Jurnal Teknologi

Full paper

Coordinated AVR-PSS for Transient Stability Using Modified Particle Swarm Optimization

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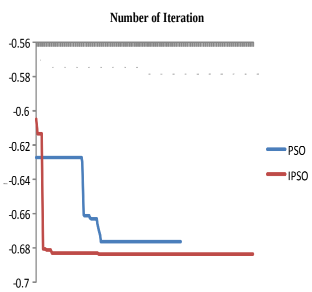
Article history

Received :23 October 2013
Received in revised form :
14 December 2013
Accepted :10 January 2014

Graphical abstract



Convergence Characteristics of PSO and IPSO based Optimization.

Abstract

This paper presents the coordination between the Automatic Voltage Regulator (AVR) and Power System Stabilizers (PSS) to increase the system damping over a wide range of systems' operating conditions in order to improve the transient stability performance and steady state performance of the system. The coordinated design problem is formulated as an optimization problem which is solved using Iteration Particle Swarm Optimization (IPSO). The application of IPSO technique is proposed to optimize the parameters of the AVR and PSS to minimize the oscillations in power system during disturbances in a single machine infinite bus system (SMIB). The performance of the proposed IPSO technique is compared with the traditional PSO technique. The comparison considered is in terms of parameter accuracy and computational time. The results of the time domain simulations and eigenvalue analysis show that the proposed IPSO method provides a better optimization technique as compared to the traditional PSO technique.

Keywords: AVR; coordinated design; IPSO; power system stability; PSS; transient stability

Abstrak

Kertas ini membentangkan penyelarasan di antara Pengatur Voltan Automatik (AVR) dan Penstabil Sistem Kuasa (PSS) bagi meningkatkan sistem redaman dalam julat operasi sistem yang lebih meluas dengan tujuan untuk meningkatkan prestasi kestabilan sementara dan kestabilan mantap sistem. Masalah rekabentuk penyelarasan diformulasikan sebagai masalah optimum yang diselesaikan dengan menggunakan Pengoptimum Kumpulan Zarah Lelaran (IPSO). Aplikasi teknik IPSO ini dicadangkan untuk mengoptimum parameter-parameter AVR dan PSS supaya ayunan sistem kuasa semasa gangguan dalam sistem mesin tunggal bas infinit (SMIB) dapat diminimumkan. Prestasi teknik IPSO yang dicadangkan dibandingkan dengan teknik PSO tradisional. Perbandingan ini diambil kira dari segi ketepatan parameter dan pengiraan masa. Hasil kajian simulasi domain masa dan analisa eigenvalue menunjukkan kaedah IPSO yang dicadangkan memberikan teknik pengoptimuman yang lebih baik berbanding teknik PSO tradisional.

Kata kunci: AVR; penyelarasan reka bentuk; IPSO; kestabilan sistem kuasa; PSS; kestabilan sementara

■1.0 INTRODUCTION

The most important issue in the reliable and efficient operations in power systems are mainly the transient and dynamic stability considerations. Electromechanical oscillations affect power system and results to disturbance which may lead to system loss of synchronism when adequate damping device is not provided. The need for high performance excitation system became more suitable to maintain the steady state and transient stability of the generators in the power systems.[1] The excitation systems of the generators are using the AVR for maintaining the magnitude of the terminal voltage of the synchronous generators at the desired level. AVR in power systems also plays another important role of controlling the reactive power to help in enhancing system stability.[2-4] Generating plants before this time in early 1950s to 1960s were equipped with a continuously acting AVR, as the number of generating plant with AVR continuous to grow; it became obvious that the high performance of these AVRs had a destabilizing effect on the power systems. These destabilizing effects are the power oscillations of small magnitude and low frequency continues to persist for a very long time. Generators are mainly affected by severe disturbances in a transient state and in a very short time they cause a severe drop on the terminal voltage of the synchronous machine. [5]

The most common among controllers for damping electromechanical oscillations and inter-area oscillations in a deregulated power systems is the power system stabilizers (PSSs).[6] It has been widely known for its great potential as the control device that provides additional damping to enhance the dynamic performance in power systems. PSSs are employed to damp the low frequency oscillations ranging from 0.2-3.0 Hz.[7] PSS are also employed to compensate for the negative damping caused by AVR[8] and damp out the rotor oscillation by modulating the input signal of the excitation system.

Large number of designs and tuning techniques known as conventional approaches has been employed to the tuning of controller parameters. The famous among conventional techniques are the pole placement technique,[9] residue methods,[10,11] eigenvalue sensitivity technique,[12] etc. These conventional designs are associated with heavy computational burdens and other flaws, such as time consuming and the ability to be trapped in a local minimum, thereby giving a false optimal solution. Recently, reasonable number of computational techniques have been reported by researchers to solve transient and steady state stability problems with particular reference to damping low frequency oscillations in power systems. Among other methods are Tabu search (TS),[13-15] Simulated Annealing (SA),[16] Genetic Algorithm (GA)[17,18] and many more. PSO technique is reported to have presented more accurate solutions than others.[19] However, the performance of the traditional PSO greatly depends on its parameters, and it often suffers the problem of being trapped in local optima.[20]

In this paper, IPSO the improved version of PSO is used to coordinate between AVR and PSS controllers to enhance the transient stability of a system and at the same time damp the power system oscillations. To examine the problem of the coordinated design, the transmission line of a single machine infinite bus system is subjected to a severe disturbance and assessed against changes in the generators loading condition.

■2.0 LINEARIZED MODEL OF THE STUDY SYSTEM

A single machine connected to infinite bus (SMIB) is the system under consideration in 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 power system may be linearized to a SMIB system, by using Thevenin's equivalent of the transmission network external to the machine.[8]

In this section, the study of small signal performance on 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 a block representation of the thyristor excitation system with AVR and PSS. Figure 3 shows the block diagram representation of the SMIB system to include the excitation system and AVR with PSS. In this representation, dynamic characteristics of the system are expressed in terms of K constants. This machine is taken as the sixth 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 and presented as follows:

$$\Delta\dot{\omega} = -\frac{K_D\Delta\omega_r}{2H} - \frac{K_1\Delta\delta}{2H} - \frac{K_2\Delta\psi_{fd}}{2H} \tag{1}$$

$$\Delta\dot{\delta} = \omega_0\Delta\omega_r \tag{2}$$

$$\Delta\dot{\psi}_{fd} = \frac{\omega_0 R_{fd}}{L_{fd}} m_1 L'_{ads}\Delta\delta - \frac{\omega_0 R_{fd}}{L_{fd}}\left[1 - \frac{L'_{ads}}{L_{fd}} + m_2 L'_{ads}\right] - \Delta\psi_{fd} - \frac{\omega_0 R_{fd}}{L_{adu}} K_A \Delta V_1 + \frac{\omega_0 R_{fd}}{L_{adu}} K_A \Delta V_s \tag{3}$$

$$\Delta\dot{V}_1 = \frac{K_5}{T_R}\Delta\delta + \frac{K_6}{T_R}\Delta\psi_{fd} - \frac{1}{T_R}\Delta V_1 \tag{4}$$

$$\Delta\dot{V}_2 = \frac{K_D K_{STAB}}{2H}\Delta\omega_r + \frac{K_1 K_{STAB}}{2H}\Delta\delta - \frac{K_2 K_{STAB}}{2H} + \Delta\psi_{fd} - \frac{1}{T_W}\Delta V_2 \tag{5}$$

$$\Delta\dot{V}_s = -\frac{K_D K_{STAB} T_1}{2HT_2}\Delta\omega_r - \frac{K_1 K_{STAB} T_1}{2HT_2}\Delta\delta - \frac{K_2 K_{STAB} T_1}{2HT_2}\Delta\psi_{fd} + \left[\frac{1}{T_2} - \frac{T_1}{T_W T_2}\right]\Delta V_2 - \frac{1}{T_2}\Delta V_s \tag{6}$$

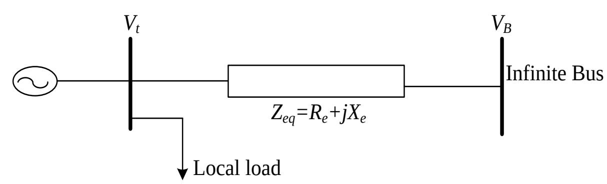


Figure 1 Single machine connected to a large power system through transmission line

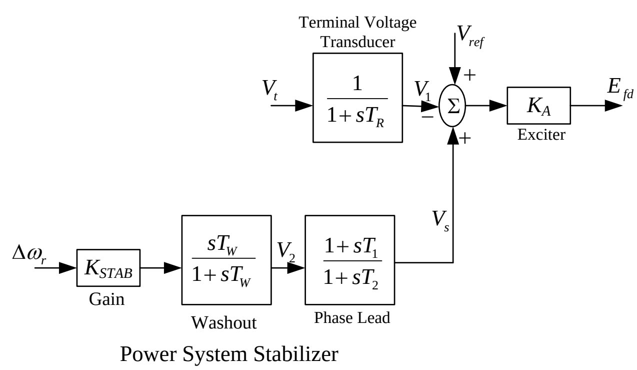


Figure 2 Block diagram of thyristor excitation system with AVR and PSS

There are six constants K_1 to K_6 that describe 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. [21] The constants K_1 to K_6 known as Heffron Phillips constants are computed using the following expressions:

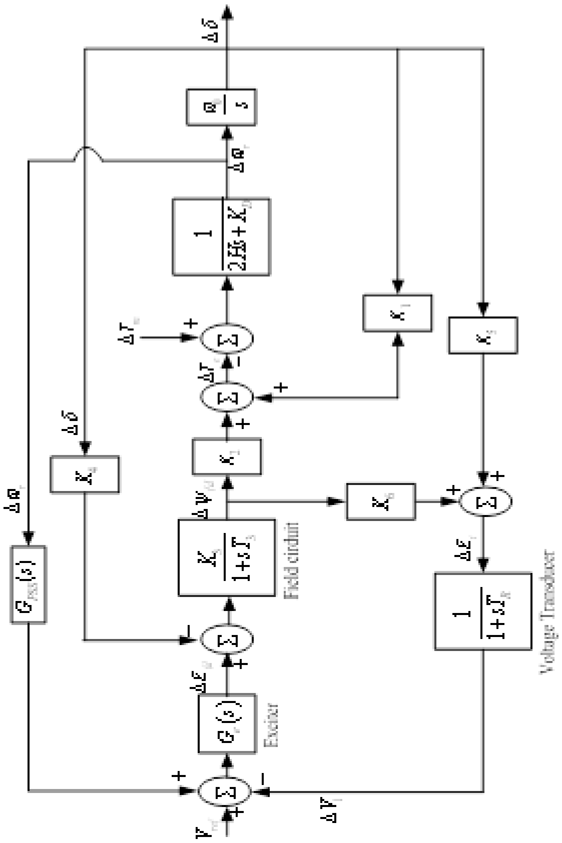


Figure 3 Linearized incremental model for synchronous machine with the exciter and stabilizer

$$K_1 = \frac{E_b E_{qo} \cos\delta_o}{x_e + x_q} + \frac{(x_q - x_d^{'})}{(x_e + x_q)} E_b i_{qo} \sin\delta_o \tag{7}$$

$$K_2 = \frac{(x_e + x_q)}{(x_e + x^{'}_d)} i_{qo} = \frac{E_b \sin\delta_o}{(x_e + x_d^{'})} \tag{8}$$

$$K_3 = \frac{(x_e - x_d^{'})}{(x_e + x_d)} \tag{9}$$

$$K_4 = \frac{(x_d - x_d^{'})}{(x_e + x^{'}_d)} E_b \sin\delta_o \tag{10}$$

$$K_5 = \frac{-x_q v_{do} E_b \cos\delta_o}{(x_e + x_q)V_{to}} - \frac{x^{'}_d v_{qo} E_b \sin\delta_o}{(x_e + x^{'}_q)V_{to}} \tag{11}$$

$$K_6 = \frac{x_e}{(x_e + x^{'}_d)} \left(\frac{V_{qo}}{V_{to}}\right) \tag{12}$$

3.0 DAMPING CONTROLLER DESIGN

The study system considered in this paper is the linearized model of SMIB equipped with AVR and PSS on Figure 3. AVR is employed to the excitation system to keep the terminal voltage at the desired level. In this work, a first order automatic voltage regulator model is used. The AVR parameters that will be adjusted are the *KA* and *TA*. *KA* is the gain of the exciter and *TA* is the exciter time constant, other parameters of the excitation system are specified. [22]

Generally speaking, the PSS are designed purposely to stabilize local and inter area modes. PSS is connected to the excitation system to introduce a component of additional damping torque proportional to speed change. The transfer functions of PSS consist of two lead-lag (phase compensation) blocks, a washout black and again block is shown in Figure 2. The phase compensation blocks supply the appropriate phase-lead characteristic to compensate for the phase lag between the exciter input and the generator electrical torque. The stabilizer gain K_{STAB} and the lead-lag time constants T_1 and T_2 are determined using the proposed IPSO method. The signal washout (T_W) is a high-pass filter that prevents the steady changes in speed from modifying the field voltage[8] and the value is not critical which can be anywhere between 1-20 seconds. It is selected at 10 seconds in this work.

3.1 Coordinated Design of AVR and PSS

Both AVR and PSS controllers are designed and optimized by minimizing the objective function (J) in order to improve the system response in terms of oscillation and settling time. Despite there are several methods to come up with the improvement of the performance of the control system [23] such as integral of squared error (ISE), integral of time weighted squared error (ITSE), integral of absolute error (IAE) and integral of time weighted absolute value of error (ITAE), but in this work, the ITAE of the speed deviation (Δ**ω**) is used as the fitness function (J) which is determined as:

$$J = \int_{t=0}^{t_{\max}} |\Delta\omega| . t . dt \tag{13}$$

For which $\Delta\omega$ is the speed deviation in rad. /sec. and T_{max} is the range of time for simulations. The nonlinear model was conducted for time domain simulations over the simulation period which is aimed at minimizing the fitness function so that the system response such as settling time and overshoots and the constraints are the boundaries of the AVR and PSS parameters. The formulation of the design problem is therefore formulated as:

$$\textit{Minimize}\; J \tag{14}$$

Subject to

$$\begin{aligned} &K_A^{\min} \le K_A \le K_A^{\max} \\ &T_A^{\min} \le T_A \le T_A^{\max} \\ &K_{STAB}^{\min} \le K_{STAB} \le K_{STAB}^{\max} \\ &T_1^{\min} \le T_1 \le T_1^{\max} \\ &T_2^{\min} \le T_2 \le T_2^{\max} \end{aligned} \tag{15}$$

The proposed Iteration Particle Swarm Optimization is applied to solve for the coordinated design problem and to search for the optimal set of AVR and PSS parameters. The boundaries for the constraints are shown in Table 1.

Table 1 Upper and Lower boundary of control parameters

Parameters	K_A	TA	K_{STAB}	T_1	T_2
Upper Limit	300	0.10	50	1.0	1.0
Lower Limit	50	0.01	1.0	0.01	0.01

4.0 MODIFIED PARTICLE SWARM OPTIMIZATION

This section presents the description of the optimization methods that has been used in this paper to analyze the effectiveness of the proposed IPSO against the standard PSO. After presenting the important guide on the operation of PSO, the procedural form of Standard PSO is given on which the IPSO is developed.

4.1 Particle Swarm Optimization

The PSO algorithm was first developed by Kennedy & 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 food in the real life. These birds can only maintain 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 changed 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 of information.[24] Thus, the modification of the position of each bird (or known as particle) is presented by the velocity concept as shown in (18).

$$V_i^{k+1} = wV_i^k + c_1r_1(P_{best-i}^k - X_i^k) + c_2r_2(G_{best}^k - X_i^k) \quad (16)$$

From the equation, the velocity of any particle will be based on the summation of 3 parts of the 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:

$$X_i^{k+1} = X_i^k + V_i^{k+1} \quad (17)$$

4.2 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 its 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:

$$c_3 = c_1(1 - e^{-c_1k}) \quad (18)$$

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

$$V_i^{k+1} = wV_i^k + c_1r_1(P_{best}^k - X_i^k) + c_2r_2\,(G_{best}^k - X_i^k) + c_1(1 - e^{-c_1k})(i_{best}^k - X_i^k) \quad (19)$$

The flow chart of the IPSO is shown in Figure 4. 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:

$$J = \mathrm{Re}\max(\lambda_{i,k}),\ i = 1,2,3\ldots N \quad (20)$$

Where λ_i is the K_{th} eigenvalue of 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.

5.0 RESULT AND DISCUSSION

After The evaluation of the coordination control of AVR and PSS is considered for different clearing fault time and operating conditions. Three operating conditions are considered:

- Nominal operating condition.
- Light operating condition (20% of the nominal values).
- Heavy operating condition (50% higher than the nominal values).

During the nominal operating condition, a 3-phase fault at the sending end is introduced and triggered at time t = 1 sec, and the fault is cleared 0.25 sec. Iteration particle swarm optimization (IPSO) compared with particle swarm optimization (PSO) is used to perform the simultaneous coordination of the AVR and PSS and the result is presented on Table 2 and the convergence characteristics are shown in Figure 5. It can be observed from the convergence characteristic that the IPSO converges around 12th iteration while PSO could only converge around 60th iteration, which IPSO is far much better than PSO. The time domain simulation results are presented in Figures 6-15. Figures 6-9 presents the responses under norminal loading condition. It can be observed that in Figure 6 the IPSO has less amplitude of oscillation and converges faster around 2 seconds and PSO could only converge around 5 seconds and the system without controller though converges, but much more later than 15 seconds and has the largest amplitude of oscillation. The larger the system oscillation the more unstable the power system becomes.

The system loading is increased by 20% (light loading condition) and the robustness of the proposed algorithm for the coordination of AVR and PSS is verified. 3-phase fault occurred at a time (1 Sec.) and is cleared after 0.255 Sec; the system response during the process is shown in Figures 10-12. The results show the speed deviation, rotor angle deviation and the terminal voltage response. It can be observed that the responses given by IPSO based AVR and PSS coordination has the best amplitude of oscillation and faster convergence time compared to the PSO based PSS (i.e they have minimum overshoot and less convergence time).

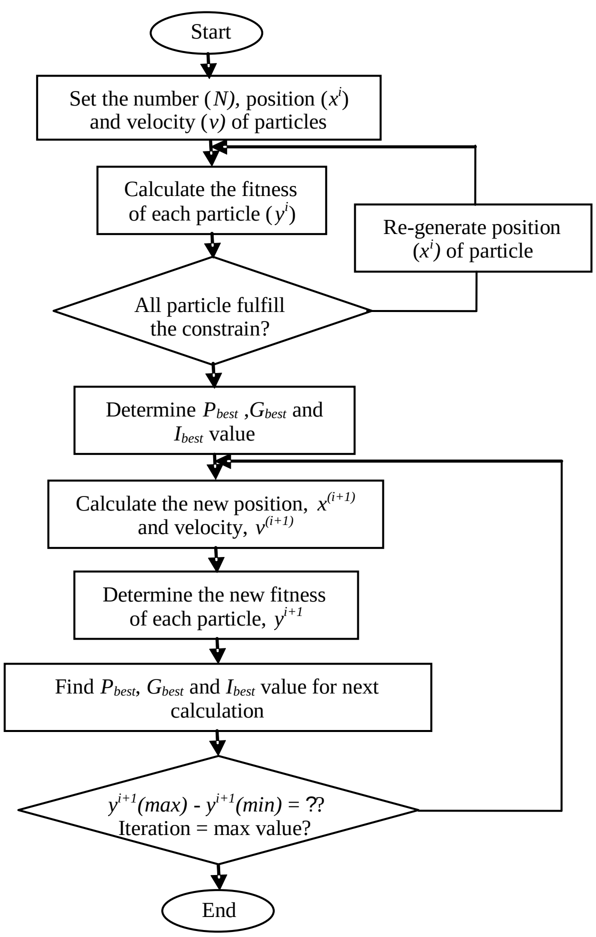


Figure 4 Flowchart of IPSO used for the optimization of PSS parameters

When the system loading is further increased by 50% to assess the robustness of the proposed algorithm. A 3-phase fault occurred at time t=1 sec, then cleared after 0.125 sec. the time domain simulation results are shown in Figures 13-15. From this Figures, it is clearly seen that the responses obtained with IPSO coordinated AVR and PSS have the best result than the PSO based results and of course better than the one without controller at all. In Figures 13-15, because of the adverse increase in the loading condition the system stability was attained at longer time than the other loading conditions of Figures 6-9 (normal operating condition) and Figures 10-12 (light loading condition). It can generally be noted that the results obtained from the coordination is always better than that without the coordination in all aspect in terms of less convergence time and minimum overshoot.

Table 2 Optimized damping controller parameters

Parameters	K_A	TA	K_{STAB}	T_1	T_2
	146.2	0.034	13.38	0.94	0.02

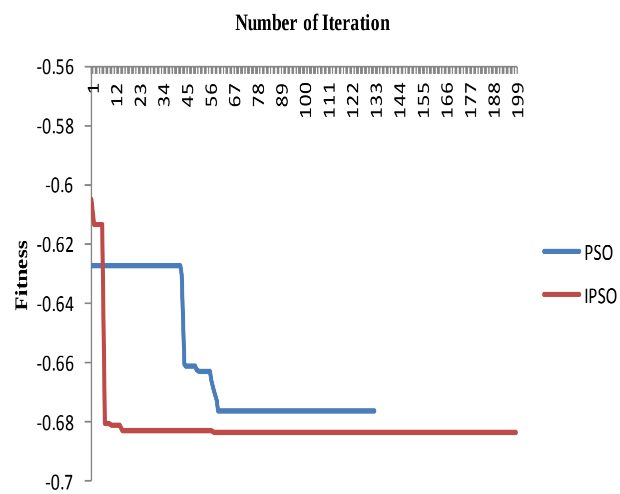


Figure 5 Convergence characteristics of PSO and IPSO based optimization

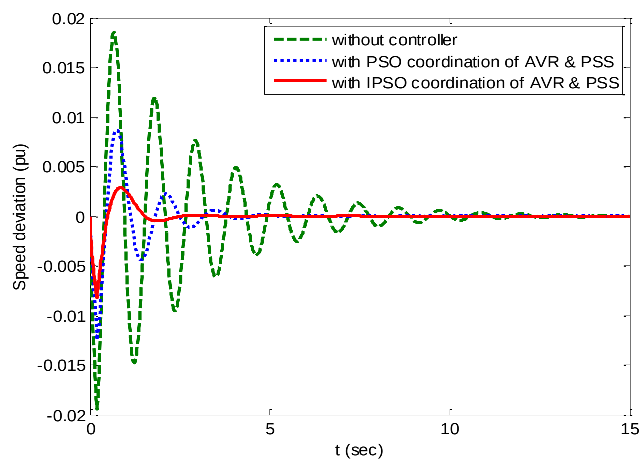


Figure 6 Speed deviation response under nominal operating condition

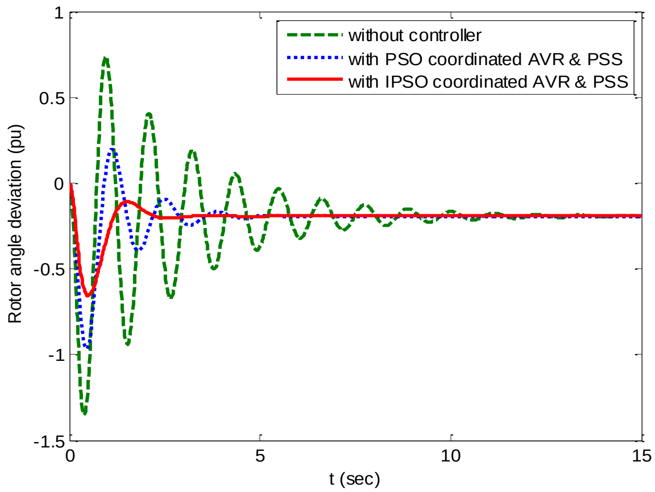


Figure 7 Rotor angle deviation under nominal operating condition

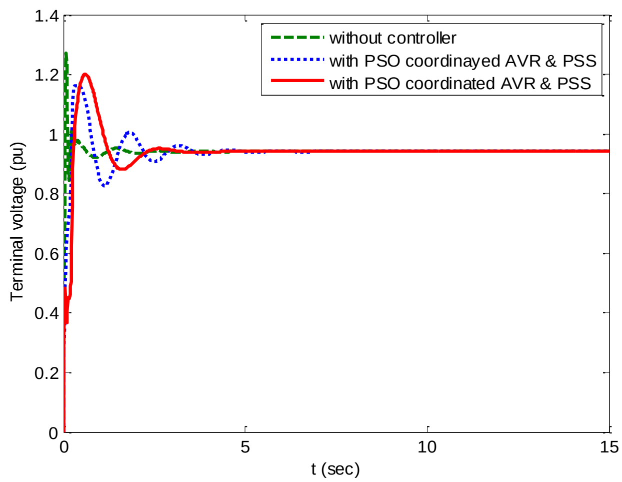


Figure 8 Terminal voltage response under nominal operating condition

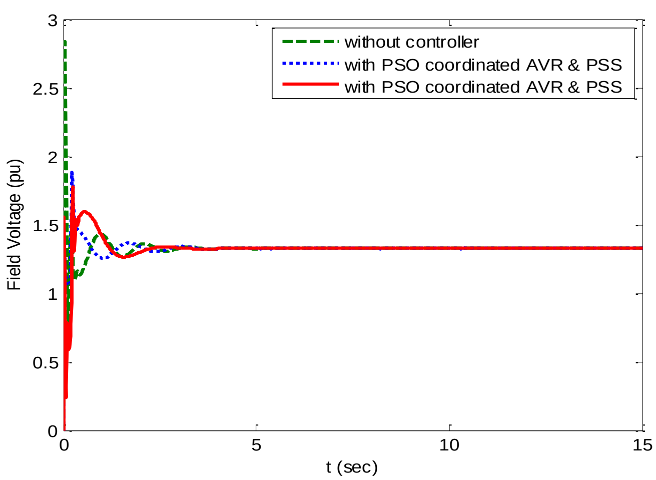


Figure 9 Field circuit voltage under nominal loading condition

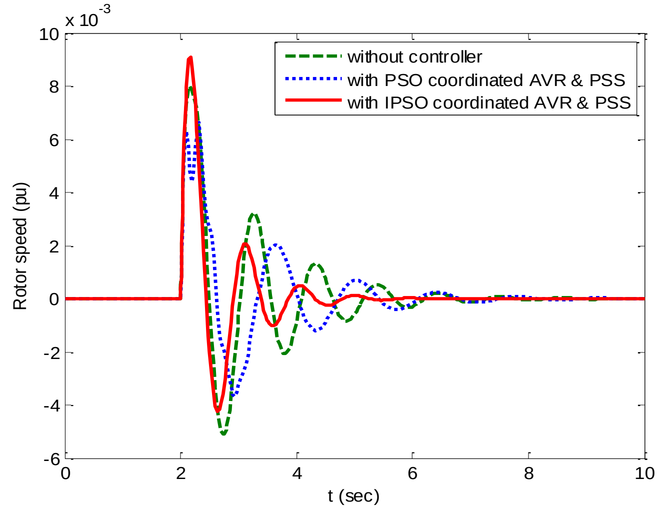


Figure 10 Rotor speed response under light loading condition

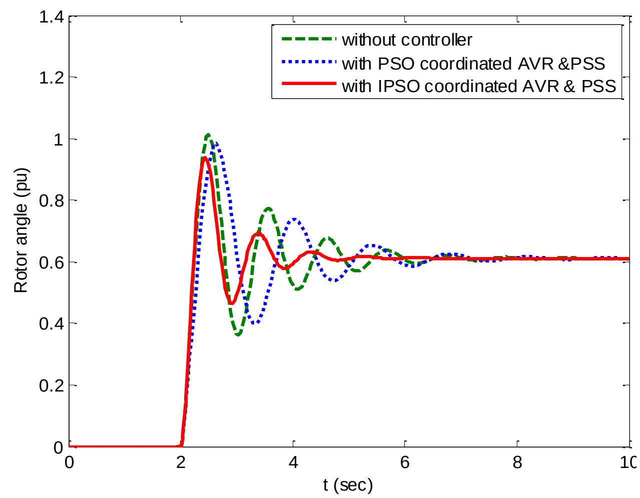


Figure 11 Rotor angle response under light loading condition

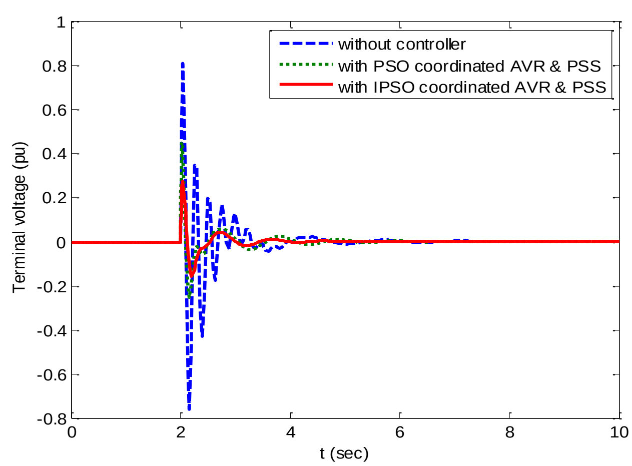


Figure 12 Terminal voltage response under light loading condition

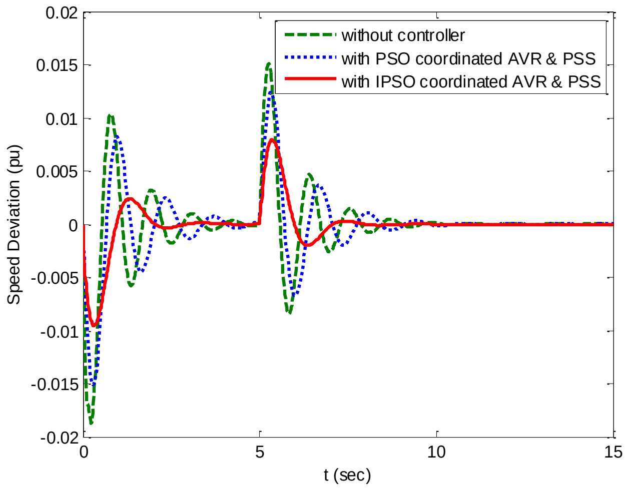


Figure 13 Rotor speed response under heavy loading condition

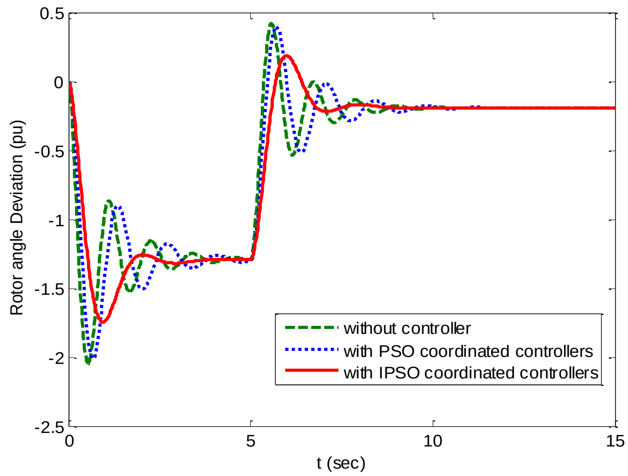


Figure 14 Rotor angle response under heavy loading condition

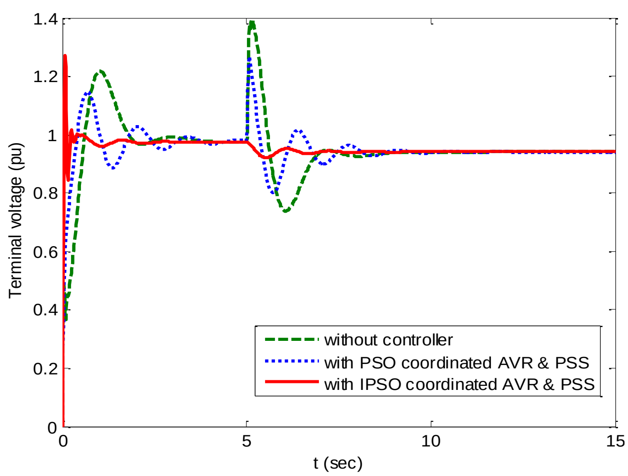


Figure 15 Terminal voltage response under heavy loading condition

■6.0 CONCLUSION

This paper presents the Iteration Particle Swarm Optimization algorithm for the simultaneous coordination of AVR and PSS in order to enhance the power system stability. A robust optimal tuning process of AVR and 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 IPSO based PSS 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 coordination of AVR and PSS design.

Nomenclatures

AVR	Automatic Voltage Regulator
c_j	Weighting factor
E_b	The infinite bus voltage in pu.
E_t	The generator terminal voltage in pu.
H	The inertia constant in MW.s/MVA
K_A	The exciter gain
K_D	The damping torque coefficient in pu torque/pu speed deviation.
K_{sd}	The d-axis saturation coefficient
X_{Tq}	The q-axis saturation coefficient
K_{STAB}	The power system stabilizer gain
K_1	Change in T_e for a change in δ with constant flux linkages in the d axis
K_2	Change in T_e for a change in d axis flux linkages with constant δ
K_3	Impedance factor
K_4	Demagnetizing effect of a change in rotor angle
K_5	Change in V_t with change in rotor angle for constant E_q'
K_6	Change in V_t with change in E_q' constant rotor angle
L_{adu}	The generator d-axis unsaturated value of the mutual inductance in pu.
L_{ads}	The generator d-axis saturated value of the mutual inductance in pu.
L_{aqu}	The generator q-axis unsaturated value of the mutual inductance in pu.
L_{fd}	The field circuit reactance in pu.
PSS	Power System Stabilizers
R_{fd}	The field circuit resistance in pu.
R_T	The total system resistance in pu.
T_R	The terminal voltage transducer time constant in seconds
T_W	The time constant of the signal washout block in seconds
T_1 , T_2	The phase compensator time constants in seconds

V_1	The output voltage of the terminal voltage transducer
V_2	The output voltage of the signal washout block
V_s	The output voltage of the phase compensator
w	Weighting function.
X_q	The total q-axis reactance of the system in pu.
X_d	The total d-axis reactance of the system in pu.
X_d'	The transient reactance of generator in pu.
X_{sd}	The synchronous reactance of the generator in pu.
X_{Td}	The total d-axis reactance of the system in pu
X_{Tq}	The total q-axis reactance of the system in pu.
ω_0	The rated rotor electrical speed in rad/s
ω_r	The angular speed of the rotor in rad/s
δ_0	The initial rotor angle in elect. rad
ψ_{fd}	The field circuit flux linkage.

Acknowledgement

The authors are delighted to express their appreciation to Universiti Teknologi Malaysia (UTM) and the Government of Malaysia for supporting this research.

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