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DAMPING LOW FREQUENCY OSCILLATIONS IN POWER SYSTEMS USING ITERATION PARTICLE SWARM OPTIMIZATIONS

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ABSTRACT

The major concern in power systems has been the problem of low frequency oscillations (LFO) that results in the reduction of the power transfer capabilities. The applications of power system stabilizers (PSS) are commonly employed to dampen these low frequency oscillations. The parameters of the PSS are tuned by considering the Heffron-Phillips model of a single machine infinite bus system (SMIB). Tuning of these parameters for the system considered can be done using iteration particle swarm optimization (IPSO) technique in this paper; mainly the lead lag type of PSS was used to damp these low frequency oscillations. The proposed technique (IPSO)'s capabilities are compared with the traditional PSO and genetic algorithm (GA) technique in terms of parameter accuracy and computational time. Also the results of nonlinear simulations and eigenvalue analysis reveals that, the IPSO is much better optimization technique as compared to traditional PSO and GA.

Keywords: heffron phillips model, iteration particle swarm optimization, low frequency oscillations, single machine infinite bus, power system stabilizers.

1. INTRODUCTION

Electric power systems are complicated interconnection nonlinear systems and constantly experience variations in generation, transmission and distribution of electric power. Most of the problems of power system stability are associated with the low frequency oscillation in the interconnected power systems [1], especially in the deregulated set up. The stability in power systems is one of the most important aspects in electric power systems [2]. Papers should be written in English and submitted in final camera-ready form. All text has to be edited by using the styles defined in this document.

Continuously occurring complexities of electric power systems has added exciting curiosity in developing effective solutions for Power System Stabilizers (PSS) design in an interconnected power systems to damp low frequency oscillations. In the deregulated settings, power systems are largely interconnected causing spontaneous system upsets at very low frequencies, electromechanical oscillations are normally referred to as weak damping in the oscillatory mode and it occurred usually in the frequency ranging from 0.2-3.0 Hz [3]. Once started, they would continue for a long period of time. In some cases, they continue to grow, causing system separation and also have adverse effect and limitations on the power-transfer capability if adequate damping is not provided [4]. These low frequency oscillations are related to the small signal stability of a power system.

However, to overcome this effect, power system damping device must be provided, the devices that are most suitable for damping both local mode and inter-area mode of small signal LFO by increasing the system damping are the PSS, thus enhancing the dynamic stability and improve transfer capability of the power systems. PSS are then installed to the synchronous generator to provide to the excitation system an enhancement feedback stabilizing signals in the excitation system [5]. Among the families of PSS, nominal structured lead-lag power system stabilizers known as (CPSS) is the most preference shared by most power Engineers and the gadgets, because it is easier to make the tuning online and its certainty associated with other variables [6], [7].

Transient and dynamic stability considerations are among the main problems militating against the reliable and efficient operation of power systems in deregulated environment [8], [9]. The problem of PSS parameters tuning have been considered by various optimization techniques as the efficient techniques. To give more chances to the tuning processes, numerous techniques have been proposed for the design, among which are the intelligent optimization methods [10], [11], [12], many other different techniques have been reported [13], [14], [15].

This article deals the tuning concept and the stability improvement to a test system (SMIB) using iteration particle swarm optimization. To show the effectiveness of the proposed algorithm, this method is compared with the GA based PSS given in [11] and the traditional PSO based PSS. The paper is arranged as follows; the linearization of the study system is described next and followed by a brief overview of lead-lag PSS in section 3. A brief description of GA, PSO and IPSO algorithms are provided in section 4. Simulation results and discussion are drawn in section 5 and finally conclusion was presented in section 6.

2. LINEARIZED MODEL OF A TEST SYSTEM FOR SMALL SIGNAL STABILITY

A single machine connected to infinite bus (SMIB) system is the system under consideration for the present investigations. A group of machines in a given power station can be considered as a single machine, when connected through a transmission line to a large system may be linearized to a SMIB system, by using Thevenin's equivalent of the transmission network external to the machine [16].

In this section, study of small signal performance of a single machine connected to a large system through transmission lines is carried out. A general system configuration is shown in Figure-1. Analysis of system having such simple configurations is greatly necessary in knowing the fundamental effects and concepts. After developing an appreciation for the physical aspects of the phenomena and gain experience with the analytical techniques, using simple low-order systems, we will be in a better position to deal with larger and complex systems. Figure-2 depicted an overall block representation of the test system with PSS. This machine is taken as the fourth order, two axis synchronous machine model. Considering the two-axis synchronous machine field winding in the direct axis without damper windings for the analysis, the equations representing the steady state process of operation of the synchronous machine connected via a transmission line with external reactance to infinite bus can be linearized as follows:

$$\Delta T_m - \Delta P = M\frac{d^2\Delta\delta}{dt^2} \tag{1}$$

$$\Delta P = K_1\Delta\delta + K_2\Delta E'_q \tag{2}$$

$$\Delta E'_q = \frac{K_3}{1+sT'_{do}K_3}\Delta E_{fd} - \frac{K_3K_4}{1+sT'_{do}K_3}\Delta\delta \tag{3}$$

$$\Delta V_t = K_5\Delta\delta + K_6\Delta E'_q \tag{4}$$

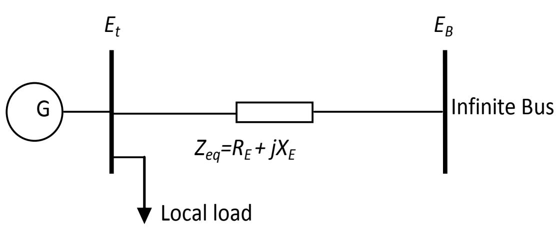

Figure-1. Single machine connected to a large power system through transmission lines.

There are six constants K_1 to K_6 that describes the relation between the rotor speed and voltage control equations of the machine which are termed as Heffron-Phillips constants. They are dependent on the machine parameters and the operating conditions. Generally K_1, K_2, $K_3$and K_6 are positive. K_4 is mostly positive except for cases where R_E is high. K_5 can be either positive or negative. K_5 is positive for low to medium external impedances ($R_E + jX_E$) and low to medium loadings. K_5 is usually negative for moderate to high external impedances and heavy loadings [17]. The constants K_1 to K_6 known as Heffron Phillips constants are computed using the following expressions:

$$K_1 = \frac{E_bE_{qo}\cos\delta_o}{x_e+x_q} + \frac{(x_q-x'_d)}{(x_e+x_q)}E_bi_{qo}\sin\delta_o \tag{5}$$

$$K_2 = \frac{(x_e+x_q)}{(x_e+x'_d)}i_{qo} = \frac{E_b\sin\delta_o}{(x_e+x'_d)} \tag{6}$$

$$K_3 = \frac{(x_e-x'_d)}{(x_e+x_d)} \tag{7}$$

$$K_4 = \frac{(x_d-x'_d)}{(x_e+x'_d)}E_b\sin\delta_o \tag{8}$$

$$K_5 = \frac{-x_qv_{do}E_b\cos\delta_o}{(x_e+x_q)V_{to}} - \frac{x'_dv_{qo}E_b\sin\delta_o}{(x_e+x'_q)V_{to}} \tag{9}$$

$$K_6 = \frac{x_e}{(x_e+x'_d)}\left(\frac{V_{qo}}{V_{to}}\right) \tag{10}$$

Terms with subscript 0 are computed using the expressions given in the Appendix. From the linearized block diagram of Figure-2, the state space form of linear differential equations can be written as [18] follows:

$$\dot{x} = Ax+Bu, \quad y = Cx+Du \tag{11}$$

Where

$$x^T = \left[\Delta\omega \quad \Delta\delta \quad \Delta E'_q \quad E_{fd}\right] \tag{12}$$

$$A = \begin{bmatrix} -\frac{D}{2H} & -\frac{K}{2H} & -\frac{K_2}{2H} & 0 \\ \omega & 0 & 0 & 0 \\ 0 & -\frac{K_4}{T'_{do}} & -\frac{1}{T'_{do}K_3} & -\frac{1}{T'_{do}} \\ 0 & -\frac{K_EK_5}{T_E} & -\frac{K_EK_6}{T_E} & -\frac{1}{T_E} \end{bmatrix} \tag{13}$$

$$B^T = \begin{bmatrix} 0 & 0 & 0 & \frac{K_E}{T_E} \end{bmatrix} \tag{14}$$

The system parameters and the operating conditions are controlled by the matrix A as its function while control matrix B controlled only the parameters. The system eigenvalues are obtained from the system matrix by considering the system parameters and operating conditions. The system without PSS is considered as an open loop system whose transfer function $G(s)$ is to be computed using the state equations and matrices [11].

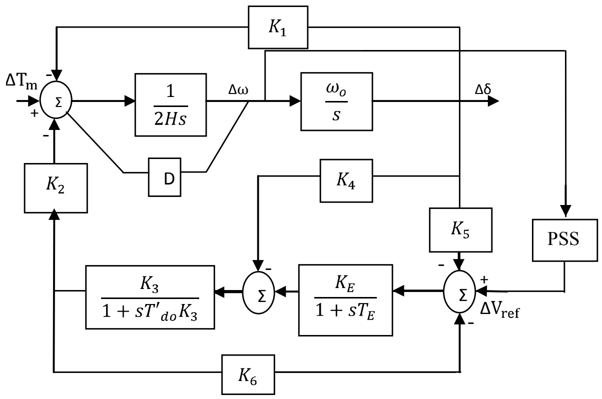

Figure-2. Overall block diagram of SMIB with PSS.

3. POWER SYSTEM STABILIZERS

PSS is a controller device that is installed to synchronous generator so as to improve the damping of power systems LFO. PSS provides an electrical damping torque *(ΔTe)* in phase with the speed deviation *(Δω)* so as to enhance damping of power system oscillations [16]. As referred before, many different methods have been applied to the design of PSS so far [19]. The structure of PSS comprises of two-stages of phase compensation blocks, a signal washout block and a gain block with gain K_{STAB}, Hence, its transfer function is:

$$V_s = K_{STAB}\left(\frac{T_w}{1+sT_w}\right)\left[\frac{(1+sT_1)}{(1+sT_2)}\frac{(1+sT_3)}{(1+sT_4)}\right]\Delta\omega(s) \tag{15}$$

Where V_s is the output voltage signal and $\Delta\omega$ is the rotor speed perturbations. The signal washout block (T_w) acts as a high-pass filter, the signals which is described with oscillations is allowed to pass unaltered in this block, while denying modification of the terminal voltage [9]. The value of T_w is normally not sharp and can be chosen within 0.2 - 20s [20]. The phase compensation blocks with time constants T_1, T_2 and T_3, T_4 gives the required phase-lead characteristics to compensate for the phase lag between the exciter and the resulting electrical torque. The time constants Tw, T_3 and T_4 are usually pre-specified. In this study, a new optimal method based on the IPSO is considered to tuning parameters of PSS. In the next section, the proposed method is briefly introduced and then designing the PSS based on the proposed methods will be carried out.

4. OVERVIEW OF APPLIED OPTIMIZATIONS METHODS

This section provides the description of the optimization methods that has been used in this paper to measure the effectiveness of the proposed IPSO with namely GA and the standard PSO. After presenting the important guide on the operation of GA, the procedural form of Standard PSO is given on which the IPSO is developed.

A. Genetic algorithms

Genetic Algorithms is a probabilistic search approach and it is inspired by evolution of living organisms and a family of computational models [21]. The algorithm can be converted into a coded form of a desired outcome to a specific case on a simple family data structure and apply cross over operators to these structures as to maintain desired solution. The normal features in genetic algorithm are described one after the other below, which is generally referred to as a breeding cycle [22].

Selection (Reproduction): The process of picking two parents out of the members of the family for crossing is referred to as selection. Generally Selection preserves the integrity of the individual populations and to inject hope in their off spring to have larger fitness. In order to have parents for reproduction, the genetic information in the form of genes in most living cell is selected from the initial population.

Crossover (Recombination): This refers to when two parents solutions are considered and from them produces a child, the process is called recombination or crossover. After the process, the individuals of that population is blessed with better solutions [11]. A group of organisms makes better strings but does not formulate new ones as a result of reproduction.

Mutation: The strings are compelled to mutation after crossover. Mutation keeps away the algorithm from being trapped by local minimum; Mutation recovers the lost genetic integrity as well as for randomly disturbing genetic information [23]. Mutation helps in maintaining the exploration of the whole search space if crossover exploits the current solution as a result of finding better ones.

Replacement: Fixed size population determines the pair of parents, if for instance breeding two children, found that not all can come back to the population size, as a result two must be replaced. This clearly shows that once off springs are produced, the algorithm must obtain which of the current family member if any, should be replaced by the new solutions [11].

These operations are carried out in Genetic Algorithm toolbox in MATLAB 7.12 environment which the following fitness function has to be defined. The problem of computing optimal solutions of a single power system stabilizer for different operating points implies that power system stabilizer must stabilize the family of N plants [11]:

$$\dot{X} = A_k X + B_k U, \quad where\ k = 1,2,3...N \tag{16}$$

Where *X (t)* is the state vector and *U (t)* is the input stabilizing signal. The important and sufficient conditions for the stability of the system with stabilizing signal is that, eigenvalues of the closed-loop system must be found in the left- hand side of the complex s-plane. The condition stated above attract interest in finding the parameters K_{STAB}, T_1, T_2, and T_w of the power systems

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stabilizers and their selection to minimize the following fitness function [11]:

$$J = \text{Re}\max(\lambda_{i,k}),\ i = 1,2,3...N \tag{17}$$

Where $\lambda_{i,k}$ is the K_{th} closed-loop eigenvalues of the i_{th} system. If a results are found such that $J < 0$, then the resulting parameters K_{STAB}, T_1, T_2, and T_w should be enough to stabilize the entire system under consideration. The procedure for the implementing the GA toolbox can be found in [11].

B. Particle swarm optimization

The PSO algorithm was first developed by Kennedy and Eberhart in 1995. The technique was established through a simulation of social behaviors of animals such as fish and birds where they are moving in the group to the food source location. The main advantage of PSO compared to others optimization techniques is due to the PSO concept that is simple and cause the algorithm need to have a few memories only. Furthermore, the PSO algorithm also required small computation time for the optimization compared to some optimization techniques [17].

By taking birds as an example in this case study, some of the birds are flocking together when looking for the food in the real life. These birds can only maintain in the group when the multitude of information is jointly possessed together during flocking. Therefore, at all time, the behavioral pattern on each individual bird in the group is changes based on several behavioral patterns authorized by the groups such as culture and the individual observations. These methodologies are the basic concepts of PSO. The modification of the individual bird position is realized by the previous position and velocity information [24]. Thus, the modification on the position of each bird (or known as particle) is presented by the velocity concept as shown in (18).

$$V_i^{k+1} = wV_i^k + c_1 r_1 (P_{best-i}^k - X_i^k) + c_2 r_2 (G_{best}^k - X_i^k) \tag{18}$$

From the equation, the velocity of any particle will be based on the summation of 3 parts of equation that consist of specific coefficient individually. The w in the first part is an inertia weight which represents the memory of a particle during a search process while the c_1 and c_2 are showing the weights of the acceleration constant that guide each particle toward the individual best and the global best locations respectively. Furthermore, the r_1 and r_2 parameters are the random numbers that distributed uniformly between (0, 1). Therefore, the effect of each particle to move either toward the local or global best is not only depended on c_1 and c_2 value, but it is based on the multiplication of c_1r_1 and c_2r_2. All these coefficients will give an impact on the exploration and exploitation of PSO in searching the global best result. As a result, every individual particle will change its location based on the updated velocity using the equation below:

$$X_i^{k+1} = X_i^k + V_i^{k+1} \tag{19}$$

C. Iteration particle swarm optimization

In this paper, IPSO method is considered for tuning lead lag type PSS. The IPSO method is an improvement of PSO technique that has been proposed by Lee, T.Y. and C.L. Chen, [25] to enhance the solution quality and computing time of the algorithm. In the algorithm, three best values are used to update the velocity and position of the particles which are $G_{best,}$ P_{best} and I_{best}. The definition and the method to find the P_{best} and G_{best} values in the IPSO are similar as traditional PSO where P_{best} is defined as the best solution that has been achieved by individual particle until the current iteration while the G_{best} is the best value among all particles in the population. In other word, each particle will have their own P_{best} value but the G_{best} is only a single value at any iteration. Meanwhile, the new parameter I_{best} is defined as the best point of fitness function that has been attained by any particle in the present iteration and causes the improvement in searching process of IPSO. Same as P_{best} and G_{best}, the I_{best} value will be updated when current I_{best} value better than previous I_{best} value. If not, the previous I_{best} value will remain as the I_{best} result. Furthermore, the authors also introduced the dynamic acceleration constant parameter, c_3 which is presented as follows:

$$c_3 = c_1(1 - e^{-c_1 k}) \tag{20}$$

Where k = the number of iterations. Therefore, the new velocity of the proposed algorithm can be updated as follows:

$$V_i^{k+1} = wV_i^k + c_1 r_1 (P_{best}^k - X_i^k) + c_2 r_2 \\ (G_{best}^k - X_i^k) + c_1(1 - e^{-c_1 k})(i_{best}^k - X_i^k) \tag{21}$$

The flow chart of the IPSO is shown in Figure-3. Most of the steps for the IPSO are similar to the traditional PSO; the slight difference appears during finding the new velocity for updating the new position. With the *Ibest* parameter, the improvement on searching capability and increases on efficiency of the IPSO algorithm in achieving the desired results in power system stabilizers design is attained. The eigenvalues of the whole system can be obtained from the linearized test system model shown in Section 2. Furthermore, same as previous discussion, the fitness function for the IPSO is also:

$$J = \text{Re}\max(\lambda_{i,k}),\ i = 1,2,3...N \tag{22}$$

Where λ_i is the K_{th} eigenvalue for the i_{th} system and the total number of the dominant eigenvalues is N. The parameters to be tuned through the process are K_{STAB}, T_w, T_1 and T_2 of system generator.

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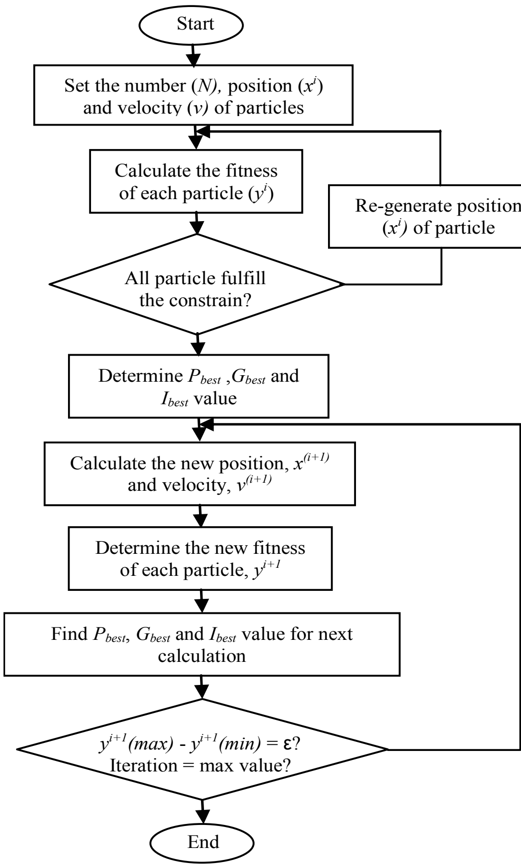

Figure-3. Flow chart of IPSO used for the optimization of PSS parameters.

5. SIMULATION RESULTS AND DISCUSSIONS

The SMIB is used to illustrate the behavior of the proposed IPSO algorithm. The test system data and the operating conditions are given in the appendix. Figure-1 represents the one line diagram of the test system. The system is known to be unstable without PSS and it has been generally adapted as a test system for PSS parameters design problems. The test system may comprise of group of generators as a single generator model, PSS can be connected to all the generators, and generator parameters are modified to add sub-transient parameters. During the tuning process, the constraints considered on PSS time constants T_1 and T_2, washout time T_W and K_{STAB} which are set with the lower and upper limits as constraints on Table-1.

Table-1. Upper and lower limits of control parameter.

Parameters	K_{STAB}	T_w	T_1	T_2
Upper limit	50	20	1.0	0.10
Lower limit	10	1	0.01	0.01

Figure-4 shows the convergence characteristics for the IPSO algorithm. From the results, since the objective function of the optimization is to obtain the minimum value, the IPSO give the lowest fitness value compared to the original PSO. Not only hat, the IPSO also gave the fastest convergence results compared to the PSO algorithm where the convergence value is achieved at the 10th iteration while PSO required nearly 33rd iteration before the results is converged. Although the different between PSO and IPSO is too small (0.003), but it will give an impact to the performance of PSS due to the eigenvalues that is generated by both optimization method.

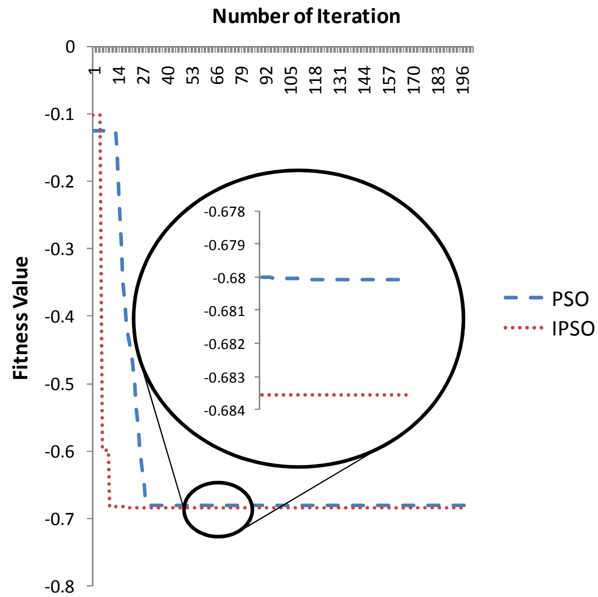

Figure-4. Convergence characteristics of PSO and IPSO based system.

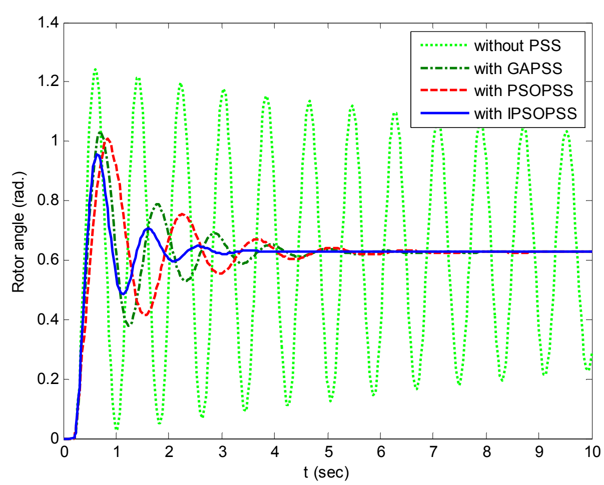

Figure-5. Rotor angle deviation.

Figure-5 presents the rotor angle response of the synchronous machine. It can be observed that the response with IPSO based PSS has the minimum amplitude of oscillation and faster convergence time compared to the GA based PSS and PSO based PSS. If the system without any PSS installed, the amplitude of oscillation keeps reducing gradually, even though it will stabilize, but in a

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very much longer time than necessary. Therefore, the GA based PSS was observed to have minimum overshoot than the system without PSS. Figure-6 shows the results of rotor speed deviation of the synchronous machine. It is clear to see that during all the operation, the IPSOPSS has a best performance than the other method in mitigating oscillations. IPSOPSS convergence characteristics in the damping of power system oscillations are in the range of acceptable requirement. Eventually between IPSOPSS, PSOPSS and GAPSS, IPSOPSS has a very significant better performance than GAPSS where the time that is required for mitigating the oscillation is only 2.5 sec. (second) then 5 sec. and 4.5 sec. for PSOPSS and GAPSS, respectively.

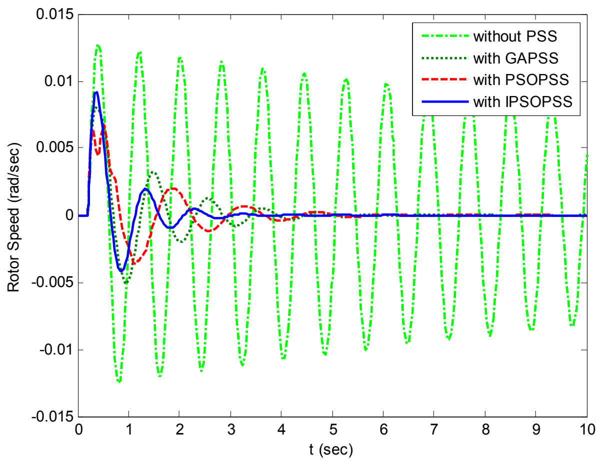

Figure-6. Rotor speed deviation.

Figure-7 shows the deviation of terminal voltage for the system when the optimization results are applied to the PSS. Even though the overshoots of the PSO and IPSO based PSS has higher altitude than the GA based PSS, but the convergence (suppress the oscillation) time is much smaller than GA based PSS. By comparing the performance of GA and IPSO, the IPSO only have 45 percent higher amplitude compared to GA results, but in term of time, the improvement made by IPSO is nearly 100 percent compared to the GA based PSS. The responses obtained clearly shows that the performance of IPSO optimized PSS are better than GA and the traditional PSO optimized PSS in terms of settling time and overshoot. As a conclusion, the IPSO is the superior methods in finding the best parameter of PSS to obtained maximum benefit for the system Table-2. Present the optimal parameters settings of lead-lag PSS for all optimization methods result.

Table-2. Optimal parameters obtained.

Parameter	K_{STAB}	T_w	T_1	T_2
GAPSS[11]	10.541	1.50	0.498	0.10
PSOPSS	14.386	1.50	0.938	0.03
IPSOPSS	19.224	1.50	0.156	0.014

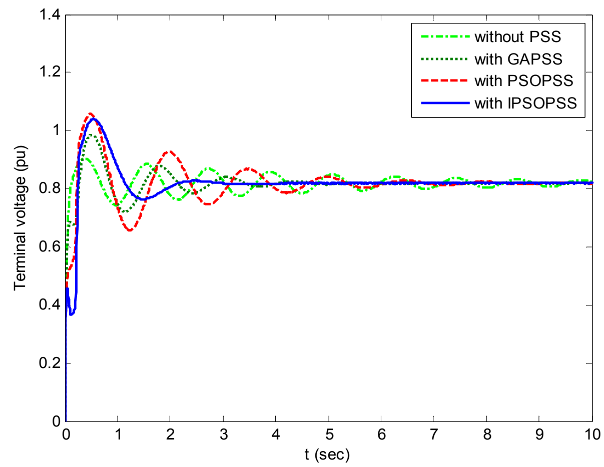

Figure-7. Terminal Voltage deviation.

6. CONCLUSIONS

In this article, a robust optimal tuning process of lead-lag PSS based on Iteration particle swarm optimization has been successfully proposed on a single machine infinite bus system containing system parametric uncertainties and various operating conditions. The fitness functions used in both optimization methods are similar with the similar constrains are applied. The simulation results demonstrated that the designed IPSOPSS can guarantee the robust stability and performance of the power system under a wide range of system operating conditions and system uncertainties. The results are promising and confirming the potential of this algorithm for optimal PSS design.

Appendix

The variables in the computation of K_1- K_6 with subscript 0 are values of variables evaluated at pre-disturbance steady state operating point from the known values of P_0, Q_0 and V_{t0}.

$$i_{qo} = \frac{P_o Q_o}{\sqrt{(P_o x_q)^2 + (V_{to}^2 + Q_o x_o)^2}}, \quad E_{qo} = v_{qo} + i_{do} x_q,$$

$$\delta_o = \tan^{-1}\frac{(v_{do} + x_e i_{qo})}{(v_{qo} - x_e i_{do})}, \quad v_{do} = i_{qo} x_q, \quad i_{do} = \frac{Q_o + x_q i_{qo}^2}{v_{qo}}$$

$$E_o = \sqrt{(v_{do} + x_e i_{qo})^2 - (v_{qo} - x_q i_{do})^2}, \quad v_{qo} = \sqrt{V_{to}^2 - v_{do}^2}$$

The system became a closed loop when the PSS structures described in equation (15) is used as a feedback. The state equation became:

$$\Delta\omega = \frac{-K_1}{2Hs}\Delta\delta - \frac{K_2}{2Hs}\Delta E_q^{'} - \frac{D}{2Hs}\Delta\omega, \quad \Delta\delta = \frac{\omega_B}{s}\Delta\omega,$$

$$\Delta E_{fd} = (-K_5\Delta\delta - K_6\Delta E_q^{'} + \Delta v_2)\frac{K_E}{1+sT_E},$$

$$\Delta v_1 = \frac{(1+sT_1)}{(1+sT_2)}\Delta v_2 \quad \text{and} \quad \Delta v_2 = k\frac{sT_w}{1+sT_w}\Delta v_s.$$

Then the system matrix A became:

$$A = \begin{bmatrix} -\frac{D}{2H} & -\frac{K_1}{2H} & -\frac{K_2}{2H} & 0 & 0 & 0 \\ \omega & 0 & 0 & 0 & 0 & 0 \\ 0 & -\frac{K_4}{T_{do}^{'}} & -\frac{1}{T_{do}^{'}K_3} & -\frac{1}{T_E} & 0 & 0 \\ 0 & -\frac{K_E K_5}{T_E} & -\frac{K_E K_6}{T_E} & -\frac{1}{T_E} & 0 & -\frac{K_E}{T_E} \\ 0 & -\frac{K_{STAB}K_1}{2H} & -\frac{K_{STAB}}{2H} & 0 & -\frac{1}{T_w} & 0 \\ 0 & -\frac{K_{STAB}K_1}{2HT_1} & -\frac{K_{STAB}K_2}{2HT_2} & 0 & -\frac{T_w - T_1}{T_w T_2} & -\frac{1}{T_2} \end{bmatrix}$$

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