International Journal of Natural and Engineering Sciences
E-ISSN: 2146-0086 13 (2): 40-48, 2019

PSO Integral-Derivative Stabilizer Design for Improving Damping in Multi-Machine Power System

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Received: 28 August 2019
Accepted: 13 November 2019

Abstract
In this paper, the design of the parameters of the integral-derivative power system stabilizer (PDPSS) is presented using particle swarm optimization algorithm (PSO). In this method, the parameters of the power system stabilizers will be optimized; furthermore, this method improves the damping coefficient and system damping. The effect of this method is displayed on a multi-machine power system and compared with genetic algorithm (GA). Simulation results indicate that PSO method was more effective than GA and the damping obtained from PSO method is much better than the damping of the GA. Moreover, through estimating and comparing the damping coefficient of the above two methods, the efficiency of the PSO method will be well presented. In the PSO method, the stability of the poles is felt more as well. Finally, the effectiveness of presented method is illustrated on a larger multi-machine power system.

Keywords: Particle swarm optimization algorithm, integral-derivative control, power system stabilizer

INTRODUCTION

One of the most important aspects of power networks is the power system stability [1,2]. During the last few decades, with the development of power systems and the importance of their stability, much attention has been paid to this concept; therefore, different ways to help maintain the power system frequency and voltage in any disturbance have been created [3,4]. These disturbances are the result of sudden load increase, the loss of a generator, changes in transmission line, fault, etc. [5,6]. In general, every power system is accompanied by oscillations; moreover, the frequency and damping of the oscillations is a function of the operating point and network structure. Oscillations which occur in the angle rotor of synchronous generators of the network, due to a change in operating point, and have a frequency of a few tenths of Hz to several Hz, are called low frequency oscillations [7,8]. These oscillations might damp quickly or exist for a long time and even intensified and finally, damage the system and the generator disconnects from the network. This issue depends on the operating point and the values of system parameters. Considering that the network load is variable, the system has to withstand the turbulence and maintain its stability and synchronization [9,10]. Thus, in such circumstances, a power system need to be able to maintain its stability using appropriate controlling methods [11,12].

The stabilizer of the power system is an economic and effective controller utilized to enhance the dynamic stability of a power system. They are one of the best controllers used for damping in the plants. Auxiliary controllers improve the dynamic performance of power systems by the addition of auxiliary signals to the excitation system [13,14]. This equipment is installed on the generator excitation system as a supplementary controller [15]. Through creating electrical torque damping and synchronization, each PSS improves the deviation of the rotor rotation. In fact, by creating positive and negative voltage when needed, PSS adjusts and optimizes the excitation voltage [16]. This stabilizer usually uses signals such as rotor speed, frequency and the power of generator terminal and favorably impacts the small signal stability of system by damping their low oscillation. In addition, this is the most economic method to damp the electro-mechanical oscillations [17]. Given that low-frequency oscillations are due to the lack of necessary damping in the mechanical model of the interconnected system, the additional favorable damping can be provided by supplementary controllers [18]. Various methods have been studied for designing stabilizers. It should be noted that the designing methods for the parameters of stabilizers and controllers should be designed for a non-linear model. Thus, the use of evolutionary algorithms to solve optimization problems are considered in recent years and intelligent algorithms are more acceptable. Classic algorithms are not commonly used due to being time-consuming and having a high computational load. Intelligent algorithms, such as artificial neural network (ANN) are used to design PSSs or locating them. The significance of this algorithm is due to its linearity, versatility and the ability to create a similar structure in analysis, design and production of valid outputs [19]. The use of neural networks to control damping of power system's oscillations is presented in [20]. In [21], the design of PSS using neural network in combination with fuzzy logic is performed on a multi-machine system and was effective on damping. In the fuzzy logic (FL), fuzzy rules and fuzzy membership functions should be well-established which are usually performed by trial and error; moreover, they are time consuming. However, no need to an exact model, simplicity and flexibility of the fuzzy controllers in challenge with nonlinear problems, make fuzzy logic an appropriate method for designing PSS [22]. In [23], PSS was designed using a fuzzy method, along with new optimization methods such as genetic and ants colony.

GA is a special type of evolutionary algorithm that applies biological methods such as inheritance and mutation. Although GA is utilized to simultaneously adjust controllers in different condition, it's not provide significant damping when the situation of stabilizer is changed [24]. The use of the non-dominated sorting GA to achieve an optimal PSS parameters using an eigenvalue-based multi-objective function for a given operating point with a renewable source of energy so as to increase the system damping and guarantee enough stability margin is show in [25]. In [26], by using the participation factor and the GA algorithm, the number and optimal location of PSSs will be determined in a multi-machine system. GA algorithm is used to set the PSS parameters. So that, along with determining the optimal location of PSSs, we could have the lowest number of PSSs with the permitted damping for all modes. Another method is the use of Tabu Search (TS). The advantage of this method is optimization without using differential equations which reduces the computational burden. Moreover, to avoid computing sensitivity factors and eigenvectors, TS is an appropriate method.

PSO algorithm is a computational method that optimizes the problem by iteration-based trying to improve the nominated solution with regard to best possible position [27,28]. PSO algorithm does not use gradient to optimize. In other words, unlike the classical optimization methods, PSO does not need differentiability of the optimization problem. Therefore, PSO can also be used for optimization problem which is partially unusual, noisy, time variant, etc. [29]. PSO algorithm optimizes the problem by a group of solutions and moves the selected particles around the search space and according to simple mathematical formulas [30]. In [31] and [32], an innovative approach has been proposed to design PSS and improve stability using PSO. In [33], design approach for a robust PSS is employed as an optimization problem and in [34], PSO is presented for adjusting and placement in multi-machine systems, with the aim of improving power system stability. According to the control theories, a PD type controller which adopts a signal and its derivation as the input is highly appropriate for adjusting. The concept of using a signal and its derivative as an input for a PDPSS is familiar for many researchers [35].

In this paper, optimized values for the parameters of a PDPSS can be design using the intelligent PSO algorithm. The design problem is formulated as an optimization problem. The stability of the system was improved by minimizing the objective function in the time domain. This performance of this method on a nine-bus system indicates the effectiveness of the proposed method and its ability to provide efficient damping of low frequency oscillations. The method was compared with the method described in [36] which clearly indicates better results and more damping. Finally, the proposed method has been implemented on a larger system with 14 buses and its effectiveness in damping has been approved. This paper is organized as follows: the proposed method is presented in the second part. In the third part, represented power system analysis and the implementation of PSO is presented and dynamic simulation results are presented in part four. Finally, the fifth part concludes the paper and justifies the superiority of the proposed method.

PROPOSED METHOD

To improve systems' performance, especially the complicated multi-machine systems, the present paper uses a method that not only be fast but also produces better results than others. PDPSS is used to increase the speed of performance. In other words, instead of using conventional PSS, the two parameters of K_P and K_D are designed so that if the PDPSS is placed in the system, better results will be achieved. PD controller, in general, eliminates the transient response faster and as a result, the damping increases and the damping ratio of the system increases as well whose results will be seen in the next part. The particle swarm algorithm is used to obtain the optimum value. In the PSO algorithm, the optimization is done by considering the swarm of a number of particles and the intended items are number, velocity, inertia weight, etc. [37]. In this paper, the appropriate K_P and K_D will be calculated based on iteration and finding the optimal value with the PSO algorithm placed in the multi-machine system. This algorithm optimizes the parameters of the stabilizer using the following equations [38,39]:

$$V^i[t] = \omega \cdot V^i[t-1] + C_1 \cdot d_1 \cdot (x^{i,Best} - x^i[t-1]) + C_2 \cdot d_2 \cdot (x^{gBest} - x^i[t-1]) \quad (1)$$

$$x^i[t] = x^i[t-1] + v^i[t] \quad (2)$$

where $x^i[t]$ and $v^i[t]$ are positions and the speed of the ith particle in iteration or the t_{th} moment, respectively. $x^{i,Best}$ and $x\,g^{Best}$ are the best position of the ith particle and the best position experienced among the particles till the t_{th} moment, respectively. W coefficient is called the particle's inertia coefficient. C_1 and C_2 coefficients are own learning coefficient and general learning coefficient, respectively. d_1 and d_2 coefficients are selected as random values between 0 and 1 in the each iteration [40]. To select the initial K_P and K_D in the PSO algorithm, first a function with random normal distribution will be selected. A normal distribution is selected to have completely random initial values of K_P and K_D; therefore, there would not be any tendency towards any side. Then, a cost function, upper limit and lower limit of variables, number of iterations and the total number of particles is determined for the variables. Since an algorithm is obtained based on the random motion of a number particles, the location of these particles, in each phase of iteration, will be optimized based on the existing parameters to achieve the desired optimum location [41]. The flowchart presented in Fig. 1 shows the K_P and K_D selection process and optimization with the help of the PSO algorithm.

The controllers' design is based on the linear control theory. Standard linear system state is determined using linearization of the controlled system around a specific operating point which is stated below [42]:

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

$$Y = CX \quad (4)$$

where X and U and Y represent the system state variables, input vector and vector output, respectively.

Power System model

Fig. 2 presents the three-machine nine-bus power system with three synchronous generators and three bus load. The first generator is considered with an infinite bus. First order differential equations for modelling each synchronous generator installed in buses are presented in equations 5-8 which define system.

The information about the system are presented in [43,44]:

$$\frac{d\delta_i}{dt} = \omega_{ri} \quad (5)$$

$$\frac{d\omega_i}{dt}=\frac{1}{J_{Mi}}T_{Mi}-\frac{E'_{qi0}}{J_{Mi}}I_{qi}+\frac{X'_{di}I_{di0}}{J_{Mi}}I_{qi}+\frac{X'_{di}I_{qi0}}{J_{Mi}}I_{di}-\frac{I_{qi0}}{J_{Mi}}E'_{qi}-\frac{X'_{qi}I_{di0}}{J_{Mi}}I_{qi}-\frac{X'_{qi}I_{qi0}}{J_{Mi}}I_{di}-\frac{D_i}{J_{Mi}}\omega_i \quad (6)$$

$$\frac{dE'_{qi}}{dt}=\frac{E'_{qi}}{T'_{d0i}}-\frac{(X_{di}-X'_{di})I_{di}}{T'_{d0i}}+\frac{E_f}{T'_{d0i}} \quad (7)$$

$$\frac{dE_f}{dt}=\frac{1}{T_A}[K_A(V_{REFi}-V_i+V_{PSSi})-E_F] \quad (8)$$

where δ_i, ω_i, E'_{qi} and E'_{Fi} (i=1,2) are the rotor angle in radians, speed in seconds/radian, transient voltage of exciter field and the excitation transient voltage from the armature perspective. Moreover, T'_{doi}, T_{Ai}, and K_{Ai} are the time constant of the field circuit, the excitation time constant and excitation gain, respectively [45].

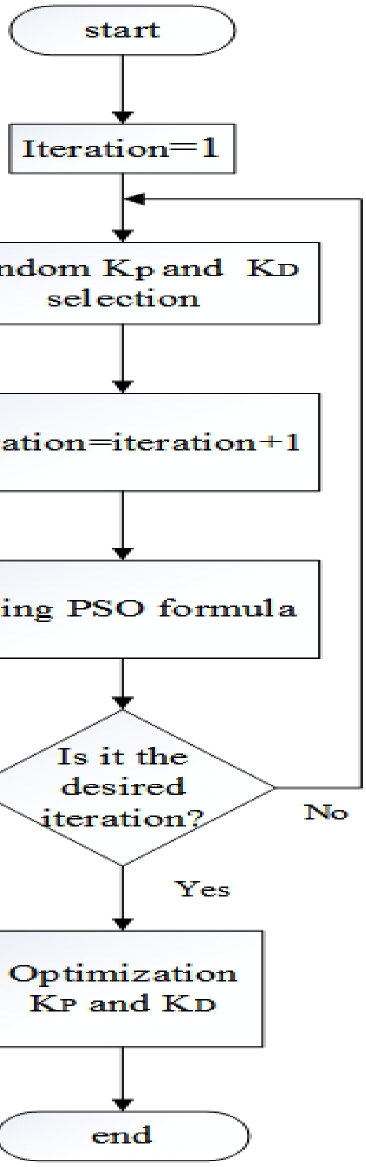

Fig. 1. PSO algorithm performance

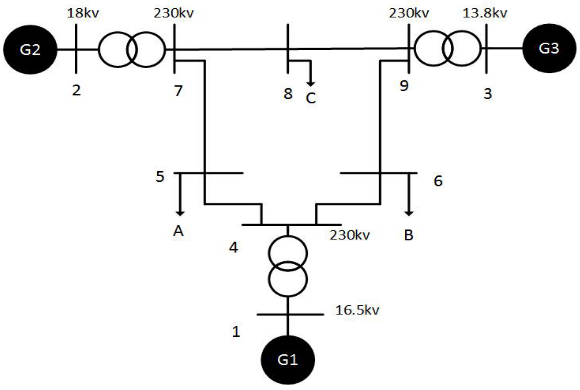

Fig. 2. Nine-bus system diagram

In the output vector, the speed deviation in the rotor of the generator 2 and generator 3 are considered as follows:

$$Y=\left[\Delta\omega_2 \quad \Delta\omega_3\right]^T \quad (9)$$

The vector X is define in (10). By linearization of the test system around the operating point and by ignoring PSSs and using K_P and K_D obtained from [36], after calculations, the state matrix A of the power system without PSS is A_{SYS} in (11). PSS is modelled with the help of the differential equation as shown in (12) [36]. Here U is considered as the PSS input signal. The rotor speed deviation in each synchronous generator is considered as the PSS input signal and the control law of PSS is as (13).

$$X = \left[\delta_2 \quad \Delta\omega_2 \quad E'_{q2} \quad E_{\text{Đ} \, 2} \quad V_{PSS2} \quad \delta_3 \quad \Delta\omega_3 \quad E'_{q3} \quad E_{\text{Đ} \, 3} \quad V_{PSS3}\right]^T \qquad (10)$$

$$A_{SYS} = \begin{bmatrix} 0 & 377 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -0.1966 & 0 & -0.2282 & 0 & 0 & 0.0489 & 0 & 0.0496 & 0 & 0 \\ -0.3539 & 0 & -0.4937 & 0.1667 & 0 & 0.1046 & 0 & 0.1584 & 0 & 0 \\ -1.8599 & 0 & -26.0984 & -2 & 5 & -1.7498 & 0 & -8.7201 & 0 & 0 \\ 0 & 0 & 0 & 0 & -5 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 377 & 0 & 0 & 0 \\ 0.1078 & 0 & 0.1299 & 0 & 0 & -0.3266 & 0 & -0.3697 & 0 & 0 \\ 0.1366 & 0 & 0.2393 & 0 & 0 & -0.4074 & 0 & -0.5987 & 0.1698 & 0 \\ 1.9029 & 0 & -9.0434 & 0 & 0 & -6.7003 & 0 & -23.4312 & -2 & 5 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -5 \end{bmatrix} \qquad (11)$$

$$\dot{V}_{PSS} = \frac{1}{T_{PSS}}(U - V_{PSS}) \qquad (12)$$

$$U = K_P \Delta\omega + K_D \Delta\dot{\omega} \qquad (13)$$

The block diagram which is the generator of the PSS input signal, using PD controller and according to the above equation, is presented in Fig. 3. In this block diagram, speed deviation and its derivative are multiplied by K_P and K_D coefficients optimized using PSO algorithm respectively, and their sum makes the control input.

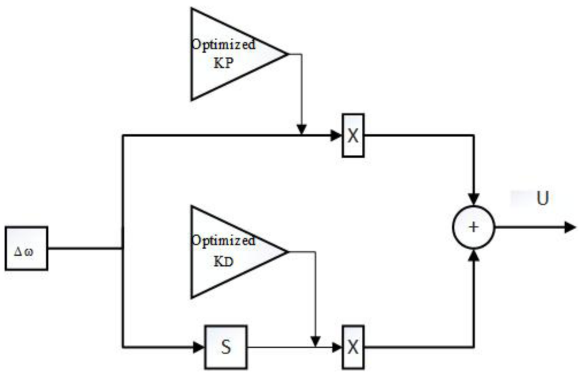

Fig. 3. Block diagram of the proposed method

Fig. 4 presents the steps of PSO method optimization iteration where the horizontal axis is the number of iteration phases and the vertical axis is the damping rate of the system. As it can be seen in this figure, after about a hundred iterations, the damping rate will converge to the optimal rate. In the PSO algorithm, the system damping rate is the objective function whose aim is the optimization of the system damping rate and reducing low frequency oscillations. Table 1 presents the optimal K_P and K_D results obtained for both generators.

Table 1. Optimal values of K_P and K_D

	G_2	G_3
K_P	-5.1033	-8.7702
K_D	-19.9161	-19.9803

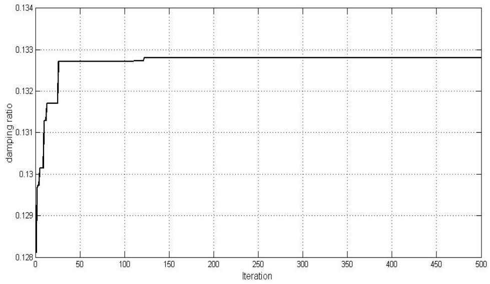

Fig. 4. Optimization diagram for the number of iterations in PSO algorithm

The state matrix of the 9-bus power system with the proposed PSS is ASYS in (15).

$$A_{SYS} = \begin{bmatrix} 0 & 377 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -0.1966 & 0 & -0.2282 & 0 & 0 & 0.0489 & 0 & 0.0496 & 0 & 0 \\ -0.3539 & 0 & -0.4937 & 0.1667 & 0 & 0.1046 & 0 & 0.1584 & 0 & 0 \\ -1.8599 & 0 & -26.0984 & -2 & 0 & -1.7498 & 0 & -8.7201 & 0 & 0 \\ 19.5811 & -25.5165 & 22.7238 & 0 & -5 & -4.8679 & 0 & -4.9396 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 377 & 0 & 0 & 0 \\ 0.1078 & 0 & 0.1299 & 0 & 0 & -0.3266 & 0 & -0.3697 & 0 & 0 \\ 0.1366 & 0 & 0.2393 & 0 & 0 & -0.4074 & 0 & -0.5987 & 0.1698 & 0 \\ 1.9029 & 0 & -9.0434 & 0 & 0 & -6.7003 & 0 & -23.4312 & -0.0050 & 0 \\ -10.7737 & 0 & -12.9764 & 0 & 0 & 32.6253 & -43.8510 & 36.9362 & -2 & -5 \end{bmatrix} \quad (14)$$

The intended PSS was designed with the help of PSO algorithm so that the optimal K_P and K_D can be obtained by a specified iteration. In this method, with faster calculations and only using one intelligent algorithm, much better results have been obtained which are as follows.

Simulation Results

Eigenvalues of the system, in the three states, namely without PSS, GAPSS and PSOPSS have been presented in Table 2.

Table 2. Eigenvalues

proposed method (PSOPSS(	GAPSS [36]	without PSS
j11.17 ± 1.497-	j11.276± -1.08	j11.67 ± -0.29
j7.083 ± -1.421	j2.538 ± -1.068	j7.9 ± -0.18
j3.09 ± -0.799	j7.458 ± -0.734	j1.996 ± -0.997
j2.128 ± -1.571	j1.527 ± -1.78	j0.96 ± -1.077
-2.91 -1.6	-3.872 -1.894	-1 -5

In the without PSS, the eigenvalues are mentioned without power system stabilizer and in the GAPSS, the system eigenvalues indicate a state in which K_P and K_D are obtained using a GA mentioned in [36]. And finally, in the PSOPSS state, the system eigenvalues are obtained by determining K_P and K_D with the help of PSO algorithm to be able to compare the three abovementioned states.

In Table 3, the damping ratio of the system modes are presented in three states, namely non- PSS, GAPSS and PSOPSS. The improvement of damping ratio of system modes in PSOPSS state is clearly identified in comparison with the other two states. In the proposed method, damping ratio has reached to 0.1967, which in comparison with 0.098 obtained from the GA, shows a significant improvement.

Table 3. Damping ratio

proposed method (PSOPSS(	GAPSS [36]	without PSS
0.1328	0.0954	0.0248
0.1967	0.0388	0.0229
0.2503	0.098	0.4469
0.594	0.0759	0.7467
1	1	1

The simulation results of the three states are presented in Figs. 5 and 6. Those present the generator 2 and the generator 3 rotor angular speed deviation in the above-mentioned states, respectively. It is evident that the system performance is the PSOPSS state is much better than the other two states and system damps much faster and with less oscillations. Optimal damping ratio presented in the Table 3 along with rotor speed response graph evidently indicate the effectiveness of the proposed method.

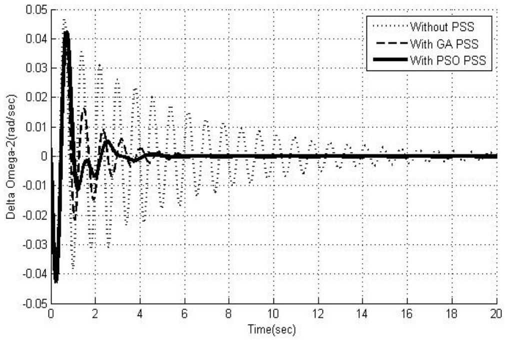

Fig. 5. Rotor speed response of generators 2

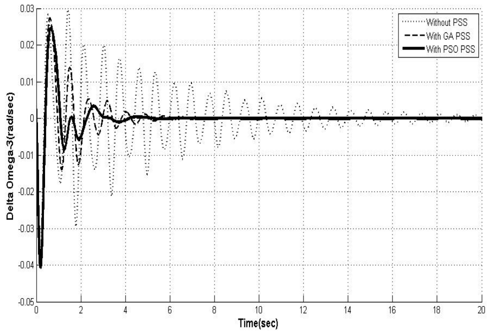

Fig. 5. Rotor speed response of generators 3

Fig. 7 presents the graph of the system poles. As it can be seen, the system poles, when the PSO algorithm is used, have better stability and incline to the left imaginary axis which indicates the effectiveness of the proposed method.

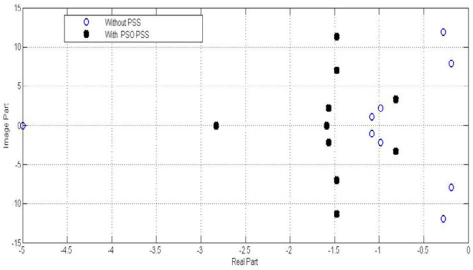

Fig. 7. Graph of the system poles

To demonstrate the impact of the proposed method on damping of the system oscillations, simulation has been implemented on a 14-bus system using MATLAB software and the results has been obtained. Fig. 8 shows the diagram of a 14-bus system. This system is a five machine system whose first generator is considered as slack. The simulation was performed with 20% overload; however, the system is well damped.

The optimization iteration phases of the PSO method are presented in Fig. 9. In this figure, the horizontal axis indicates the number of iteration phases and vertical axis indicates the damping rate of the system. It is clear that after about a hundred and fifty iterations, the damping rate will converge to the optimal rate. In the PSO algorithm, the objective function is the damping rate of the system aimed at optimizing the damping rate of the system and reducing the low frequency oscillations.

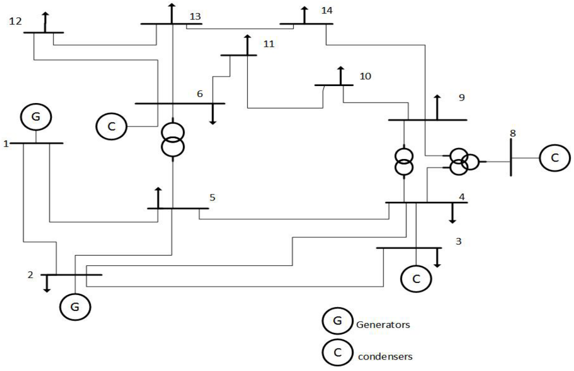

Fig. 8. Block diagram of the power system

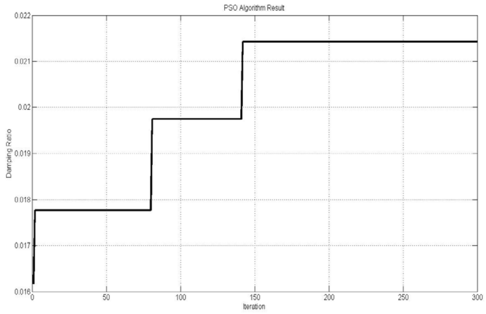

Fig. 9. Optimization for the number of iterations in the PSO algorithm

Table 4 presents the K_P and K_D optimal results obtained from PSO algorithm for all machines. The damping ratio of system modes, in without PSS and PSOPSS are presented in Table 5. The improvement of the damping ratio of system modes, in the PSOPSS state is clearly identifiable in the comparison with the other state. In the proposed method, the damping ratio in comparison with the non-PSS system reveal a significant improvement.

Table 4. K_P and K_D optimal values

	G_2	G3	G4	G5
K_P	-81.4207	-81.4296	-99.6043	-74.4861
K_D	-0.8229	-1.1602	-3.2619	-0.6608

Table 5. Damping ratio

PSOPSS	without PSS
0.0249	0.0167
0.0235	0.0151
0.0207	0.0205
0.9872	0.0186
1	1

The simulation results in these two abovementioned states are presented in Fig. 10. It shows the generator rotor angular speed deviation in the abovementioned states. It is clear that the system performance in the PSOPSS state is much better than the other states and the system damps much faster and with less oscillations. Optimal damping rate presented in Table 5 along with the rotor speed response graph clearly indicates the effectiveness of the proposed method.

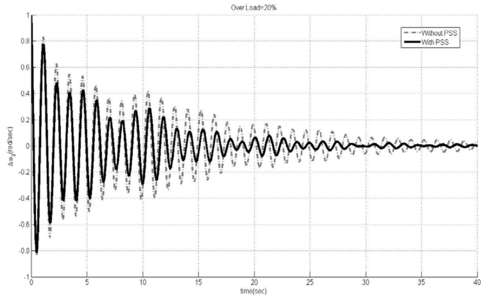

Fig. 10. Generator rotor speed response diagram

CONCLUSION

In this paper, the use of PDPSS for the power system oscillations' damping were investigated and the particle swarm intelligent algorithm was used to improve the PSS parameters. The results are better than similar algorithms, specifically, the proposed method was compared with the genetic algorithm in this paper and the simulation results clearly indicate the superiority of the proposed method. As it has been stated in this paper and the results can be seen in the tables, damping ratio of the system has considerably increased and the damping of the 9-machine system is improved. At the same time, the computing has increased compared with the previous methods and there is no need to spend a lot of time to find the optimal values. To indicate the effectiveness of the proposed method, it was implemented on a larger system which is a 14-bus system with 5 machines. The results indicated that the damping ratio has been improved and the system oscillations have reduced and damped which clearly reveals the superiority of the proposed method.

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