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# DAMPING POWER SYSTEM OSCILLATIONS USING PARTICLE SWARM-BASED CONTROLLER

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## ABSTRACT:

In this paper, the Particle Swarm Optimization (PSO) technique is used to develop a controller for damping power system oscillations. The speed deviation $\Delta\omega$ and its rate of change $\Delta\dot{\omega}$ are selected as input signals to the proposed controller. The objective is to get optimal gains values of the controller within pre-specified limits to improve the system dynamics.

In order to ensure the reliability of the PSO based controller, a comparison has been made between the effect of the developed controller and that of an $\mathcal{H}^{\infty}$ controller on the dynamic performance of a single machine connected to infinite bus. The simulation results show that the PSO-based controller offer effective damping to system oscillations in a wide range of operating conditions and system parameters.

**Kew words:** Power System Stabilizer, Particle Swarm Optimization

## INTRODUCTION:

One of the earliest power system stability problems is power system low frequency oscillations (LFO) in the range 0.1 – 5.0 Hz [1]. These LFO are generally affected by control actions taken in the systems. These oscillations in turn affect system and security. Causes of LFO include sudden load changes, considerable structural changes, pumping of harmonic oscillations by some load source and existence of negative damping due to: a) interaction between uncoordinated controllers, b) changes in system state or control parameters, or c) performance of controllers during severe conditions while they are tuned at different operating conditions.

The introduction of robust controller design is the main idea of having improved system performance over certain prespecified range of operating conditions and parameters uncertainty more than having optimal performance in a very narrow range around some operating point [2].

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PSO represents one of the computational methods recently employed for optimization of continuous nonlinear functions [3]. The PSO main idea was to make use of the behavior of the natural creature swarms inside computer programs. Such creatures get benefits of exchanging knowledge and experiences of different individuals. PSO requires only primitive mathematical operators, and is computationally inexpensive from the point of view of memory and speed requirements. Early testing of the PSO has shown that its implementation is effective in several kinds of problems [4].

Many design techniques have been investigated to improve transient stability and damping characteristics using PSO [5-7]. The method used in reference [5] is the Backstepping control design method that has been developed for the purpose of controlling nonlinear systems. They applied the method to a multi-machine power system using rotor angle, speed of shaft, and electric power as inputs and tuning the gains with a PSO.

In [6], the PSO technique was applied on conventional lead-lag PSS type to select optimal settings of its parameters according to either one of two different eigenvalue-based objective functions (minimizing maximum real part or, maximizing minimum damping ratio of electromechanical modes). A decentralized nature was assumed to get easier tuning and installation for two or more PSSs in two different study systems.

In [7], the PSO technique was presented for estimation of synchronizing and damping torque coefficients of a synchronous machine using digital samples of the machine time response (as a dynamic estimation problem) by minimizing the error square in the estimated coefficients. It was shown that the PSO algorithm can successfully estimate the required coefficients even in very critical stable cases where other methods (genetic algorithm, least square) may fail.

In this paper, PSO is applied to find optimum parameters of a power system stabilizer (PSS) applied to single machine connected to an infinite bus. The optimization process is performed according to eigenvalue-based objective functions to enhance damping of electromechanical modes.

## PARTICLE SWARM OPTIMIZATION TECHNIQUE:

Kennedy and Eberhart [3] developed a PSO concept. PSO is basically developed through simulation of bird flocking in two-dimension space. The position of each particle is represented by XY axis position and the velocity is expressed by $v_x$ and $v_y$ (the particle velocities in the x direction and y direction respectively). Modification of the agent position is realized by the position and velocity information. This modification can be represented by the concept of velocity. Velocity of each agent can be modified by the following equations:

$$v_i^{k+1} = K[v_i^k + c_1 rand_1 * (pbest_i - s_i^k) + c_2 rand_2 * (gbest - s_i^k)] \qquad (1)$$

where, $K = \textit{the constriction factor} = \dfrac{2}{\left|2-\varphi-\sqrt{\varphi^2-4\varphi}\right|}, \quad \textit{and} \quad \varphi = c_1 + c_2, \varphi > 4$

$v_i^k$ : velocity of agent i at iteration k,

$c_j$ : weighting factor,
$rand_j$ : 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 the group.

The current position (searching point in the solution space) can be modified by the following equation:

$$s_i^{k+1} = s_i^k + v_i^{k+1} \qquad (2)$$

Note that; all velocities and positions are represented by vectors in an m dimensional space (number of space dimensions is the number of parameters to be optimized).

## POWER SYSTEM MODEL:

The block diagram and full representation of single machine-infinite bus study system is shown in Figure 1 [11]. Damper windings effect and transient process in armature winding are neglected in the model. Only field winding circuit and torque equations were represented by differential equations. Complete data of the system are given in appendix A.

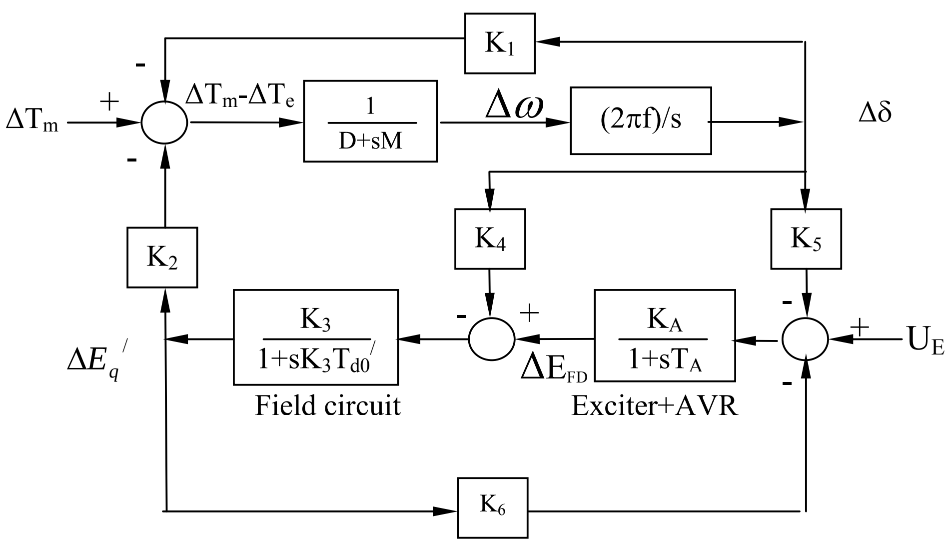


**Figure 1 Transfer function block diagram of the study system**

The linearized mathematical model of the system can be written in the state space form as:

$$\dot{X} = AX + BU \qquad (3)$$

where

$$X = \lfloor \Delta\omega \quad \Delta\delta \quad \Delta E_q^{/} \quad \Delta E_{FD} \rfloor \qquad (4)$$

$$A = \begin{bmatrix} -D/M & -K_1/M & -K_2/M & 0 \\ \omega_b & 0 & 0 & 0 \\ 0 & -K_4/T_{d0}^{\prime} & -1/(T_{d0}^{\prime}K_3) & 1/T_{d0}^{\prime} \\ 0 & -K_A K_5/T_A & -K_A K_6/T_A & -1/T_A \end{bmatrix} \tag{5}$$

$$B = \begin{bmatrix} 0 & 0 & 0 & K_A/T_A \end{bmatrix} \tag{6}$$

where,

| | |
|---|---|
| $\Delta$ | = incremental change |
| f | = system frequency |
| $\omega$ | = angular velocity = $2\pi f$ |
| $\delta$ | = generator power angle |
| $E_{FD}$ | = field voltage |
| D | = mechanical damping coefficient |
| M | = inertia constant |
| $T_{d0}^{\prime}$ | = field circuit time constant |
| $E_q^{\prime}$ | = emf behind transient reactance. |
| $K_A$ | = equivalent excitation system overall gain |
| $T_A$ | = equivalent excitation system time constant |

The proposed system was widely investigated in many studies at different operating conditions for comparing different controllers, especially power system stabilizers.

The constants in the block diagram depend on system parameters and operating point. The system response has been tested for different values of $K_A$ [12]. The worst system dynamics occur at $K_A = 25$. This gain has been chosen in the forgoing work to design the PSS necessary for keeping system stability and improving its dynamic performance.

The eigenvalues of the system for the operating point and system parameters (appendix A) are found to be [0.32625 ± j3.05433, -4.2287, -16.61952]. The roots of the mechanical mode, 0.32625 ± j3.05433, indicate system instability. It should be noted that the system in this case is not provided with any PSS.

This operating condition has been selected intentionally to put the proposed controller in front of a challenge to:

1- derive the system to a stable region of operation.

2- improve the system response in case of any additional disturbance.

## PSO BASED PSS:

The configuration of the proposed PSO based PSS is shown in Figure 2. The deviation in angular velocity $\Delta\omega$ and its rate of change $\Delta\dot{\omega}$ are used as input signals to the PSO based-

PSS. $T_7$ and $T_8$ are assumed equal to 0.05 sec. The PSO technique is employed to find the optimum values of gains $K_7$, $K_8$.

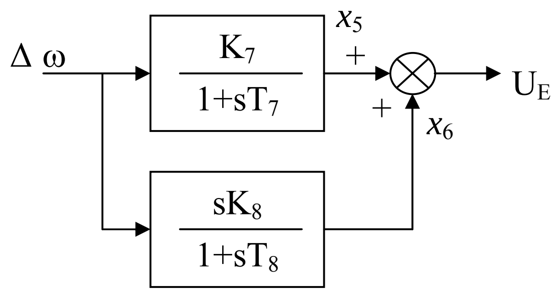


**Figure 2 the proposed PSO-based PSS**

A Particle Swarm Optimization Toolbox (PSOt) for use with the Matlab scientific programming environment has been developed in [13]. It is modified and employed to get the optimal values of parameters according to the given predefined ranges. In addition to the main PSO program, additional programs were designed to get the state-space representation of the system. The sequence is as follows:

1. Identify the system to be stabilized.
2. Select the PSS configuration.
3. Make a complete analog and state-space model for the power system.
4. Choose the function to be optimized (objective function).
5. Derive a function program to evaluate the objective function for the stabilized system as a function of the system parameters to be estimated.
6. The main PSO program is started and given the following data:
   (a) The function to be optimized.
   (b) The number of parameters to be optimized, and their search ranges.
7. The proposed PSS with the selected parameters is examined by using the real time simulation and eigenvalue analysis
8. Evaluation of obtained results.

***Objective function:***

To increase the system damping, the eigenvalue-based objective function is considered as follows:

$$J = \max\{\mathrm{Re}\,al\,(\lambda_i)\ \} \tag{7}$$

where $\lambda_i$ is the i$^{\text{th}}$ electromechanical mode eigenvalue. In the optimization process, it is aimed to minimize $J$ in order to shift the poorly damped eigenvalues to the left in S-plane. The optimization problem can be formulated as follows:
minimize ($J$) subject to

$$\begin{aligned} k_7^{\min} \le k_7 \le k_7^{\max} \\ k_8^{\min} \le k_8 \le k_8^{\max} \end{aligned} \tag{8}$$

Typical ranges of the optimized parameters are [-100 : 100] for all gains

The dynamic equations of the stabilized system can be written as:
$X^{\bullet}(t) = AX(t)$
The state vector becomes;

$$X(t) = \left[\Delta\omega(t) \quad \Delta\delta(t) \quad \Delta e'_q(t) \quad \Delta E_{FD}(t) \quad \Delta x_5(t) \quad \Delta x_6(t)\right]^T \tag{9}$$

The system A matrix after adding the stabilizing signals becomes:

$$A = \begin{bmatrix} -D/M & -K_1/M & -K_2/M & 0 & 0 & 0 \\ \omega_b & 0 & 0 & 0 & 0 & 0 \\ 0 & -K_4/T'_{d0} & -1/T'_{d0}K_3 & 1/T'_{d0} & 0 & 0 \\ 0 & -K_A K_5/T_A & -K_A K_6/T_A & -1/T_A & K_A/T_A & K_A/T_A \\ K_7/T_7 & 0 & 0 & 0 & -1/T_7 & 0 \\ -DK_8/MT_8 & -K_1 K_8/MT_8 & -K_2 K_8/MT_8 & 0 & 0 & -1/T_8 \end{bmatrix} \tag{10}$$

Using PSO technique the obtained optimum values of the stabilizer gains values are
$K_7$=38.55; $K_8$=10;

Table 1 shows the corresponding system eigenvalues, and damping ratio for all system modes.

Table 1

| eigenvalus | damping ratio |
|---|---|
| -25.73 | 1.00 |
| -20.00 | 1.00 |
| -3.75 ±3.23i | 0.76 |
| -3.5 ±3.0i | 0.76 |

## $\mathcal{H}^{\infty}$ MIXED SENSINSITIVITY PSS [12]:

The $\mathcal{H}^{\infty}$ mixed sensitivity controller has the form :

$$C(s) = -\frac{-0.14875s^3 - 2.9847s^2 - 7.495s + 6.5322}{0.0133s^4 + 0.408s^3 + 4.226s^2 + 2.177s + 0.5859} \tag{11}$$

It is designed in [12] at nominal operating conditions. This PSS is used for the sake of performance comparison with the proposed PSO-based PSS. The block diagram representation of the $\mathcal{H}^{\infty}$-based PSS used is shown in Figure 3. The accelerating torque is employed as input signal to the $\mathcal{H}^{\infty}$-mixed sensitivity PSS. The obtained $\mathcal{H}^{\infty}$-mixed sensitivity PSS data and the corresponding system eigenvalues are given in Appendix B.

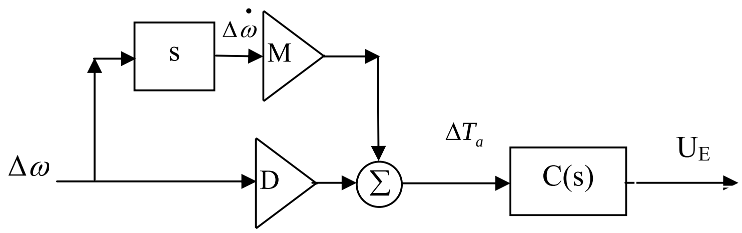


Figure 3 $\mathcal{H}^{\infty}$-based PSS block diagram.

## STUDY CASES

A wide range of operating conditions of the system has been studied. The following loading conditions have been selected to cover the full operating range of the system:

1-Output power = 0.9 +j 0.5 pu
2-Output power = 0.922+j 0.5 pu
3-Output power = 1.0 +j 0.5 pu
4-Output power =1.06 +j0.5pu
5-Output power = 0.922-j 0.5 pu
6-Output power = 0.922+j 0.6 pu
7-Output power =0.2 +j0.13 pu

In addition, to check the robustness of the designed controller, it was tested at different values of system parameters. For this purpose another value of line reactance (X=0.5 instead of X=0.997pu) was considered at output power = 1.0+j0.5 . The input disturbance in all cases is $\Delta T_m$ =0.01pu.

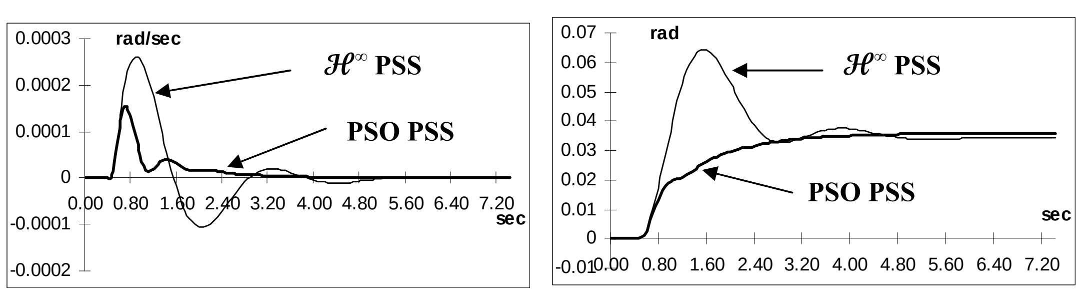


**Figure 4 System dynamic response to $\Delta T_m$ =0.01pu at P=0.9pu, & Q=0.5pu**

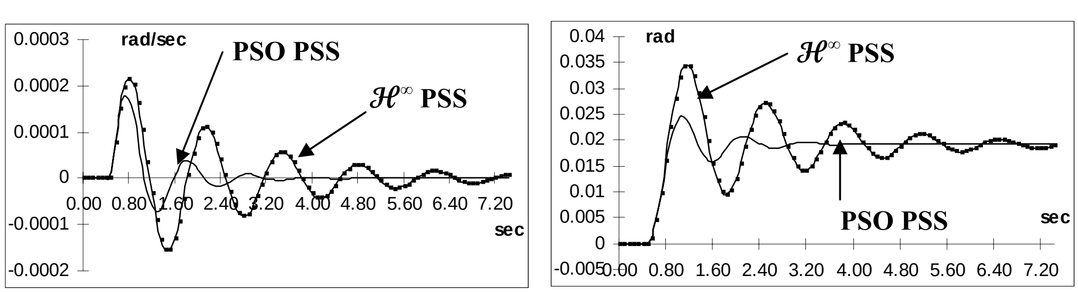

**Figure 5.a System dynamic response at P=0.2pu, & Q=0.13pu**

Table 2 PSO-based system eigenvalues and damping ratios for case in Figure 5.a.

Table 2

| eigenvalues | damping ratio |
|---|---|
| -0.74 ±5i | 0.144 |
| -3.55 | 1 |
| -12 | 1 |
| -23.2 | 1 |
| -20 | 1 |

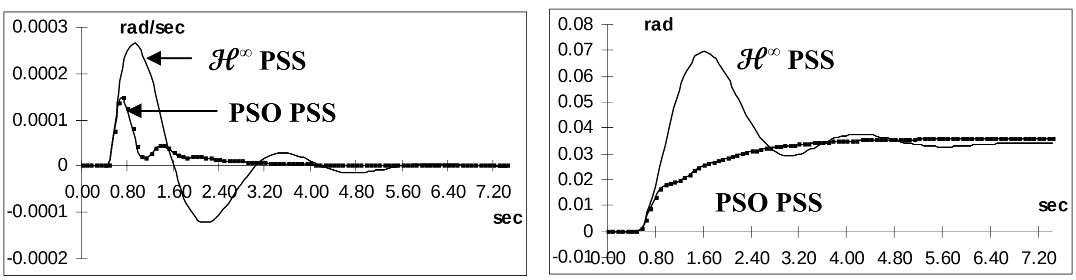


**Figure 5.b System dynamic response at P=1.06pu, & Q=0.5pu.**

Table 3 PSO-based system eigenvalues and damping ratios for case in Figure 5.b.

Table 3

| eigenvalues | damping ratio |
|---|---|
| -26.13 | 1.00 |
| -20.00 | 1.00 |
| -4.6 ±4.7i | 0.7 |
| -2.46 ±2.4i | 0.72 |

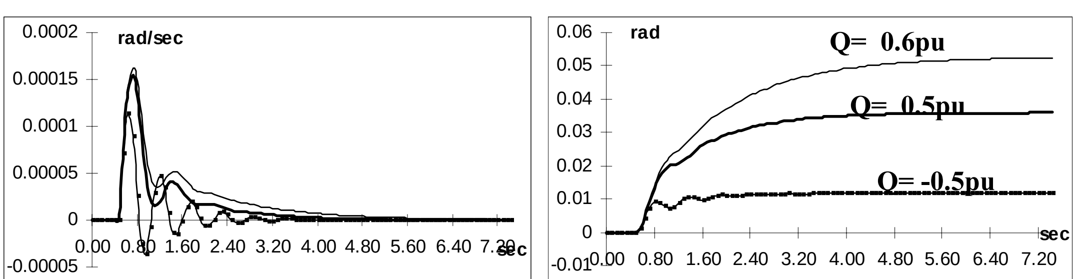

**Figure 6 System dynamic response with PSO based PSS at P=0.922pu.**

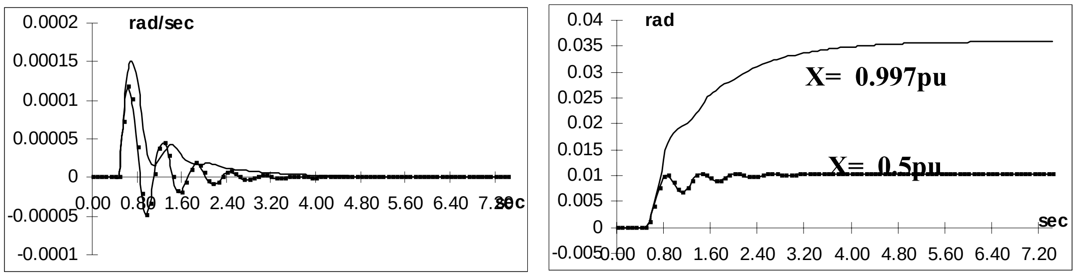


**Figure 7 System dynamic response with PSO based PSS at P=1.0pu, & Q=0.5.**

Table 4 PSO-based system eigenvalues and damping ratios for case in Figure 7.

Table 4

| X = 0.997pu | | X = 0.5 pu. | |
|---|---|---|---|
| eigenvalues | damping ratio | eigenvalues | damping ratio |
| -26 | 1.00 | -26 | 1.00 |
| -20.00 | 1.00 | -20.00 | 1.00 |
| -4.4 ±4.3i | 0.71 | -1.5 ±8i | 0.71 |
| -2.7 ±2.4i | 0.74 | -8.4 | 1 |
| | | -2.7 | 1 |

## Comments On Results:

1. Figure 4 shows a comparison between system response under the effect of the PSO-based PSS and the $\mathcal{H}^{\infty}$-based PSS under the same operating conditions. The figure shows that the PSO-based PSS is more effective than the $\mathcal{H}^{\infty}$-based PSS in damping system oscillations.
2. Figure 5.a shows the effect of another loading conditions on the system response for both the PSO-based PSS and the $\mathcal{H}^{\infty}$-based PSS. This figure assumes that the PSO-based PSS is still better than the $\mathcal{H}^{\infty}$-based PSS at the lowest loading conditions of the generator.
3. Figure 5.b shows the system response under the effect of both PSS's at the highest loading condition of the generator. The figure assures also the superiority of the PSO based PSS at this loading condition.
4. Figure 6 demonstrates the system response under the effect of the PSO-based PSS at different values of reactive power delivered by the generator. The figure shows that the system response becomes worse at higher values of the inductive power and becomes better at capacitive reactive power.

5. Figure 7 shows the system response under the effect of the developed PSO based PSS for two different values of transmission system reactance. The selected reactances could represent a single-circuit (X=0.997pu) and double-circuit (X=0.5pu) operation of the transmission system.
6. The results shown in Figures (4-6) assure the robustness of the developed PSO based PSS at different loading conditions of the system and at different system parameters (Figure 7).

## CONCLUSION:

Throughout this work, PSO-based PSS is designed to suppress low frequency oscillations in a study power system consisting of a single machine with a local load connected to infinite bus bar through a transmission system.

It was sufficient for simplicity to assume single input / single output type PSS's. Comparison with $\mathcal{H}^{\infty}$ mixed sensitivity based PSS confirm the efficiency of the proposed PSO based PSS. Simulation results show that the controller is robust and powerful throughout a wide range of operating conditions and system parameters.

### Appendix A

System parameters of reference [3]:

$f = 60$ Hz, $D \approx 0$, $M = 9.26$ s, $T_{d0}^{/} = 7.76$ s, $x_d = 0.973$, $x_d^{/} = 0.19$,
$x_q = 0.550$, $K_A = 25$, $T_A = 0.05$ s, $R = -0.034$, $X = 0.997$, $G = 0.249$,
$B = 0.262$, $P_{eo} = 0.9$, $Q_{eo} = 0.5$, $V_{to} = 1.05$,

It was declared in [11] that the negative R stems from deriving the one-machine, infinite-bus model for multimachine system by equavalencing smaller generators by equivalent impedances with negative resistances.

### Appendix B

The controlled system eigenvalues in case of the $\mathcal{H}^{\infty}$ mixed sensitivity based PSS are :

| eigenvalues | damping ratio |
|---|---|
| -11.354 ±7.55 | 0.83 |
| -4.945 | 1.00 |
| -1.0036 ±2.63 | 0.36 |
| -0.3508 ±0.30 | 0.76 |

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