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Optimal tuning of power systems stabilizers and AVR gains using particle swarm optimization

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Abstract

In this paper, the problem of simultaneous and coordinated tuning of stabilizers parameters and automatic voltage regulators (AVRs) gains in multi-machine power systems is considered. This problem is formulated as an optimization problem, which is solved using particle swarm optimization technique. The objective of the parameters optimization is formulated as nonlinear problem with constraints to represent the allowable region of the system parameters. The effectiveness of the proposed technique for tuning of multi-controllers in a large power system is tested by applying it to the well-known New England system.

Keywords: Power system control; Power system stabilizers; Particle swarm optimization

1. Introduction

An increase in the damping of the system response is desirable, not only because it reduces the fluctuations in the controlled variables and hence improving the quality of the electric service, but mainly because this damping is translated into an increase in the power transmission stability limits. Higher stability limits bring significant economic savings as the need for the expansion of the transmission system can be postponed.

A supplementary control signal in the excitation system and/or the governor system of a generating unit can be used to provide extra damping for the system and thus improve the dynamic performance. Power system stabilizers (PSSs) contribute in maintaining power system stability and improve dynamic performance by providing a supplementary signal to the excitation system. This is an easy, economical and flexible way to improve power system stability in interconnected AC power systems.

An overview of the research effort developed in the last decades and also on trends of small-signal studies in power system dynamic analysis are presented in Feliachi, Zhang, and Sims (1988); Gibbard, Martins, Sanchez-Gasca, Uchida, Vittal, and Wng (2001); Kundur (1994); Urdaneta, Bacalao, Feijoo, Flores, and Diaz (1991), which discuss the modeling, control techniques and analysis tools available.

Do-Bomfim, Taranto, and Flacao, (2000) proposed a method that simultaneously optimizes both phase compensations and gain settings for the stabilizers using Genetic Algorithms (GAs). Although GA is very sufficient in finding global or near global optimal solution of the problem, it requires a very log run time that may be several minutes or even several hours depending on the size of the system under study. That is why for this kind of application it could not be applied on-line.

The concept of induced torque coefficients is introduced in Gibbard, Vowles, and Pourbeik (2000); Pourbeik and Gibbard (1996); Pourbeik and Gibbard (1998) for the systematic coordination of stabilizers with linear programming of a multi-machine system. Techniques for the coordination of stabilizers based on calculation of eigenvalue shifts from the residues are developed in Martins and Lima (1990); Pagola, Perez, and Verghese (1989).

Pourbeik and Gibbard (2002)) shows that both techniques, using residues or induced torques, are mathematically equivalent in regard to eigenvalue shifting estimation. In Zanetta and Da Cruz (2005), the authors focused on mathematical programming methods for tuning stabilizers in multi-machine power systems using residues of transfer functions. At each step of the tuning procedure, a linearly constrained mathematical programming problem is solved to minimize a particular measure of the overall stabilizer's gain.

In this paper, the problem of simultaneous and coordinated tuning of stabilizers parameters as well as the AVRs gains in

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List of symbols

ω_0	the rated rotor electrical speed in rad/s.
ω_r	the angular speed of the rotor in rad/s.
ψ_{fd}	the field circuit flux linkage.
δ_0	the initial rotor angle in elect. rad.
K_D	the damping torque coefficient in pu torque/pu speed deviation.
H	the inertia constant in MW.s/MVA.
R_{fd}	the field circuit resistance in pu.
L_{fd}	the field circuit reactance in pu.
E_B	the infinite bus voltage in pu.
E_t	the generator terminal voltage in pu.
E_i	the generator internal voltage in pu.
X_{Tq}	the total q-axis reactance of the system in pu.
X_{Td}	the total d-axis reactance of the system in pu.
R_T	the total system resistance in pu.
L_{adu}	the generator d-axis unsaturated value of the mutual inductance in pu.
L_{aqu}	the generator q-axis unsaturated value of the mutual inductance in pu.
L_{ads}	the generator d-axis saturated value of the mutual inductance in pu.
X_d	the synchronous reactance of the generator in pu.
X'_d	the transient reactance of the generator in pu.
X_L	the generator leakage reactance in pu.
K_{sq}, K_{sd}	the q-axis and d-axis saturation coefficients, respectively.
K_A	the exciter gain.
T_R	the terminal voltage transducer time constant in seconds.
K_{STAB}	the power system stabilizer gain.
T_w	the time constant of the signal washout block in seconds.
T_1, T_2	the phase compensator time constants in seconds.
v_1	the output voltage of the terminal voltage transducer.
v_2	the output voltage of the signal washout block.
v_s	the output voltage of the phase compensator.
v_i^k	velocity of agent i at iteration k.
w	weighting function.
c_j	weighting factor.
rand	random number between 0 and 1.
s_i^k	current position of agent i at iteration k.
pbest$_i$	pbest of agent i.
gbest	gbest of group.

a multi-machine power system is addressed. This problem is formulated as an optimization problem, which is solved using particle swarm optimization technique. The objective of the parameters optimization is formulated as nonlinear problem with constraints to represent the allowable region of the system parameters.

The paper will be arranged as follows. First, the linearized model of the system for small-signal study is presented. Second, an overview on the particle swarm optimization (PSO) technique is introduced. After that, the problem formulation of the optimization problem and the application of the PSO technique to such problem are presented. Finally, the simulation results of a well-known test system are introduced.

2. Linearized model of a single-machine infinite-bus system for small-signal stability

The system considered for small-signal performance study is shown in Fig. 1. The synchronous generator considered is equipped with a thyristor exciter with high gain. A block diagram of the system is shown in Fig. 2 and the thyristor excitation system with AVR and PSS is shown in Fig. 3.

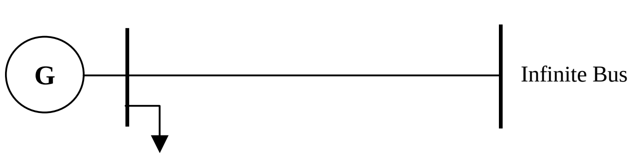

Fig. 1. One machine-infinit bus system.

The details of the study system can be found in (Kundur, 1994). This study system is described by the following state space representation:

$$\dot{x} = Ax + \mathrm{Bu} \qquad y = Cx + \mathrm{Du} \tag{1}$$

where

$$x^T = [\Delta\omega_r \Delta\delta \Delta\psi_{fd} \Delta v_1 \Delta v_2 \Delta v_s] \tag{2}$$

The matrices A, B, C and D are as follows:

$$A = \begin{bmatrix} a_{11} & a_{12} & a_{13} & 0 & 0 & 0 \\ a_{21} & 0 & 0 & 0 & 0 & 0 \\ 0 & a_{32} & a_{33} & a_{34} & 0 & a_{36} \\ 0 & a_{42} & a_{43} & a_{44} & 0 & 0 \\ a_{51} & a_{52} & a_{53} & 0 & a_{55} & 0 \\ a_{61} & a_{62} & a_{63} & 0 & a_{65} & a_{66} \end{bmatrix} \tag{3}$$

$$\mathrm{BT} = \begin{bmatrix} 0 & 0 & \mathrm{b}_3 & 0 & 0 & 0 \end{bmatrix} \tag{4}$$

$$\mathrm{BT} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{5}$$

$$\mathrm{BT} = [\,0\,] \tag{6}$$

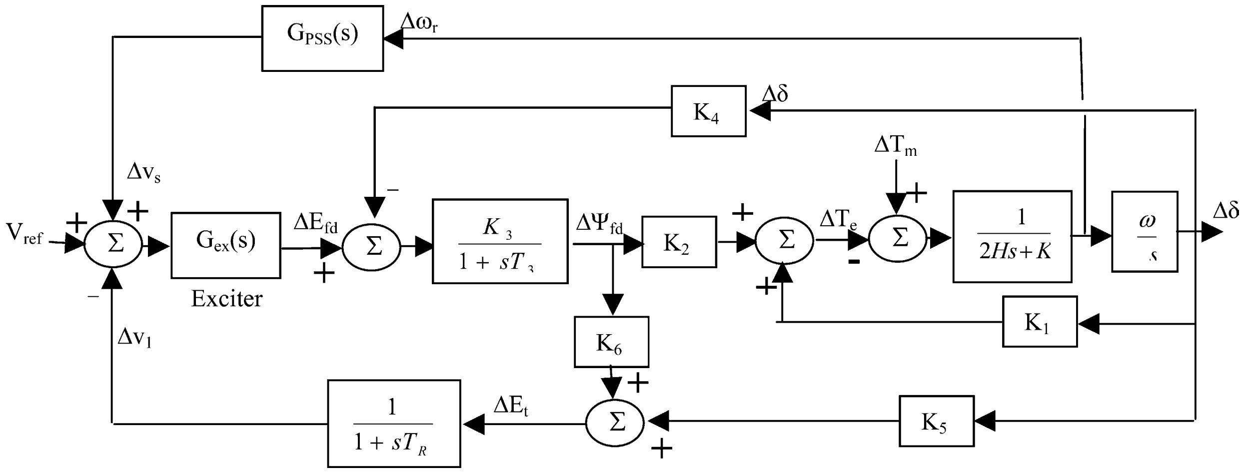

Fig. 2. Block diagram representation with AVR and PSS.

where

$$a_{11} = -\frac{K_D}{2H} \quad a_{12} = -\frac{K_1}{2H} \quad a_{13} = -\frac{K_2}{2H} \quad a_{21} = \omega_0$$

$$a_{32} = -\omega_0 \frac{R_{\mathrm{fd}}}{L_{\mathrm{fd}}} \frac{E_{\mathrm{B}}}{D_{\mathrm{T}}} (X_{\mathrm{T}q} \sin \delta_0 - R_{\mathrm{T}} \cos \delta_0) \frac{L_{\mathrm{ads}} L_{\mathrm{fd}}}{L_{\mathrm{ads}} + L_{\mathrm{fd}}}$$

$$a_{33} = -\omega_0 \frac{R_{\mathrm{fd}}}{L_{\mathrm{ads}} + L_{\mathrm{fd}}} \left[1 + \frac{X_{\mathrm{Tq}}}{D_{\mathrm{T}}} (X_d - X_d') \right]$$

$$a_{34} = -\frac{K_{\mathrm{A}} \omega_0 R_{\mathrm{fd}}}{L_{\mathrm{adu}}} \quad a_{36} = \frac{\omega_0 R_{\mathrm{fd}}}{L_{\mathrm{adu}}} K_{\mathrm{A}} \quad a_{42} = \frac{K_5}{T_{\mathrm{R}}}$$

$$a_{43} = \frac{K_6}{T_{\mathrm{R}}}$$

$$a_{44} = -\frac{1}{T_{\mathrm{R}}} \quad a_{51} = K_{\mathrm{STAB}} a_{11} \quad a_{52} = K_{\mathrm{STAB}} a_{12}$$

$$a_{53} = K_{\mathrm{STAB}} a_{13} \quad a_{55} = -\frac{1}{T_{\mathrm{w}}} \quad a_{61} = \frac{T_1}{T_2} a_{51}$$

$$a_{62} = \frac{T_1}{T_2} a_{52} \quad a_{63} = \frac{T_1}{T_2} a_{53} \quad a_{65} = \frac{T_1}{T_2} a_{55} + \frac{1}{T_2}$$

$$a_{66} = -\frac{1}{T_2} \quad b_3 = \frac{K_{\mathrm{A}} \omega_0 R_{\mathrm{fd}}}{L_{\mathrm{adu}}} \quad D_{\mathrm{T}} = R_{\mathrm{T}}^2 + X_{\mathrm{Tq}} X_{\mathrm{Td}}$$

The description of K1–K6 is shown in details in (Kundur, 1994).

3. Overview of particle swarm optimization

PSO is one of the optimization techniques and belongs to evolutionary computation techniques (Fukuyama, 1999; Kennedy & Eberhart, 1995; Naka, Genji, Yura, & Fukuyama, 2001). The method has been developed through a simulation of simplified social models. The features of the method are as follows:

(1) The method is based on researches on swarms such as fish schooling and bird flocking.
(2) It is based on a simple concept. Therefore, the computation time is short and it requires few memories.

According to the research results for bird flocking, birds are finding food by flocking (not by each individual). It leaded the assumption that information is owned jointly in flocking. According to observation of behavior of human groups, behavior pattern on each individual is based on several behavior patterns authorized by the groups such as customs and the experiences by each individual (agent). The assumptions are basic concepts of PSO.

PSO is basically developed through simulation of bird flocking in two-dimension space. The position of each

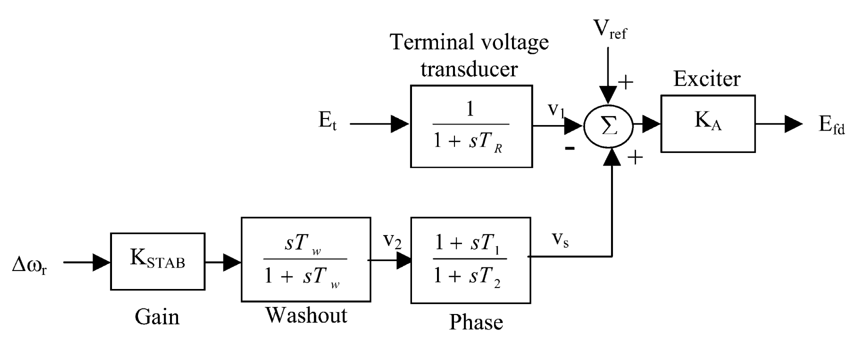

Fig. 3. Thyristor excitation system with AVR and PSS.

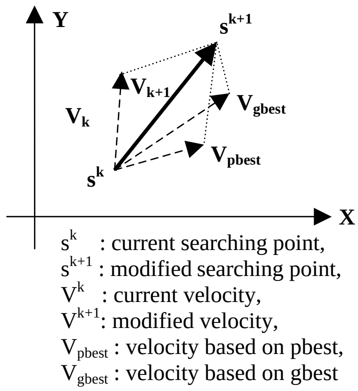

Fig. 4. Concept of modification of a searching point by PSO.

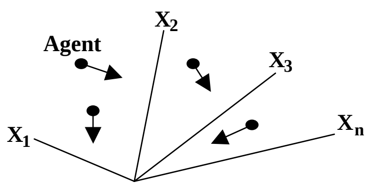

Fig. 5. Searching concept with agents in a solution space by PSO.

individual (agent) is represented by XY axis position and the velocity is expressed by v_x (the velocity of X axis) and v_y (the velocity of Y axis). Modification of the agent position is realized by the position and velocity information.

An optimization technique based on the above concept can be described as follows: namely, bird flocking optimizes a certain objective function. Each agent knows its best value so far (pbest) and its XY position. Moreover, each agent knows the best value so far in the group (gbest) among pbests. Each agent tries to modify its position using the following information:

1 the current positions (x,y),
2 the current velocities (v_x,v_y),
3 the distance between the current position, and pbest and gbest.

This modification can be represented by the concept of velocity. Velocity of each agent can be modified by the following equation:

$$v_i^{k+1} = wv_i^k + c_1\text{rand} \times (p\text{best}_i - s_i^k) + c_2\text{rand} \times (g\text{best} - s_i^k) \quad (7)$$

Using the above equation, a certain velocity, which gradually gets close to pbest and gbest can be calculated. The current position (searching point in the solution space) can be modified by the following equation:

$$s_i^{k+1} = s_i^k + v_i^{k+1} \quad (8)$$

Fig. 4 shows a concept of modification of a searching point by PSO and Fig. 5 shows a searching concept with agents in a solution space.

4. Problem formulation

For the linearized system model presented in Section 2, the eigenvalues of the total system can be evaluated. The proposed method is aiming to search for the optimal parameters set of the exciter and the power system stabilizers so that a comprehensive damping index (CDI) (Cai & Erlich, 2005) can be minimized:

$$\text{CDI} = \sum_{i=1}^{n}(1 - \zeta_i) \quad (9)$$

where ζ_i is the damping ratio and n is the total number of the dominant eigenvalues. The objective of the optimization is to maximize the damping ratio as much as possible.

The control parameters to be tuned through the optimization algorithm are K_A, K_{STAB}, T_w, T_1 and T_2 of each generator in the system. The proposed algorithm will proceed as follows:

1 Input system data: the following data are input,
   - The network configuration during the operating conditions under study.
   - The load values at each bus during the same operating conditions.

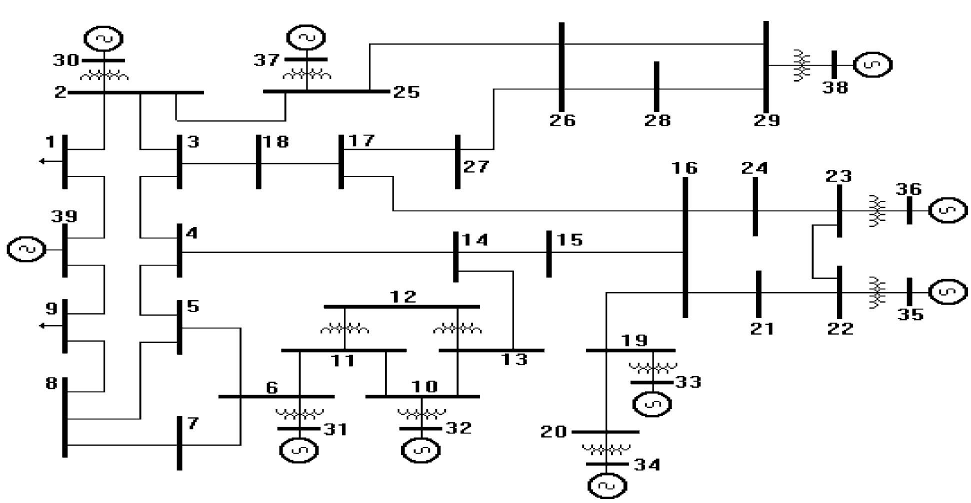

Fig. 6. Single line diagram of New England 39-bus system.

Table 1
Operating conditions

Conditions	Characteristics
1	Base case (normal operation)
2	Lines out: 3–18; 25–26
3	Lines out: 4–14; 16–17
4	Line out: 6–11
5	Load increase of 360 MW
6	Lines out: 4–14; 16–17; 25–26
7	Lines out: 4–14; 16–17; 25–26; 21–39
8	Line out: 21–22
9	Line out: 9–39
10	Load reduction 30%
11	Load increase 15%
12	Load increase 20%
13	Load reduction 20%
14	Load increase of 50% in bar 16 and 50% in bar 21 and line out: 21–22

Table 2
Upper and lower limits of control parameters

Parameter	K_A	K_{STAB}	T_w	T_1	T_2
Upper limit	400	50	10	0.5	0.05
Lower limit	50	20	1	0.05	0.005

- The generators data and parameters.
- The upper and lower limits of the parameters to be optimized.

2 Initialize the swarm with random positions and velocities.
3 Evaluate the fitness of each particle (objective value) as described by Eq. (9).
4 Determine the personal and global best positions.
5 Update the velocity of agents using Eq. (7).
6 Update the position of agents using Eq. (8).
7 Perform the position check (the boundaries of each parameter). If violated then repair the algorithm then go to step 8. If not violated go to step 8.
8 Check the stopping criterion. If met go to step 9 and if not met go back to step 3.
9 Output the optimal solution, which is the optimal values of the control parameters of each generator in the system.

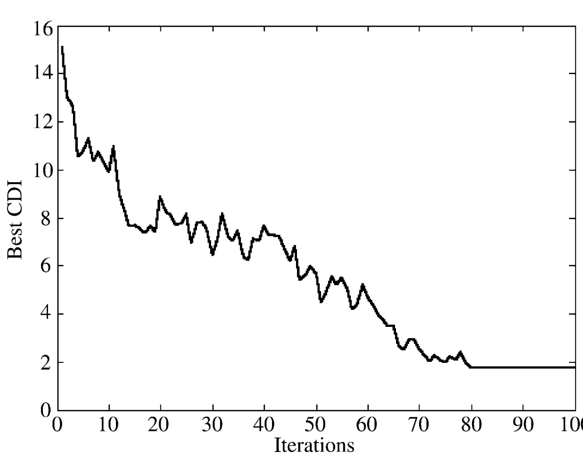

Fig. 7. Convergence process of the 39-bus test system.

Table 3
Optimal control parameters

	K_A	K_{STAB}	T_w	T_1	T_2
Gen. 1	99	20	10	0.5	0.05
Gen. 2	400	50	10	0.06	0.007
Gen. 3	400	25	9	0.07	0.005
Gen. 4	69	50	9	0.5	0.005
Gen. 5	400	50	10	0.06	0.005
Gen. 6	346	50	10	0.08	0.008
Gen. 7	67	50	10	0.3	0.006
Gen. 8	61	50	8	0.3	0.008
Gen. 9	79	49	9	0.5	0.007

5. Simulation results

The case study here is a modified version of the New England system consisting of nine synchronous machines with power systems stabilizers and machine number 10 at bus 39 modeled as an infinite bus. The single line diagram of the system is shown in Fig. 6 and the system data can be found in (Byerley & Sherman, 1978) or with the author. The change that was done in the system for simplicity is that a thyristor excitation system was used.

In order to guarantee that the control parameters selected were optimal the system response under different operating conditions was studied. Table 1 contains the different operating conditions considered, as proposed in (Do-Bomfim et al., 2000). The upper and lower limits of the control parameters as given in the literature are given in Table 2.

For simulation, the swarmsize was chosen to be 20 and the number of iterations to be 100. Fig. 7 shows the fitness value throughout the iterations. The simulation time was about 75 s and the optimal values of the control parameters were found to be as given in Table 3.

Fig. 8 shows the time-domain non-linear simulation of the behavior of the generator on bus 31 during normal operation with and without all PSSs. The eigenvalues (λ), damping ratios (ζ) and natural frequencies (ω_n) are given in Table 4.

Finally, Fig. 9 shows the time-domain non-linear simulation of the behavior of the generator on bus 31 with and without all

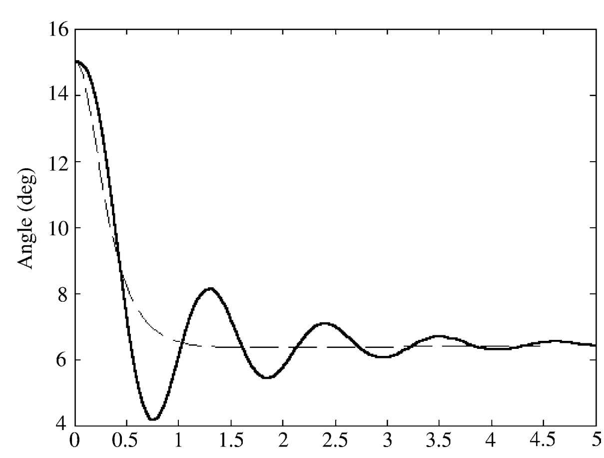

Fig. 8. Time-domain evaluation of the damping introduced by PSS during normal conditions.

Table 4
Results for case 1

State no.	Gen. 1		Gen. 2		Gen. 3		Gen. 4		Gen. 5		Gen. 6		Gen. 7		Gen. 8		Gen. 9	
	ζ	ω_n	ζ	ω_n	ζ	ω_n	ζ	ω_n	ζ	ω_n	ζ	ω_n	ζ	ω_n	ζ	ω_n	ζ	ω_n
1	1	0.1	1	0.1	1	0.11	1	0.13	1	0.1	1	0.11	1	0.11	1	0.14	1	0.12
2	0.285	4.24	0.185	4.73	0.979	4.66	1	1.23	1	2.97	1	1.96	1	1.13	1	1.1	1	1.23
3	0.285	4.24	0.185	4.73	0.979	4.66	1	1.83	1	12.4	1	8.89	1	6.97	1	5.42	1	1.97
4	1	4.57	1	28.7	1	17.9	1	35.3	1	46.7	1	26.1	1	11.7	1	11.5	1	34.3
5	1	19.8	1	70.1	1	81.4	1	94.8	1	59.9	1	72.6	1	96.5	1	95.6	1	91.8
6	1	96.2	1	130	1	193	1	165	1	179	1	116	1	161	1	115	1	121

Table 5
Results for case 2

State no.	Gen. 1		Gen. 2		Gen. 3		Gen. 4		Gen. 5		Gen. 6		Gen. 7		Gen. 8		Gen. 9	
	ζ	ω_n	ζ	ω_n	ζ	ω_n	ζ	ω_n	ζ	ω_n	ζ	ω_n	ζ	ω_n	ζ	ω_n	ζ	ω_n
1	1	0.1	1	0.1	1	0.11	1	0.13	1	0.1	1	0.11	1	0.11	1	0.14	1	0.12
2	0.18	4.3	1	4.7	0.97	4.66	1	1.15	1	2.9	1	1.92	1	1.12	1	1.1	1	1.14
3	0.18	4.3	1	9.3	0.97	4.66	1	1.9	1	12.	1	8.97	1	6.9	1	5.5	1	2.1
4	1	4.5	1	28.6	1	18	1	35.9	1	47.3	1	26.2	1	11.9	1	11	1	34.9
5	1	19.8	1	70.3	1	81.4	1	94.7	1	59.5	1	72.	1	96.5	1	95.7	1	91.7
6	1	96.2	1	130	1	193	1	164	1	179	1	116	1	160	1	115	1	120

PSSs during case 2 of Table 1. The eigenvalues (λ), damping ratios (ζ) and natural frequencies (ω_n) are given in Table 5.

6. Conclusion

This paper presents an effective technique to maximize the damping ratios of the system by optimally determining the values of the control parameters of the system generators. The optimization problem was solved using the particle swarm optimization technique. The proposed technique proved to be efficient in determining the optimal values of the control parameters such that the system response is satisfactory under different operating conditions. Besides being effective, the particle swarm optimization technique proved to be fast compared with other artificial intelligent optimization techniques such as genetic algorithms and compared to mathematical programming optimization approaches such as linear programming and quadratic programming methods.

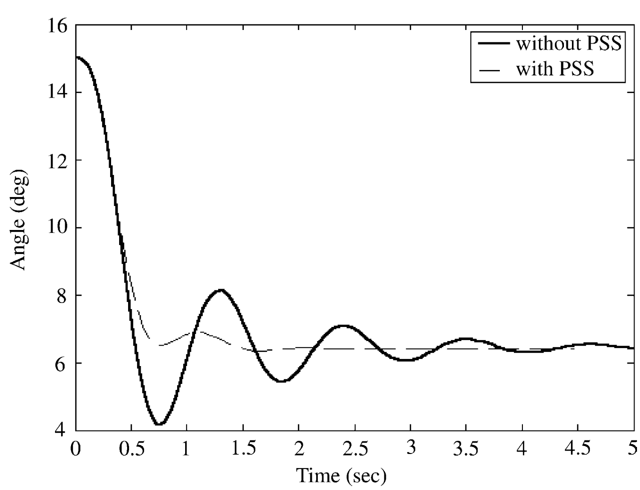

Fig. 9. Time-domain evaluation of the damping introduced by PSS during Case 2 of Table 1.

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