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PSO–BASED POWER SYSTEM STABILIZER FOR MINIMAL OVERSHOOT AND CONTROL CONSTRAINTS

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Power systems are subjected to severe repetitive oscillations that might cause generators shaft fatigue and consequently breakdown. The paper presents a simple design technique for power system stabilizers (PSS) that minimize the maximum overshoot; thus generator shaft fatigue is alleviated. The levels of control signal, as well, have to be maintained within certain bounds imposed by physical and practical considerations. According to this regard, a technique based on Particle Swarm Optimization (PSO) is introduced to identify the parameters of a fixed structure lead compensator through the solution of a min-max problem while satisfying systems constraints. To robustify the PSS performance under wide loading conditions, a set of operating points is considered within our approach. The designed PSS is applied to a single machine infinite bus system operating at different loading conditions and the results demonstrated the effectiveness of the developed technique.

K e y w o r d s: particle swarm optimization, power system stabilizer, small signal stability

1 INTRODUCTION

Power system stabilizers (PSS) have been extensively used as supplementary excitation controllers to damp out the low frequency oscillations and enhance the overall system stability. Fixed structure stabilizers have practical applications and generally provide acceptable dynamic performance. The typical ranges of PSS parameters values are found in [1] and summarized in the appendix. There have been arguments that these controllers, being tuned for one nominal operating condition, provide suboptimal performance when there are variations in the system load. There are two main approaches to stabilize a power system over a wide range of operating conditions, namely adaptive control [2–4] and robust control. However, adaptive controllers have generally poor performance during the learning phase unless they are properly initialized.

Robust control provides an effective approach to deal with the uncertainties introduced by variations of operating conditions. Many robust control techniques have been used in the design of PSS such as pole placement [5], the structured singular value [6] and linear matrix inequality (LMI) [7]. Variable structure control applied to PSS results in high control activity (chattering) [8]. The H_∞ approach is applied to the design of PSS for a single machine infinite bus system in [9]. The basic idea is to carry out a search over operating points to obtain a frequency bound on the system transfer function. Then, a controller is designed so that the worst-case frequency response lies within pre- specified bounds. It is noted that the H_∞ design requires an exhaustive search and results in a high order controller. PSS design based on Kharitonov theorem [10, 11] leads to conservative design as well. The theorem assumes that the parameters of the closed loop characteristic polynomial vary independently. This never happens as these parameters depend on power system loading conditions. Though practical operating conditions require the magnitude of the control signal to be within a certain limit, it seems that none of the above-mentioned papers consider the control limit constraints. Constraints on rotor angle deviation have also to be considered, otherwise repetitive oscillations with severe overshoots may cause fatigue and damage to the generator shaft. In view of the above it is desirable to develop a design technique that obtains the PSS parameters avoiding: (1) the conservatism in robust designs (2) large overshoots (3) control signal violation. The paper considers the optimum tuning of fixed structure lead controller to stabilize a single machine infinite bus system. The lead controllers have found applications in power system control problem for their simplicity and ease of realization. The tuning scheme proposed in this paper uses the particle swarm search technique that minimizes the overshoot as well as control signal violation. Minimizing the overshoot is equivalent to increasing system damping. However we are confronted with a necessary compromise between swiftness of response and allowable overshoot. To achieve robustness and avoiding conservatism in design, the maximum overshoot is selected to be the worst over three operating

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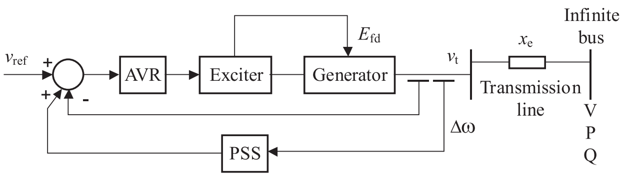

Fig. 1. Single machine infinite bus system.

regimes (heavy, nominal and light loading). The problem is formulated in section 2 of the manuscript. The mathematical tools for designing the proposed PSS are stated in section 3. Simulation results are depicted in section 4. Finally, the paper is concluded in section 5.

2 PROBLEM FORMULATION

Figure 1 shows the system under study, which represents a single machine infinite bus system. The infinite bus represents the Thevenin equivalent of large interconnected power system.

The nonlinear equations of the system are:

$$\begin{aligned}
\dot{\delta} &= \omega_0 \omega\,, \\
\dot{\omega} &= \frac{T_m - T_e}{M}\,, \\
\dot{E}'_q &= \frac{1}{T'_{d0}}\Big(E_{fd} - \frac{x_d + x_e}{x'_d + x_e}E'_q + \frac{x_d + x'_d}{x'_d + x_e}V\cos\delta\Big), \\
\dot{E}_{fd} &= \frac{1}{T_E}\big(K_E E_{ref} - K_E V_t - E_{fd}\big)\,.
\end{aligned} \tag{1}$$

The above equations can be linearized for small oscillation around an operating point [1] and be cast in the block diagram shown in Fig. 2.

The parameters of the model are function of the loading (P, Q). The state equation for the system under study is given by [1]

$$\begin{aligned}
\dot{x} &= Ax + Bu\,, \\
y &= Cx
\end{aligned} \tag{2}$$

where

$$x = \begin{bmatrix} \Delta\delta & \Delta\omega & \Delta E'_q & \Delta E_{fd} \end{bmatrix},$$

$$A = \begin{bmatrix} 0 & \omega_0 & 0 & 0 \\ -\frac{k_1}{M} & 0 & -\frac{k_2}{M} & 0 \\ -\frac{k_4}{T'_{do}} & 0 & -\frac{1}{T} & -\frac{1}{T'_{do}} \\ -\frac{k_5 k_E}{T_E} & 0 & -\frac{k_6 k_E}{T_E} & -\frac{1}{T_E} \end{bmatrix}, \quad B = \begin{bmatrix} 0 \\ 0 \\ 0 \\ \frac{k_E}{T_E} \end{bmatrix}, \tag{3}$$

$$C = \begin{bmatrix} 0 & 1 & 0 & 0 \end{bmatrix}, \quad T = k_3 T'_{do}\,.$$

Constants k_1 to k_6 represent the system parameters at a certain operating condition [1]. Analytical expression for these parameters as a function of the loading (P,Q) are derived in [5, 10] and summarized in the Appendix.

Typical data for such a system are as follows: For the synchronous machine we have (pu):

$$x_d = 1.6\,,\ \dot{x}_d = 0.32\,,\ x_q = 1.55\,,$$
$$\omega_b = 2\pi \times 50\,\text{rad/sec},\ T'_{d0} = 6\,\text{sec and}\ \ M = 10\,,$$

while for the transmission line (pu): $x_e = 0.4$.

To cover wide operating conditions of the machine under study, the following three loading regimes are selected (pu):

Load	P	Q
Heavy	1.2	0.2
Normal	1	0
Light	0.7	0.3

The selected regimes for designing PSS are chosen to cover heavy, medium and light loading. The proposed controller is designed based on the selected regimes. Testing the obtained controller is checked on the selected ones as well as other operating conditions.

The resulting matrices of the state equation are:

1. Heavy load regime:

$$A = \begin{bmatrix} 0 & 314 & 0 & 0 \\ -0.1360 & 0 & -0.1194 & 0 \\ -0.2547 & 0 & -0.4633 & 0.1667 \\ -42.1430 & 0 & -248.0059 & -20 \end{bmatrix}, B = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 500 \end{bmatrix},$$

$$C = \begin{bmatrix} 0 & 1 & 0 & 0 \end{bmatrix}.$$

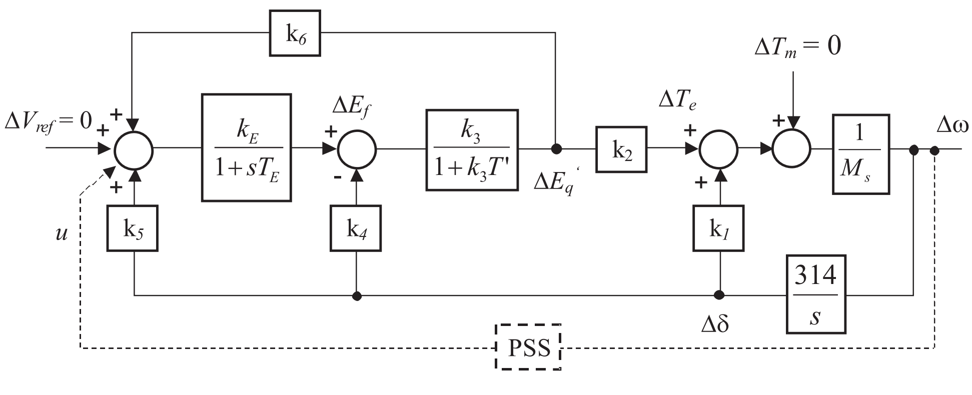

Fig. 2. Linearized model of the power system

2. Normal load regime:

$$A = \begin{bmatrix} 0 & 314 & 0 & 0 \\ -0.1206 & 0 & -0.1236 & 0 \\ -0.2636 & 0 & -0.4633 & 0.1667 \\ 32.1430 & 0 & -225.6232 & -20 \end{bmatrix}, B = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 500 \end{bmatrix},$$

$$C = [\,0 \quad 1 \quad 0 \quad 0\,]\,.$$

3. Light load regime:

$$A = \begin{bmatrix} 0 & 314 & 0 & 0 \\ -0.1186 & 0 & -0.0906 & 0 \\ -0.1934 & 0 & -0.4633 & 0.1667 \\ -5.9319 & 0 & -225.7990 & -20 \end{bmatrix}, B = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 500 \end{bmatrix},$$

$$C = [\,0 \quad 1 \quad 0 \quad 0\,]\,.$$

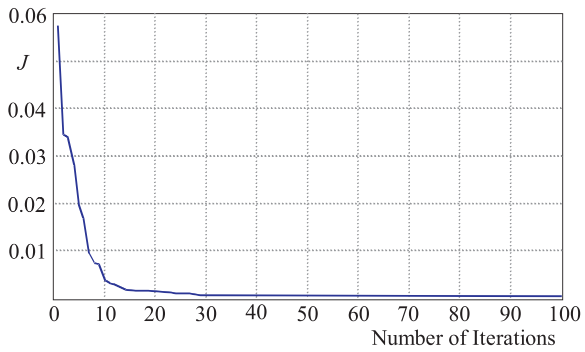

Fig. 3. Objective function global best values *vs* iterations

The problem we are interested in is defined as follows:

(1) Given the system (1), find a lead PSS controller in the form:

$$u = G_c(s)\Delta\omega\,, \quad G_c(s) = k\frac{s-Z}{s-P} \tag{4}$$

which stabilizes the system while minimizing the max. overshoot of $\Delta\delta(t)$ over the operating range. This robust minimal-overshoot controller can be obtained by solving the following mini-max optimization problem

$$\underset{K,Z,P}{\text{minimize}}\, J_1 = \max[\Delta\delta(t)_{\max} - \Delta\delta_{ss}]/\Delta\delta_{ss} \qquad \forall \text{ selected regimes} \tag{5}$$

where J_1 represents the worst overshoot over the selected regimes, $\Delta\delta_{\max}$ and $\Delta\delta_{ss}$ represent respectively the maximum and steady state values of torque angle deviation.

(2) The control signal should not exceed bounds imposed by practical considerations. This can be cast as a performance index J_2 as follows

$$\text{if } u_{\min} < u < u_{\max} \text{ then } J_2 = 0 \tag{6}$$

Otherwise,

$$\underset{K,Z,P}{\text{minimize}}\, J_2 = \max\big(\text{abs}(u-u_{\min}), \text{abs}(u-u_{\max})\big) \qquad \forall \text{selected regimes.}$$

Combining (5), (6) we get the following overall objective function:

$$\underset{K,Z,P}{\text{minimize}}\, J = \alpha J_1 + \beta J_2 \tag{7}$$

where α and β are weighting parameters.

It is worth mentioning that as $\beta \to \infty$, control constraints given by (6) are satisfied. However, if (7) includes only J_1 one of the system constraints is not included in the optimization problem. In other words, if the constraints given by (6) are included by clipping the control signal, then in this case the compensator output is no longer active during the clipping period. Accordingly, the values of the design parameters will not take into consideration control constraints. We may get a controller, but by no means is it optimal. By injecting βJ_2 in the cost function we guarantee that the designed compensator minimizes the overshoot as well as satisfying control constraints (to a certain extent since $\beta \neq \infty$).

3 PSS DESIGN VIA SWARM OPTIMIZATION

The above mini-max optimization problem can be solved using Particle Swarm Optimizer (PSO). This technique belongs to the class of evolutionary programming approaches for optimization [12]. It is a multi agent search technique that traces its evolution to the emergent motion of a flock of birds (agent, particle) searching for food. Each bird traverses to the search space looking for the global minimum (or maximum). The PSO technique is computationally simple since it neither requires gradient calculations nor necessitates the convexity of the function to be optimized. It is a stochastic optimization technique with a large number of agents, so it is unlikely to be trapped at a local minimum. While the agents in the PSO algorithm are searching the space, each agent remembers two positions. The first is the position of the best point the agent has found (self-best), whilst the second is the position of the best point found among all agents (group-best). The equations that govern the motion of each agent are

$$\begin{aligned} \mathbf{S}_{\text{new}} &= \big[\mathbf{S} + \boldsymbol{v}\big]_{\text{old}}\,, \\ \boldsymbol{v}|_{\text{new}} &= \big[\gamma\boldsymbol{v} + ar(0,1)\big(\mathbf{S}_{\text{self-best}} - \mathbf{S}\big) \\ &\quad + br(0,1)\big(\mathbf{S}_{\text{group-best}} - \mathbf{S}\big)\big]_{\text{old}} \end{aligned} \tag{8}$$

where $\mathbf{S}$ is a position vector of a single particle,
$\boldsymbol{v}$ is the velocity of this particle,
a, b are two scalar parameters of the algorithm,
γ is an inertia weight,
$r(0,1)$ is a uniform random number between 0 and 1,

group-best is the best solution of all particles and self-best is the best solution observed by the current particle. A maximum velocity ($v_{\max}$) that cannot be exceeded may also be imposed. Application of PSO to power system control is given in [13–15]

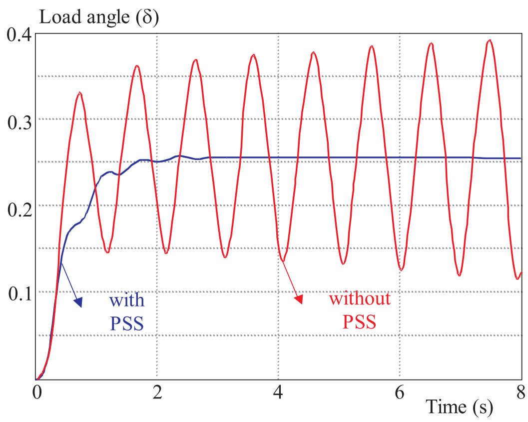

Fig. 4. Step response $\Delta\delta(t)$ for heavy load

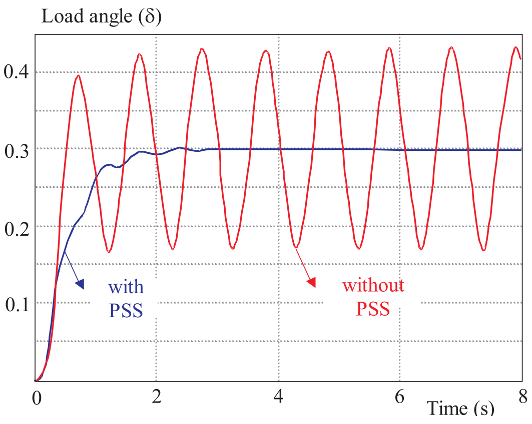

Fig. 5. Step response $\Delta\delta(t)$ for normal load

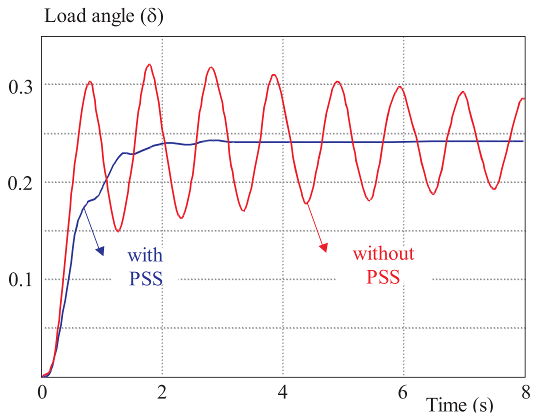

Fig. 6. Step response $\Delta\delta(t)$ for light load

4 PSS DESIGN

4.1 Robust PSS with Minimal Overshoot and without Control Constraints

The parameters of the controllers are tuned using PSO by minimizing (7) with $\beta = 0$ (no control constraints). To achieve this, a proper adjustment of the PSO parameters is needed [12]. Table 1 shows the parameters of PSO that provide best results.

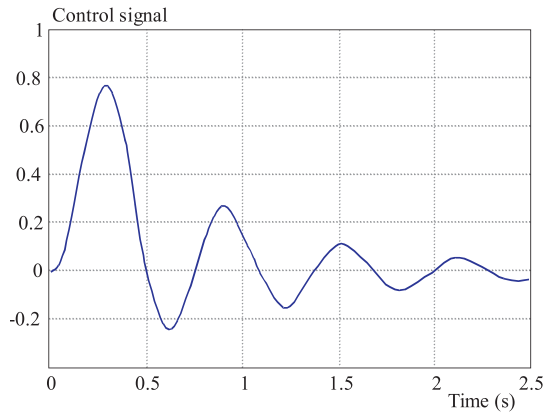

Fig. 7. The control signal $u(t)$ for heavy load

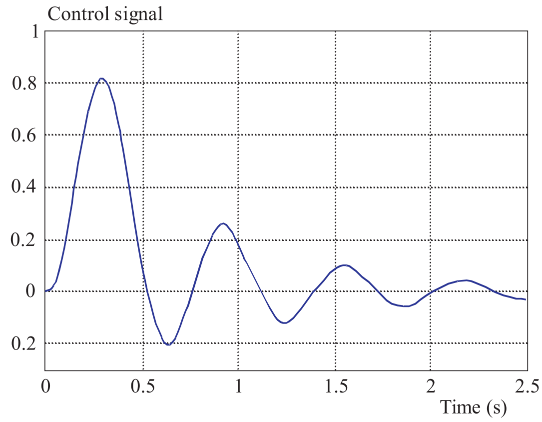

Fig. 8. The control signal $u(t)$ for normal load

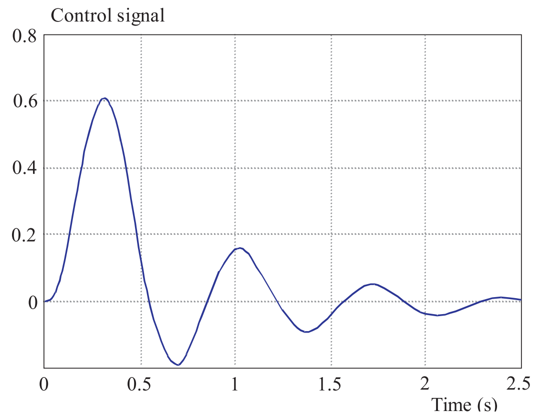

Fig. 9. The control signal $u(t)$ for light load

Table 1. PSO parameters.

No. Of swarm birds (particles)	30
Particle dimension	3 (k, Z, P)
Max. particle speed, $V_{\max}$	10
γ, a, b	0.6, 0.95, 0.75

The poles, zeros and the gains of the controllers within the population are randomly initialized. Figure 3 shows

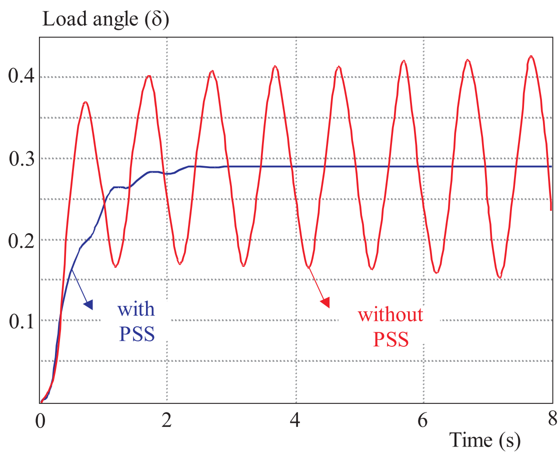

Fig. 10. ($P = 1.1$, $Q = 0.1$)

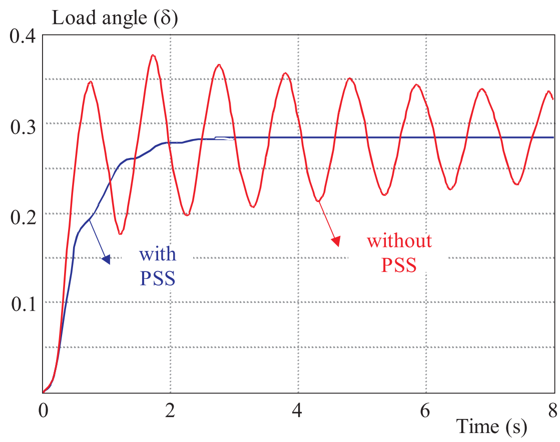

Fig. 11. ($P = 0.8$, $Q = 0.2$)

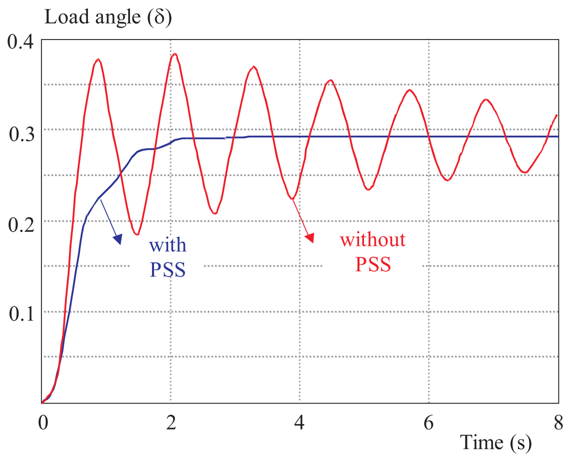

Fig. 12. ($P = 0.4$, $Q = 0.1$)

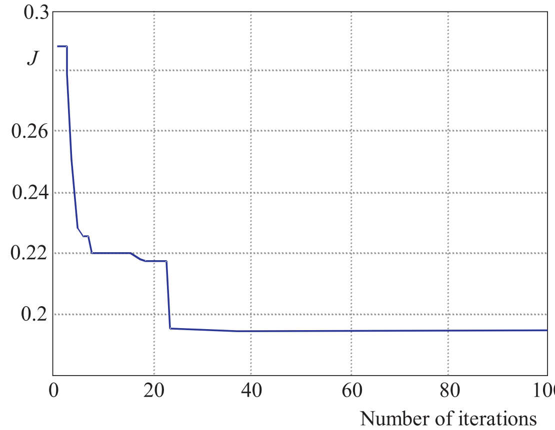

Fig. 13. Objective function for constraint global best *vs* iterations

the evolution of the value of the objective function for the global best solution with iteration. The worst overshoot over the operating regimes (Heavy, normal and light loading) is reduced from 0.06 to 0.000514 in nearly 30 iterations. This result is achieved while using the following controller:

$$G_c(s) = 47.95\frac{1+0.3176s}{1+0.077s} \tag{9}$$

The step response $\Delta\delta(t)$ for heavy, normal and light loading are shown in Figs. 4–6 respectively, while the corresponding control signals are given in Figs. 7–9

Remarks

1. Although the proposed design does require calculating the eigenvalues, it is to be noticed that the worst relative stability (max real part of closed loop eigenvalues) over the selected regimes is -1.2094. This shows that the proposed PSS is very robust and provides an excellent setting time as well.

2. The effectiveness of the proposed controller is checked for operating regimes other than the selected ones. The performance is shown in Figures 10 to 12.

4.2 Robust PSS with Minimal Overshoot and Control Constraint

Although Figs. 4–9 showed acceptable responses for $\Delta\delta(t)$, the control signal reached a level of 0.82 p.u. which violates the acceptable limits imposed by physical considerations. Therefore, our interest in this subsection is to handle the same problem while satisfying control constraints. Two cases will be considered.

Case 1: The control signal must not violate ± 0.2

By substituting for $\alpha = 1$ and $\beta = 2$ in (7), the constrained min-max optimization problem is solved using the same population size. Figure 13 shows the progress of the objective function for the global best with the iteration number. From these results, it is clear that the objective function J is reduced from 0.29 to 0.1963 in nearly 27 iterations. The value of J_1, which corresponds to the maximum overshoot, at the optimal solution is 0.1963 while $J_2 = 0$. At the optimal solution, the structure of the lead controller is given by:

$$G_c = 3.665\frac{1+1.12s}{1+0.14s}\,. \tag{10}$$

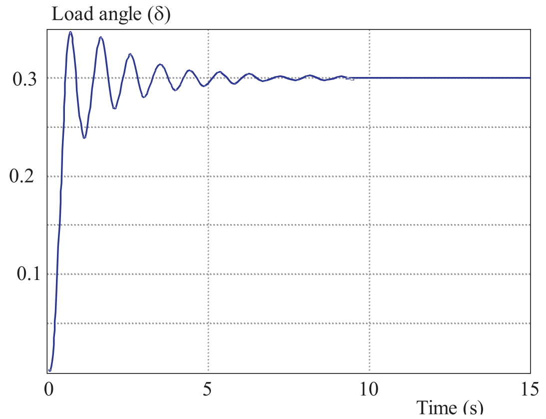

Fig. 14. Step response $\Delta\delta(t)$ for the worst case

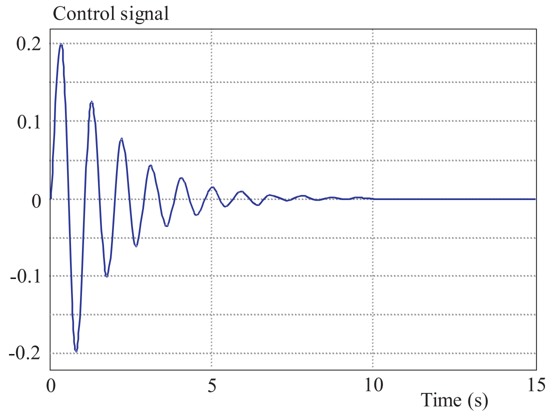

Fig. 15. The control signal $u(t)$ for the worst case

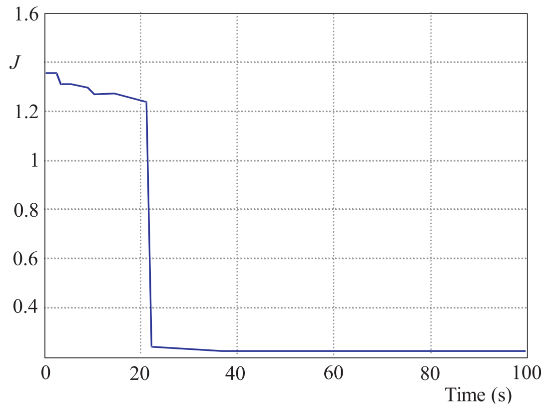

Fig. 16. Objective function for constraint global best *vs* iterations

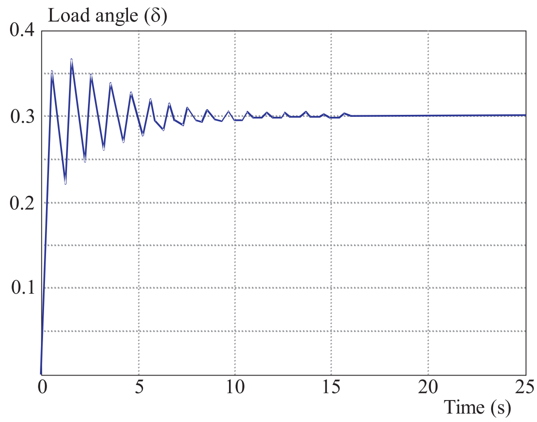

Fig. 17. Step response $\Delta\delta(t)$ for the worst case

Figure 14 shows the optimal response of $\Delta\delta(t)$ for the worst case out of three operating regimes. The control behavior for this case is presented in Fig. 15. From these results it is clear that we achieved the possible minimal value of the maximum overshoot while satisfying system constraints.

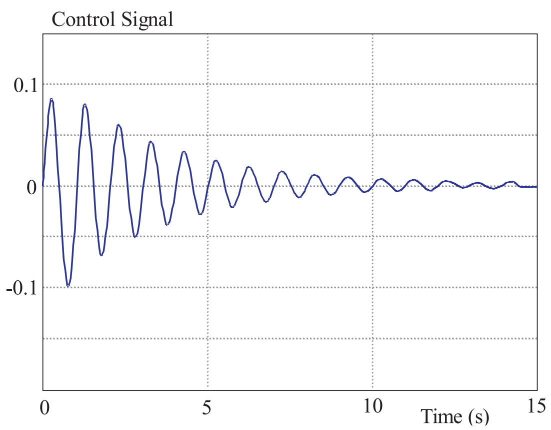

Fig. 18. (The control signal $u(t)$ for worst case..

Case 2: The control signal must not violate ± 0.1

Selecting $\alpha = 1$ and $\beta = 10$ and following the same lines as above, J is reduced from 1.39 to 0.223 (Fig. 14). The optimal value thus obtained are $J_1 = 0.223$ and $J_2 = 0$.The step response for the worst case and its corresponding control signal are shown in Figs. 17 and 18. The obtained lead controller is:

$$G_c = 1.2\frac{1 + 1.27s}{1 + 0.092s}\,. \tag{11}$$

Out of the previous figures, it is clear that the severer control constraint imposed, the dynamic performance is sacrificed.

5 CONCLUSIONS

In this paper, a technique based on particle swarm optimization is developed for tuning the parameters of a fixed structure PSS. Besides ensuring system stability, the proposed controller provides a minimal-overshoot response over a wide range of power system operation while satisfying control constraints imposed on the system.

The algorithm offers designers the flexibility to achieve a compromise between conflicting design objectives, the overshoot and control constraint.

The design of such a controller is done off-line, so the computational time is not of prime importance. Application of the developed method to a typical problem showed its effectiveness in achieving the stated design objectives.

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Appendix

1. Typical values of the parameters of PSS

The lead transfer function of the power system stabilizer is given by

$$G_c(s) = K_{PSS}\frac{1+T_1 s}{1+T_2 s}$$

Typical values of the parameters are:
K_{PSS} is in the range of 0.1 to 50,
T_1 is the lead time constant, 0.2 to 1.5 sec,
T_2 is the lag time constant, 0.02 to 0.15 sec.

2 The k-parameters of the machine expressed in terms of P and Q

$$k_1 = C_3\frac{P^2}{P^2+(Q+C_1)^2} + Q + C_1\,,$$

$$k_2 = C_4\frac{P}{\sqrt{P^2+(Q+C_1)^2}}\,,$$

$$k_3 = \frac{x'_d + x_e}{x_d + x_e}\,,$$

$$k_4 = C_5\frac{P}{\sqrt{P^2+(Q+C_1)^2}}\,,$$

$$k_5 = C_4 x_e\frac{P}{V^2+Qx_e}\Big[C_6\frac{C_1+Q}{p^2+(C_1+Q)^2}\Big],$$

$$k_6 = C_7\frac{\sqrt{P^2+(Q+C_1)^2}}{V^2+Qx_e}\Big[x_e + \frac{C_1 x_q(C_1+Q)}{p^2+(C_1+Q)^2}\Big],$$

$$C_1 = \frac{V^2}{x_e+x_q}\,, \qquad C_2 = k_3$$

$$C_3 = C_1\frac{x_q - x'_d}{x_e + x'_d}\,, \qquad C_4 = \frac{V}{x_e+x'_d}\,,$$

$$C_5 = \frac{x_d - x'_d}{x_e + x'_d}\,, \qquad C_6 = C_1\frac{x_q(x_q - x'_d}{x_e+x_q}\,,$$

$$C_7 = \frac{x_e}{x_e + x'_d}$$

List of Symbols

All quantities are in p.u. except the time constants and M are in seconds.

T_m : mechanical torque.
T_e : electrical torque.
V_t : terminal voltage.
emf : electro motive force.
E_q : induced emf proportional to field current.
E_{fd} : generator field voltage.
V_{ref} : reference value of generator field voltage.
x'_d, x_d, x_q : generator direct-axis transient reactance, direct and quadrature-axis synchronous reactance respectively.
x_e : external (line) reactance.
δ : angle between quadrature axis and infinite bus bar.
$\Delta\omega$: speed deviation.
ω_0 : $2\pi f$, $f = 50$ Hz.
T'_{do} : open circuit direct — axis transient time constant.
M : inertia coefficient.
k_E, T_E : exciter gain and time constant.
U : stabilizing signal (PSS output).
V : infinite busbar voltage.
P, Q : real and reactive power loading; respectively.
$k_1,\dots,k_6$: the k-parameters of the synchronous generator block diagram.
s : the Laplace operator.

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