30, 100, 2, 2, 0.4, 0.9, 4 and 0.3 respectively.

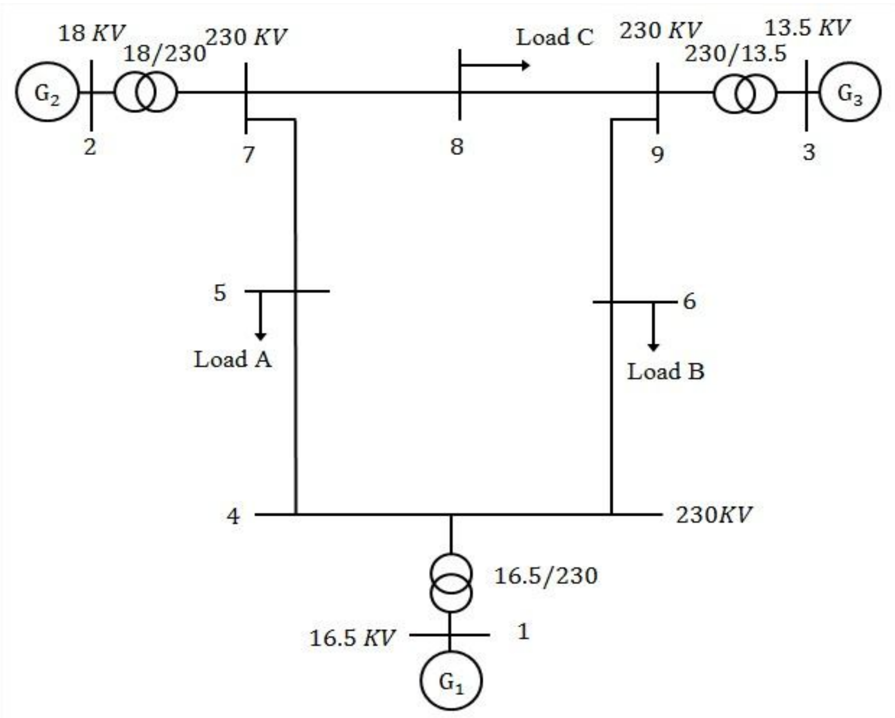


Figure 4: single-line diagram of the multi-machine power system.

5. Case Study

5.1. Test on the Three-Generator Power System

The example of single-line diagram for multi-machine power system is considered which consists of one area, three-generator and nine-bus system as shown in Figure 4. The data details of the power system are given in the Ref. (Anderson & Fouad, 2002). Two FACTS devices namely SVC and TCSC are modeled at same time in this power system.

5.2. Eigenvalues Analysis without any damping controller

The eigenvalues of the open loop system without any damping controller are computed by solving the system characteristic equation $|\lambda I - A| = 0$ for nominal operating condition using the MATLAB software, which are given in Table 1.

Table 1: Eigenvalues analysis of 3-generator power system.

Eigenvalues (λ)	**damping ratio** (ζ)
$\lambda_{1,2} = -1.4716 \pm 13.9300i$	0.1051
$\lambda_{3,4} = -0.3567 \pm 9.2370i$	0.0386
$\lambda_{5,6} = -9.8412 \pm 11.556i$	0.6483
$\lambda_{7,8} = -10.3110 \pm 6.8270i$	0.8338
$\lambda_{9,10} = -11.2750 \pm 3.1190i$	0.9638
$\lambda_{11,12,13,14} = -3.8355$, -2.2889 , -0.0901 , -2.0000	1.0000

The first and second bolded rows of this table represent the electromechanical modes (EM). It can be directly understood that the performance of this system is stable with high number of oscillations. It would take a long time to reach the steady state value due to the existence of two low damped modes $(\lambda_{1,2})$ and $(\lambda_{3,4})$. To improve the stability of the system and overcome the LFO problem, supplementary damping controller is required to link the generator excitation system in the form of PSS or FACTS device as damping controller. The participation factor technique is applied to identify the electromechanical modes and proper allocation of PSSs while modal analysis method is used to select locations of TCSC and SVC devices properly for a multi-machine power system in order to achieve maximum damping by integrating damping controller to their main control system (Kundur, 1994; Glover & Sarma, 2002). Therefore, PSS is installed at generator 2 and SVC device at (B− 5) bus. While the place of TCSC device is chosen to be between buses (B− 5 and B− 7).

6. Nonlinear Time− Domain Simulation and Comparison Results

In this section, we focused on damping of low frequency oscillations based on PSS and FACTS− POD controllers where applied independently and also through the simultaneous dual and triple-coordinated designs of the multiple damping controllers in a multi-machine power system. The parameters of the damping controller for individual and coordinated designs are optimized utilizing CPSO technique based on eigenvalue objective function. To assess the effectiveness and robustness of the proposed three control schemes, simulation study has been carried out by applying severe disturbance for a 6-cycle three-phase fault at time $(t = 0.5sec.)$ on bus B− 7 at the end of line 5− 7 is considered. The fault is cleared by permanent tripping of the faulted line.

Scheme 1: Figures 5− 7 show the speed deviation responses of the generators G1, G2 and G3 with the proposed individual controllers PSS, SVC− POD and TCSC− POD under above mentioned disturbance in a multi-machine power system. It can be seen that TCSC− POD controller and PSS are the most effective in damping the system oscillations. However, the system oscillations are poorly damped by applying SVC− POD controller.

Scheme 2: Figures 8− 10 show the speed deviation responses of the generators G1, G2 and G3 with the proposed dual-coordinated designs (PSS & TCSC− POD), (PSS & SVC− POD) and (TCSC− POD & SVC− POD) under above mentioned disturbance in a multi-machine power system. These figures should be compared with figures of their individual controllers. In general, the responses of the generators with dual-coordinated designs show improvement in the damping parameters overshoot and settling time compared to their individual controllers and the best one among the individual controllers TCSC− POD. In addition, the coordinated designs solved the problem of low damping when only the SVC− POD controller is considered. Finally, figure 8 shows the best responses for the generators in scheme 2 while using the coordinated design (PSS & TCSC− POD).

Scheme 3: Figure 11 shows the speed deviation responses of the generators G1, G2 and G3 with the proposed triple-coordinated design (PSS & TCSC− POD & SVC− POD) under above mentioned disturbance in a multi-machine power system. It can be seen from the result that the better dynamic response is obtained by triple-coordinated design, which is much faster and has less number of oscillations, settling time and overshoot than the individual controllers and dual-coordinated designs.

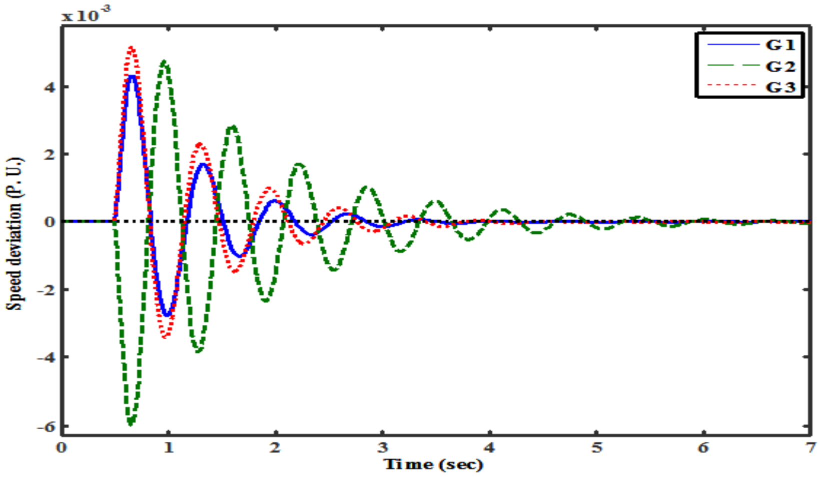


Figure 5: Speed deviation responses with individual damping controller P□S .

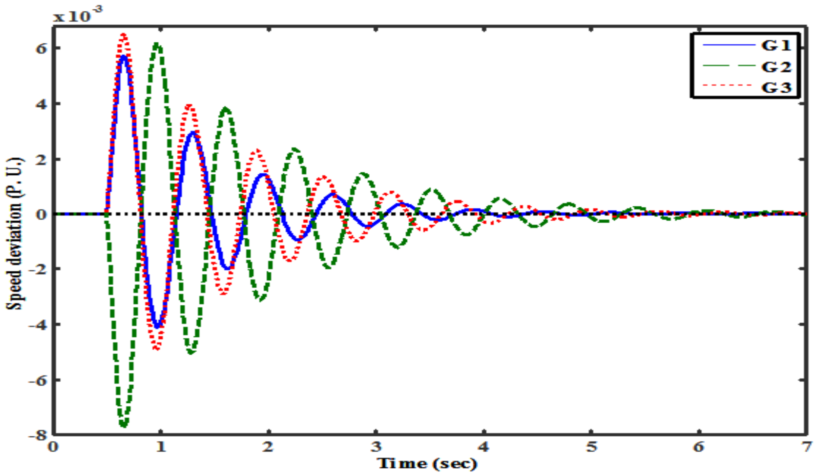


Figure 6: Speed deviation responses with individual damping controller SVC – □OD .

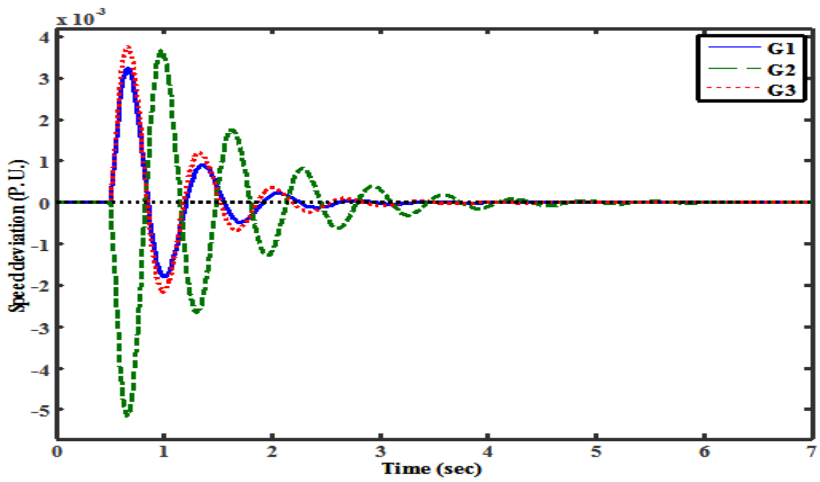


Figure 7: Speed deviation responses with individual damping controller TCSC – POD .

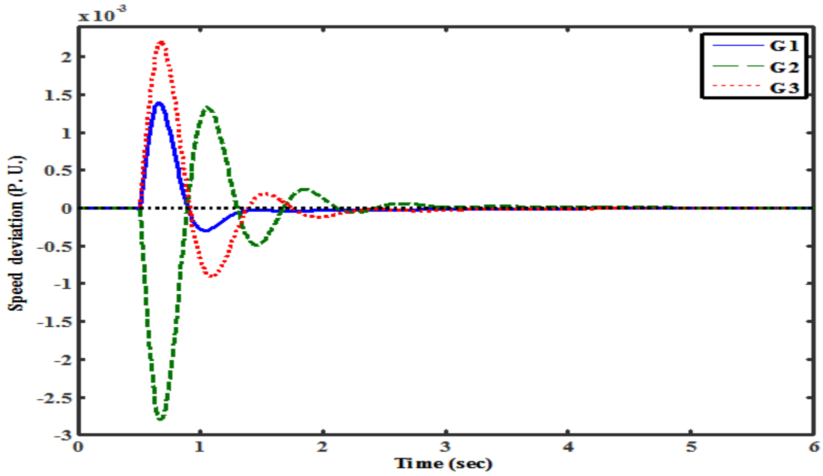


Figure 8: Speed deviation responses with dual coordinated design PSS & TCSC− POD.

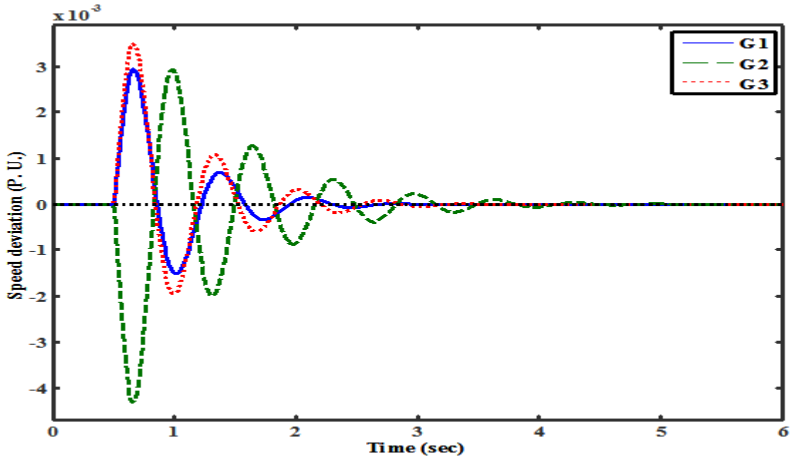


Figure 9: Speed deviation responses with dual coordinated design PSS & SVC− POD.

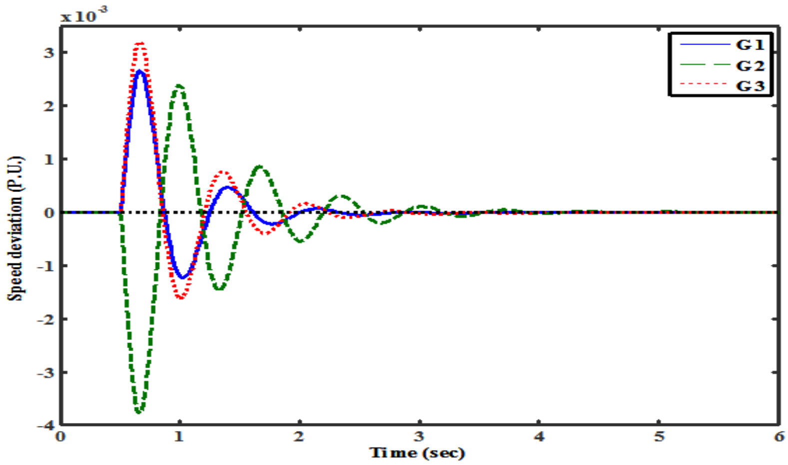


Figure 10: Speed deviation responses with dual coordinated design TCSC− POD & SVC− POD.

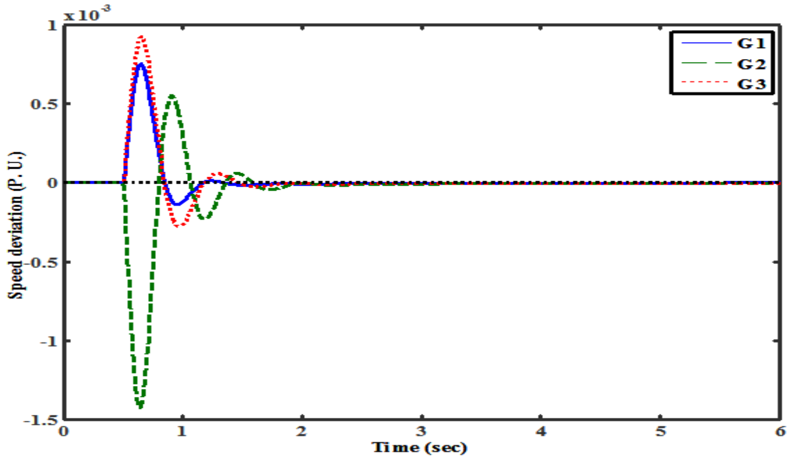


Figure 11: Speed deviation responses with triple coordinated design PSS & TCSC− POD & SVC− POD.

7. Conclusions

This paper is concerned with the damping of LFO and stability enhancement of the power system based on PSS and FACTS− POD controllers when applied independently and also through the simultaneous coordinated designs in a multi-machine power system. The simple PSO greatly depends on its parameters, and this made it difficult and unable to reach the accurate solution criteria in some cases, especially when the size of optimization problem is relatively large. A chaos theory merged with a PSO algorithm to form a chaotic particle swarm optimization (CPSO) is used to tune the parameters of the damping controllers based on the eigenvalue objective function in both the individual and the coordinated designs to achieve the optimal characteristics. Based on the results of nonlinear time simulation under severe fault disturbances have been presented in this work for different control schemes, the following conclusions have been drawn:

i. The eigenvalue objective function has been successfully implemented for FACT− POD controller and PSS independently and also through the simultaneous coordinated designs.
ii. The result showed the potentiality of hybrid technique CPSO for optimal settings of the damping controllers for individual and the simultaneous coordinated designs.
iii. The results of an individual damping controllers showed the TCSC− POD controller and PSS have good effects in improving the system damping. However, the SVC− POD controller has poorly damped the oscillation.
iv. The dual-coordinated designs PSS & TCSC− POD, PSS & SVC− POD and TCSC− POD & SVC− POD provide more damping with less effort than the individual controllers and it solved the problem of low effectiveness when only the SVC− POD controller is considered. In addition, the dual-coordinated design PSS & TCSC− POD shows the best responses for the generators in scheme 2.
v. Finally, the triple-coordinated design PSS & TCSC− POD & SVC− POD in scheme 3 has high ability in damping oscillations of the system compared to the best individual damping controller TCSC− POD and the best dual-coordinated design PSS & TCSC− POD.

8. References

Abdel-Magid, Y. L., & Abido, M. A. ,2004, Robust coordinated design of excitation and TCSC-based stabilizers using genetic algorithms. *Electric Power Systems Research, 69*(2–3), 129–141.

Abido, M. A., & Abdel-Magid, Y. L.,2002, Eigenvalue assignments in multimachine power systems using tabu search algorithm. *Computers and Electrical Engineering, 28*(6), 527–545.

Anderson, P. M., & Fouad, A. A.,2002, *Power System Control and Stability*. USA: Wiley-IEEE Press.

Babaei, E., & Hosseinnezhad, V.,2010, A QPSO based parameters tuning of the conventional power system stabilizer. *Proceedings of the 9th International Power & Energy Conference (IPEC 2010)*, Singapore, 467–471.

Eslami, M., Shareef, H., Mohamed, A., & Khajehzadeh, M.,2012, An efficient particle swarm optimization technique with chaotic sequence for optimal tuning and placement of PSS in power systems. *Electrical Power and Energy Systems, 43*(1), 1467–1478.

Ghoshal, S. P., Chatterjee, A., & Mukherjee, V.,2010, Application of evolutionary optimization techniques for PSS tuning. In B. K. Panigrahi, A. Abraham & S. Das (Eds.), *Computational intelligence in power engineering* (pp. 325–366). Berlin Heidelberg: Springer-Verlag.

Glover, J. D., & Sarma, M. S.,2002, *Power System Analysis and Design*. Australia: Thomson Learning.

Farahani, M.,2013, Intelligent control of SVC using wavelet neural network to enhance transient stability.*Engineering Applications of Artificial Intelligence,26*(1),273–280.

Furini, M. A., Pereira, A. L. S., & Araujo, P. B.,2011, Pole placement by coordinated tuning of power system stabilizers and FACTS-POD stabilizers. *Electrical Power and Energy Systems, 33*(3), 615–622.

Hemmati, R., Boroujeni, S. M. S., Behzadipour, E., & Delafkar, H.,2011, Supplementary stabilizer design based on STATCOM. *Indian Journal of Science and Technology, 4*(5), 525–529.

Karpagam, N., & Devaraj, D.,2009, Fuzzy logic control of static var compensator for power system damping, *International Journal Innovative Research in Science & Engineering* , *3*(4) 534–540.

Kennedy, J., & Eberhart, R.,1995, Particle swarm optimization. *Proceedings of IEEE International Conference on Neural Networks*, University of Western Australia, Perth, Western Australia, 1942–1948.

Kundur, P.,1994, Small-Signal stability. In N. J. Balu & M. G. Lauby (Eds.), *Power System Stability and Control* (699–717). New York, USA: McGraw-Hill, Inc.

Lu, CF., Hsu, CH., & Juang, CF.,2013, 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, 28*(1), 385–392.

Mukherjee, V., & Ghoshal, S. P.,2007, Comparison of intelligent fuzzy based AGC coordinated PID controlled and PSS controlled AVR system. *International Journal of Electrical Power & Energy Systems, 29*(9): 679–689.

Panda, S., & Padhy, N. P.,2007, Comparison of particle swarm optimization and genetic algorithm for TCSC-based controller design. *International Journal of Electrical and Electronics Engineering, 1*(5), 305–301.

Sadiković, R.,2006, *Use of FACTS devices for power flow control and damping of oscillations in power systems.* Thesis (PhD). Swiss Federal Institute of Technology Zurich.

Shayeghi, H., Safari, A., & Shayanfar, H. A. ,2010, PSS and TCSC damping controller coordinated design using PSO in multi-machine power system. *Energy Conversion and Management, 51*(12), 2930–2937.

Shi, Y., & Eberhart, R.,1998,A modified particle swarm optimizer. *Proceedings of the IEEE World Congress on Computational Intelligence (WCCI 98)*, Anchorage, USA, 69–73.

Yu, YN. ,1983, *Electric power system dynamics*. New York, USA: Academic Press.