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Full Length Research Paper

Design of particle swarm optimization (PSO) based automatic generation control (AGC) regulator with different cost functions

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This article deals with the tuning of the parameters for automatic generation control (AGC) of three-area interconnected power system. Areas of the power system consists of reheat thermal turbines with proportional-integral (PI) regulator. Particle swarm optimization (PSO) algorithm has been applied to optimize the regulator parameters. The effectiveness of different cost functions through PSO is considered which is based on the variation in area control errors (ACEs) of all the areas. Cost functions like integral square error (ISE), integral absolute value of the error (IAE), integral time-multiplied square error (ITSE) and integral time-multiplied absolute value of the error (IATE) are investigated. Performance of the proposed optimization algorithm is compared with traditional Ziegler Nichols (ZN) technique for the AGC problems of the power systems.

Key words: Area control errors (ACEs), automatic generation control (AGC), power system, Ziegler Nichols (ZN) technique, particle swarm optimization (PSO) algorithm, cost functions.

INTRODUCTION

The generation of electrical power is produced depending upon the availability of generating plants. To meet the load demand in geographical areas the generators are interconnected by transmission network and form large complex power systems. The large power systems are normally divided into control areas based on the principle of coherency. The coherent areas are interconnected through tie-lines which are used for contractual energy exchange between areas and provide inter area support during exceptional operations. A mismatch in real power balance affects primarily the system frequency. The problem of controlling the generation in an area for maintaining the frequency at desired level by eliminating the mismatch between generation and load and also eliminating the inadvertent exchange of power with other areas via tie-lines is known as AGC (Elgerd, 2001; Kothari and Nagrath, 2003).

Regions or areas are originated from a multi-area interconnection, and tie-lines are used for interconnection. The advantage of furnished inter-area help is initiated by tie-lines for abnormal situations as well as transmission way for contractual energy exchanges between the areas. The area limits are evaluated by tie-line reading for AGC and contractual billing purposes. Power or energy flows are calculated. Energy reading is generally based on an hour and the values of data applied for recording functions must be identical after auditing for each corporate people using the tie-line (Elgerd and Fosha, 1970).

AGC in more than one area is operated alone by frequency pulses in an interconnection. There will be huge amount of power oscillations between controlling areas except when regulating operations developed by all areas and can be realized at the same time. In addition, the operation of such an interconnection would feel a greater severe problem if the areas trying to control frequency had measurement disturbance. Frequency measurement of an area at a value more than others would minimize its generation, while others increased. Both of them are measure to influence the frequency of the specified value (Nanda and Kaul, 1978).

Many investigations in the area of AGC problem of

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interconnected power systems have been reported in the past six decades (Ibraheem and Kothari, 2005; Shayeghi et al., 2009). A number of control schemes have been employed in the design of AGC controllers in order to achieve better dynamic performance. Among the various types of AGC controllers, the most widely used are classical proportional-integral and proportional-integral-derivative (PID) controller.

During the past days, Sahraian and Kodiyalam (2000) developed a methodology for optimal tuning of PID controllers in which ISE and IAE measure containing the closed-loop response error in the controlled variable was minimized by using response surface optimization in single-input/single-output and multi-input/multi-output control system. These AGC controllers are designed for centralized or decentralized power systems. Most of the AGC schemes analyzed decentralized type power systems because centralized power systems control schemes are not fit to handle the fast dynamic condition of the perturbations in the multi-area power systems. In a decentralized power systems, Yang and Cimen (1996) have built an ITAE criteria used to control. It was exhibited that, subject to a condition based on the structured singular values, each local area load frequency controller designed independently and a sufficient gain and phase margin defined in classical feedback theory during each independent linear quadratic regulator design approach and variable structure (Das et al., 1991).

After that Nanda et al. (2006) dealt with AGC of a multi-area hydro-thermal system including generation rate constraints. Optimization of integral controller and electric governor parameters had been carried out using ISE criterion. Investigations had been made for the selection of suitable value for governor speed regulation parameter and to explore the effect of tie line strength on the dynamic response. However, the recent advancement in optimal control theory and availability of fast digital computers coupled with enormous capability of handling large amount of data with different type of interconnections motivated the power system engineers to devise recent AGC strategies. There have been a vast variety of research articles (Ibraheem and Kothari, 2005) relating to AGC controller designs which had made classical controllers structure as the basis for the development of more advanced and even intelligent technique (IT) based controllers for AGC applications in power systems.

ITs show its capability in the different scenarios of AGC problems of the power systems. Among these techniques, Particle swarm optimization (PSO) technique seems to be good methods to solve optimization problems than the other intelligent techniques that may be known as evolutionary algorithm (EA). The application of PSO technique for AGC of interconnected power systems thoroughly investigates its merits over other types of AGC schemes. The real power systems optimization problems are usually of multi-furious nature. The ultimate goal of this optimization algorithm is to find a global solution from a group of local solutions. These optimization algorithms are applicable to functions that are multi-modal, non-differentiable and discontinuous. PSO is a stochastic, population based Energy Management System problem solving algorithm; it is a kind of swarm intelligence that is based on social principles and provides insights into social behavior, as well as contributing to power systems.

Valle et al. (2006) have analyzed a comprehensive coverage of PSO applications in solving optimization problems in the area of electric power systems. It clearly indicated its applicability and the fast growing interest in PSO utilization in this research area. The following were the major areas in which PSO was applied (i) Economic dispatch (ii) reactive power control and power losses reduction (iii) optimal power flow (iv) power system controller design (v) artificial neural net-work training (vi) other power system areas. Furthermore, a huge amount of voluminous research monographs and articles are available in the literature of load frequency control (LFC) gathered by Shayeghi et al. (2009).

Best efforts have been made to develop the tuning of parameters for a two-area interconnected hydro-thermal system with PI controller with the help of PSO algorithm as well as genetic algorithm scheme by Patel (2007). ISE and ITAE considered for optimization. The effectiveness of a cost function was considered based on the variation in tie-line power and change in frequency in both the areas, and then they (Luo and Shi, 2010) have addressed PSO algorithm to AGC strategy in interconnected power grid in the control performance standard (CPS) standard. PSO was analyzed on ACE and CPS to AGC strategy.

Gozde and Aplamacioglu (2011) have integrated an improved controller based on PSO technique and have been proposed to novel gain scheduling PI control strategy for AGC of the two-area thermal power system with governor dead band non-linearity. Two different cost functions with tuned weight coefficients were derived. One of the cost functions ISE was derived through the frequency deviations of the control areas and tie-line power changes. On the other hand, the other one ITSE included the rate of changes which can be variable, depending on the time in these deviations. These weight coefficients of the cost functions were also optimized as the controller gains had been done through the craziness based PSO algorithm.

A complex power system networks that are highly non-linear and non-stationary and enhanced particle swarm controller for solving constrained optimization problems for power system applications, in particular, the optimal allocation of multiple STATCOM units by Valle et al. (2008). The study focused on the capability of the algorithm to find feasible solutions in a highly restricted hyperspace. The performance result of the enhanced

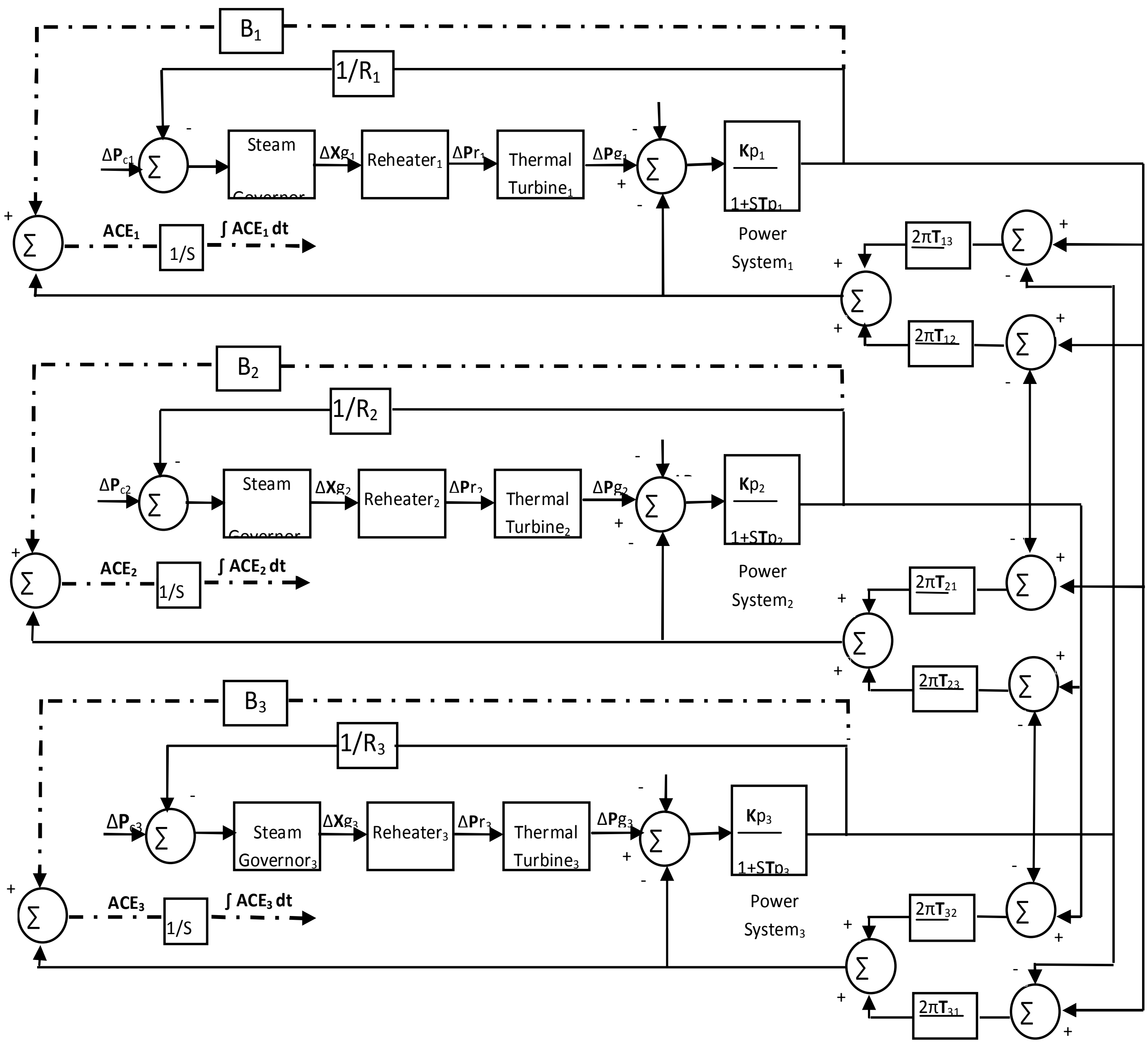

Figure 1. Model of interconnected power systems consisting of reheat turbines with PSO (PI).

particle swarm controller proved its capability in comparison with the classical PSO algorithm, genetic algorithm and bacterial foraging algorithm. Additionally, the enhanced PSO was capable of finding the global optimum without getting trapped in local minima.

In this paper, the beauty and simplicity of PSO technique is demonstrated. The AGC controllers are designed based on PSO optimal control strategies. The AGC controller designs are investigated for load disturbance in a three-area reheat interconnected power systems model. Firstly, it introduced a cost function ISE with standard ZN algorithm based classical PI and optimal PSO technique based PI controller. Secondly, other cost functions that is, IAE, ITSE and ITAE are evaluated and compared to each other through PSO.

POWER SYSTEMS MODEL UNDER INVESTIGATION

For the present study, a three-area interconnected power systems consisting of power plants with reheat thermal turbines is considered and is interconnected via alternating current (AC) transmission line only. The transfer function model is also presented in Figure 1 (Sahraian and Kodiyalam, 2000).

In the power systems model, considering PI controller which is using standard ISE cost or fitness or objective function for developing controlling parameters. This cost function is also evaluated with other cost functions using PSO technique. According to this, different types of adequate cost functions are tested for this study. These cost functions deals according to its parameters inherent performing nature. Proper parameter setting is of great importance for a system to be stable. Having secured a stable system, cost must be to adjust the system parameters until an optimum response is achieved. Performance indices or cost function have proved to be the most meaningful measures of dynamic performance. Such a cost function is usually formed of the structure:

$$C=\int_0^\infty F(e_1, e_2, e_3, \ldots.., e_n)\, dt \quad (1)$$

where; C is the costs of the function and e1, e2, e3, ……, en are the different errors that is, ACEs that control system is designed to eliminate (Sahraian and Kodiyalam, 2000). Popular performance indices are ISE, IAE, ITSE and ITAE. Selection of an appropriate J will lead to better optimal values of the gain parameters, which in turn gives better dynamic response. Classical PI control scheme is used ISE as a cost function.

PERFORMANCE INDEX MODELING

Systems performance quantification is achieved through a performance index. The performance selected depends upon the process under consideration and is chosen such that emphasis is placed on specific aspects of the systems performance. Alternatively a performance index is a quantitative measure of systems, and is chosen so that a set of parameters in the systems can be adjusted to meet the required specification optimally. Minimum or maximum value of this index then corresponds to the optimum set of parameter value (Dorf and Bishop, 2008).

When J is a cost function it has to optimize (minimize). Different performance indices used in practice are:

$$ISE=\int_0^\infty e^2(t)dt \quad (2)$$

$$IAE=\int_0^\infty |e(t)|dt \quad (3)$$

$$ITSE=\int_0^\infty te(t)^2dt \quad (4)$$

$$ITAE=\int_0^\infty t|e(t)|dt \quad (5)$$

In all of the above 'e(t)' is the error at time 't'. Area control errors that is, ACE_1, ACE_2 and ACE_3 are the errors which are the $input_1$, $input_2$ and $input_3$ respectively in the power systems model.

$ACE_1 = B_1\ \Delta F_1+\Delta P_{tie12}$, for area-1, $ACE_2 = B_2\ \Delta F_2+\Delta P_{tie23}$, for area-2 and for area-3, $ACE_3 = B_3\ \Delta F_3+\Delta P_{tie31}$

The ACE_i (i=1, 2 and 3) is the summation of frequency biasing, deviation in the frequency and change in tie-line power flows. The ACE_is of respective areas is taken as the input to the PI regulator which can be expressed as:

$$U_{PI} = K_P ACE_i + K_I \int_0^t ACE_i dt \quad (6)$$

The control parameters to be tuned through the optimization algorithm are feedback gains of PI and frequency biasing of outputs of the regulator in the power systems.

In this study, the optimum values of the controller parameters, which minimize the objective function, are accurately computed using PSO algorithm.

OVERVIEW OF PSO TECHNIQUE

PSO is a population based optimization technique based on intelligent scheme developed by Kennedy and Eberhart (1995) (Kennedy et al., 2007). PSO has emerged as one of the most assuring optimizing scheme for effectively dealing near to global optimization tests. The inspiration of the mechanism is established by the social and cooperative nature represented by flying birds. The algorithm simulates a simplified social milieu in capable solutions of a swarm which means that a single particle bases its search on its own experience and information given by its neighbours in the specified region.

Particles are flown in the solution region with their randomized assigned velocity. Among these particles, each particle keeps track of its coordinates in the solution region which are associated with the best fitness it has achieved so far. This value is known as '*pbest*'. Another '*best*' value that is tracked by the particle is the best value, obtained so far by any particle in the group of the particles. This best value is also known as a global best '*gbest*' and the pattern is forwards to successful solutions. These solutions contribute to the increase of Nthe fame of PSO algorithm (Eberhart and Shi, 2001; Beielstein et al., 2003; El-Zonkoly, 2006).

This random velocity is usually limited to a certain maximum limit. PSO technique using equation (7) is known as the *gbest* structure. PSO is a population based EA that has many primitive benefits over other optimization techniques.

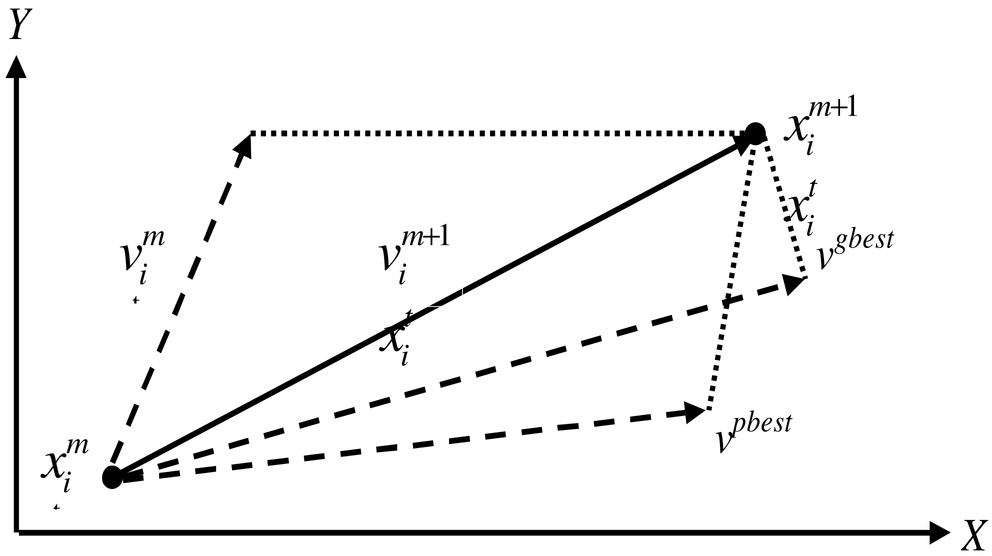

Figure 2. Concept of modification of searching point.

A most attractive quality of the PSO approach is its simplicity as it involves only two main reference equations. Each particle coordinates represent a possible solution assisted with two real vectors, the position x_i and velocity v_i vectors in this technique. $x_i = [x_{i1}, x_{i2}, x_{i3, \ldots\ldots} x_{iN}]$ and $v_i = [v_{i1}, v_{i2}, v_{i3}, \ldots.., v_{iN}]$ are the two vectors assisted with each particle 'i' in N-dimensional search space. Number of particles or possible solutions of a swarm can go forward through the feasible solution place to explore optimal solutions. Each particle modifies its position based on its own best exploration, and overall experience of best particles (Beielstein et al., 2003). This particle also considers its previous velocity vector according to the following reference equations:

Velocity modifications

Each particle velocity can be modified by the following equation:

$$v_i^{m+1} = v_i^m + c_1 * r_1 * (pbest_i - x_i^m) + c_2 * r_2 * (gbest - x_i^m) \quad (7)$$

Position modifications

Positions of the particles are modified at each interval of the flying time. The position of the particle may be change or not change, depending on the solution value.

$$x_i^{m+1} = x_i^m + v_i^{m+1} \quad (8)$$

where, v_i is velocity of particle 'i' at iteration m, v_i^m = modified velocity of particle 'i' at iteration m, c_1 and c_2 are accelerating constant, and select value of c_1 , c_2 is 2. Random numbers r_1 and r_2 are in between 0 to 1, x_i^m is current position of particle 'i' at iteration m, x_i^{m+1} = Modified position of particle 'i ' at iteration (m +1), *pbesti* is *pbest* of particle 'i', and *gbest$_i$* is *gbest* of the group of the particles.

Depictions in the Equations (7) and (8), (Kennedy et al., 2007) describes the velocity and modify position, respectively. Equation (7) predicts a new velocity for each particle based on the particle's previous velocity, the particle's location at which the best fitness has been achieved so far, and the population global location at which the best fitness has been achieved so far. In addition, c_1 and c_2 are positive constants known as the social parameters, respectively. These constants provide the correct balance between individuality and sociality of the particles. Acceleration is weighted by a random term, with separate random numbers being generated for acceleration toward *pbest* and *gbest* locations. The random numbers provide a stochastic characteristic for the particles velocities in order to simulate the real behavior of the birds in a flock. Figure 2 shows the concept of modification of searching points highlighted by indications in the Equation (7).

An inertia weight parameter *w* was introduced in order to improve the performance of the original PSO model (Eberhart and Shi, 2001). This parameter deals with the role of balancing the global search and local search capability of PSO. It can be a positive constant or even a positive linear or non-linear function of time.

A better method of near to global optimum within a reasonable number of iterations can be achieved by incorporating this parameter into the velocity update in Equation (7), as follows:

$$v_i^{m+1} = w^* v_i^m + c_1{}^* r_1{}^*(pbest_i - x_i^m) + c_2{}^* r_2{}^*(gbest - x_i^m) \quad (9)$$

Typical values for the inertia parameter are in the range [0.5, 1]. On the other side several different approaches using a construction factor *s*, which increase the algorithm's capability to converge to a better solution and the equation used to modify the particle's velocity becomes:

$$v_i^{m+1} = s^*(v_i^m + c_1{}^* r_1{}^*(pbest_i - x_i^m) + c_2{}^* r_2{}^*(gbest_i - x_i^m)) \quad (10)$$

Where,

$$s = \frac{2}{|2-\varphi-\sqrt{\varphi^2-4\varphi}|}, \quad c_1 + c_2 = \varphi \leq 1 \qquad (11)$$

The PSO algorithm with constriction factor can be considered as a special case of the algorithm with inertia weight since the parameters are interacted through the Equation (11). From investigational studies, the best approach to use with PSO as a rule of thumb is to utilize the constriction factor approach or utilize the inertia weight approach while selecting *w*, c_1 and c_2 according to Equation (9). All parameters introduced in Equations (9 to 11) may vary depending on the characteristics of the problem at hand. Adjustments of these parameters are different for every type of power systems problem and need to be carefully adjusted in order to achieve better performance of the algorithm. In this paper, apply the inertia weight approach to use with PSO on multi-area case study of AGC.

DESIGN OF PSO BASED CONTROLLER

The proposed algorithm will proceed as follows: Twenty particles are used, and two hundred iterations are chosen for converging to solution in the PSO algorithm.

Step 1: Inputs (real data of the systems) consisting of ACE_i in the AGC of power systems model.

Step 2: Initialize the particle with random positions, and velocities. The group of the particles are determined according to the ACE_i under real dimensions.

Step 3: Calculate and compare the fitness value for each particle (control parameters U_{PI}) in the group of particles.

Step 4: Particle correspondence, the lowest fitness will be *pbest*. If the new fitness value for U_{PI} is less than that obtained with $pbest_i$, then replace the coordinates of $pbest_i$ with the present coordinates of U_{PI}.

Step 5: Check the velocity *v* of each particle according to

$v_i^{m+1} > v^{max}$, then $v_i^{m+1} = v^{max}$

$v_i^{m+1} > v^{min}$, then $v_i^{m+1} = v^{min}$

Step 6: Compare the fitness values of $pbest_i$ of all particles to determine the best particle and store the coordinates of the best particle as *gbest*.

Step 7: Modify the velocity of each particle according to Equation (10).

Step 8: Modify the position of each particle according to Equation (8).

Step 9: If the number of iterations reaches the maximum, then go to Step 10. Otherwise, go to Step 3.

Step 10: The particle that creates the newest *gbest* is the optimal solution of the AGC problem (optimal values of K_P and K_I for the controller, and B for the systems).

Step 11: Stop (a sufficiently good fitness value or a maximum number of iterations). After the fitness function has been calculated or the number of the iteration determines, the evolution procedure is stopped.

RESULTS AND DISCUSSION

The observations are performed on MATLAB 7.10.0 software which has technical specifications like Core2 Duo of 2.4 GHz and 2 GB RAM etc. The digital computer based dynamics are investigated in the case of multi-area interconnected power systems consisting of reheat turbines with perturbations in area-1 (ΔP_{d1} = 0.01 pu MW). The optimal controlling parameters for the ISE function of the classical and proposed optimal PI controller are shown in Table 1 at the end of the test period. Table 2 represents the settling times with respect to the frequency and tie-line power deviations. Other types of proposed cost functions like IAE, ITSE and ITAE along with ISE and controlling parameters are also presented in the Table 3 and the dynamic response plots of the settling time of system dynamics according cost function ISE is shown in Figure 3 respectively.

The investigations of response plots given in Figures 4 to 12 reveal that implemented PSO (PI) AGC regulator reduces the overshoots to a great extent and completely removes the oscillations from the dynamic responses as compared to that obtained with classical PI AGC controller in the power systems. The observations show that the proposed control configuration with optimal cost function achieves good dynamic performance of the proposed PI controller. Especially, the investigated cost functions parameters expose better solutions than the standard cost functions. In addition to this, the proposed

Table 1. Tuned parameters with standard and proposed ISE.

Regulator	Tuned parameter	Area-1	Area-2	Area-3	Cost function
	K_P	-0.0000	-2.3201	-2.3093	
Classical PI	K_I	-0.3419	-0.1302	-0.1295	0.0017
	B	0.4250	0.4250	0.4250	
	K_P	-2.000	-1.9000	-1.9400	
PSO (PI)	K_I	-0.3494	-0.3583	-0.3583	6.4171e-004
	B	0.2873	0.2873	0.2873	

Table 2. Settling times with standard and proposed ISE.

Regulator	Time (s)					
	ΔF_1	ΔF_2	ΔF_3	ΔP_{tie12}	ΔP_{tie23}	ΔP_{tie31}
PI	11.3	12	12	10.6	12	12
PSO (PI)	4.2	8.3	8.1	4.4	8.6	8.2

Table 3. Compared the different type of PSO (PI) based cost functions ISE, IAE, ITSE and ITAE.

Cost function	Ki_1	Area-1	Area-2	Area-3	Cost function value
	K_P	-2.000	-1.9000	-1.9400	
ISE	K_I	-0.3494	-0.3583	-0.3583	6.4171e-004
	B	0.2873	0.2873	0.2873	
	K_P	-2.2000	-2.2000	-2.0000	
IAE	K_I	-0.2954	-0.2000	-0.2006	0.1400
	B	0.2394	0.2394	0.2394	
	K_P	-3.2000	-3.2000	-3.4000	
ITSE	K_I	-0.3722	-0.3608	-0.3608	0.0011
	B	0.2162	0.2162	0.2162	
	K_P	-0.6000	-0.6000	-0.6000	
ITAE	K_I	-1.7679	-0.3000	-0.3000	0.5381
	B	0.2595	0.2595	0.2595	

PI controller using ISE function with the rates of changes in the frequency and tie-line deviations shows the better results than classical PI controller for the AGC. It can be clearly seen that the PSO based gain scheduling of PI controller, improves the AGC scheme in order to minimize the ACE_i. It also improves the movement of governor valve position according to the level of the perturbations in the power systems.

Dynamic response plots presented that the PSO based PI controller with different cost functions improve AGC scheme within order to inputs (ACE_i) and outputs ($U_{PI,\,i}$) of the proposed controller. These deviations determining the settling times are also depicted in Figures 13 to 18. Comparisons of the controller and power systems parameters of these cost functions like K_P, K_I, B and cost functions values are shown in Table 3.

Conclusion

Optimization of the PI controller gains for a three-area interconnected power systems using PSO algorithm has been proposed. The PSO technique is utilized to evaluate the PI controller gains which improve the dynamic performance of the system to an operating condition with perturbations.

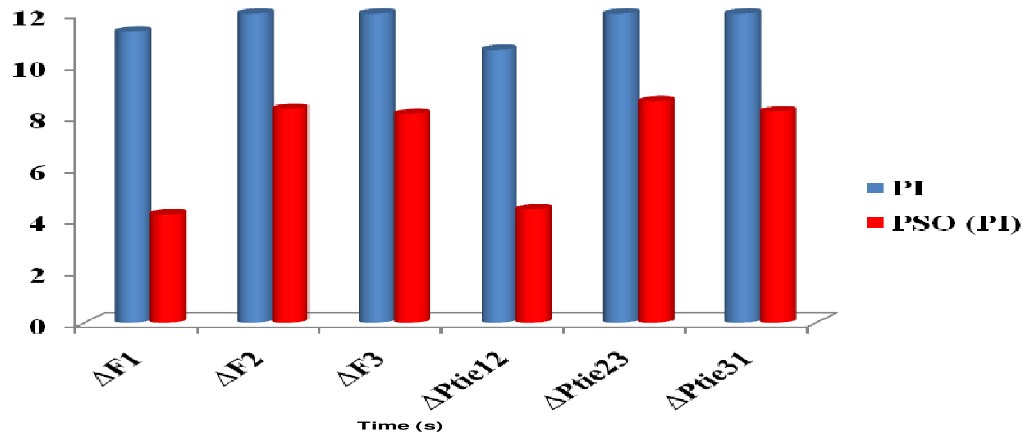

Figure 3. The comparison of settling times according to ISE cost function.

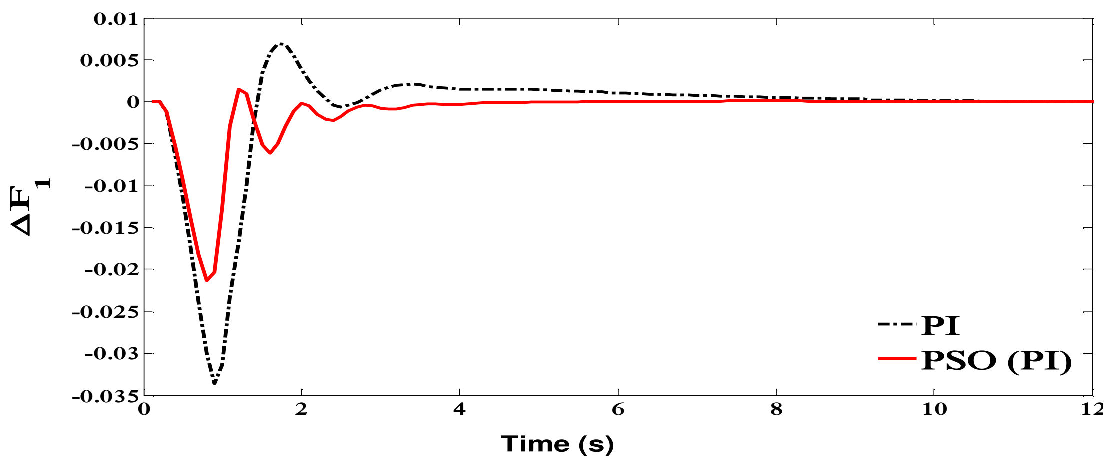

Figure 4. Dynamic response of ΔF_1 for 1% load disturbance in Area-1.

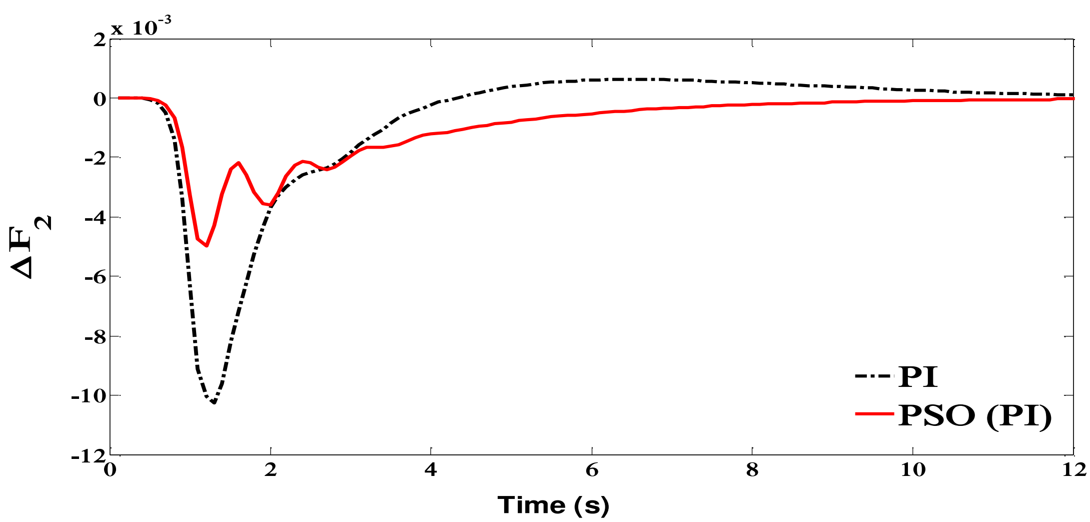

Figure 5. Dynamic response of ΔF_2 for 1% load disturbance in Area-1.

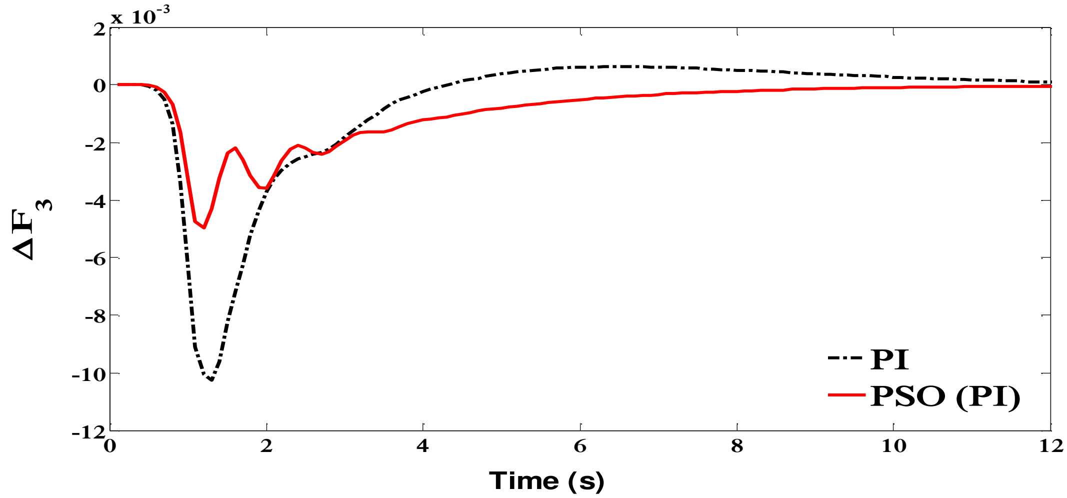

Figure 6. Dynamic response of ΔF_3 for 1% load disturbance in Area-1.

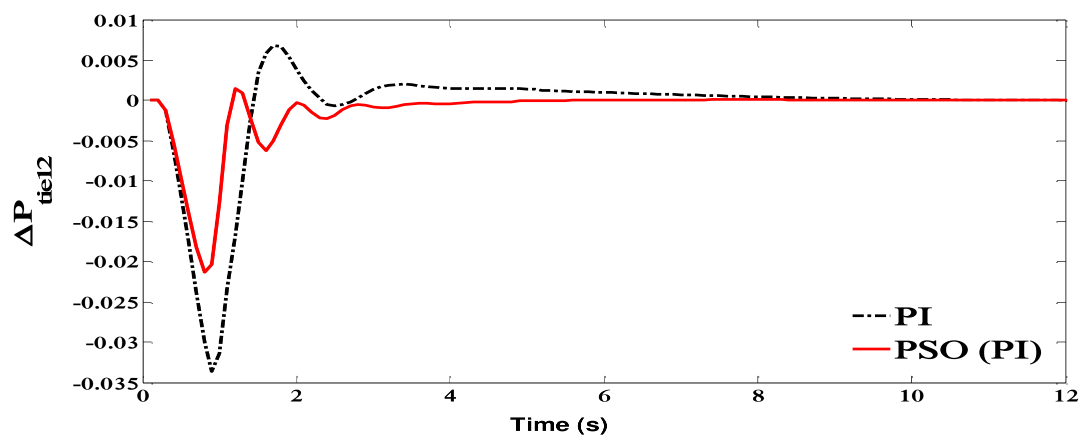

Figure 7. Dynamic response of ΔP_{tie12} for 1% load disturbance in Area-1.

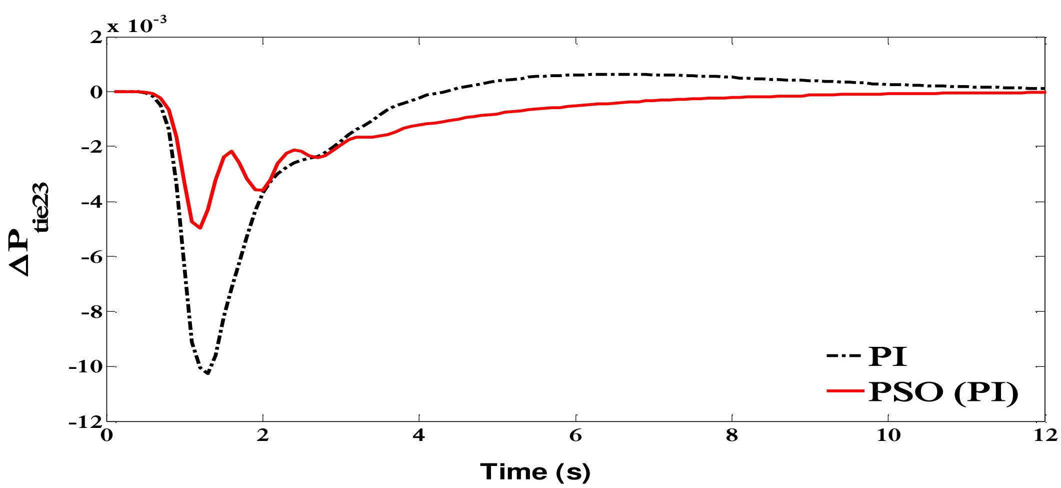

Figure 8. Dynamic response of ΔP_{tie23} for 1% load disturbance in Area-1.

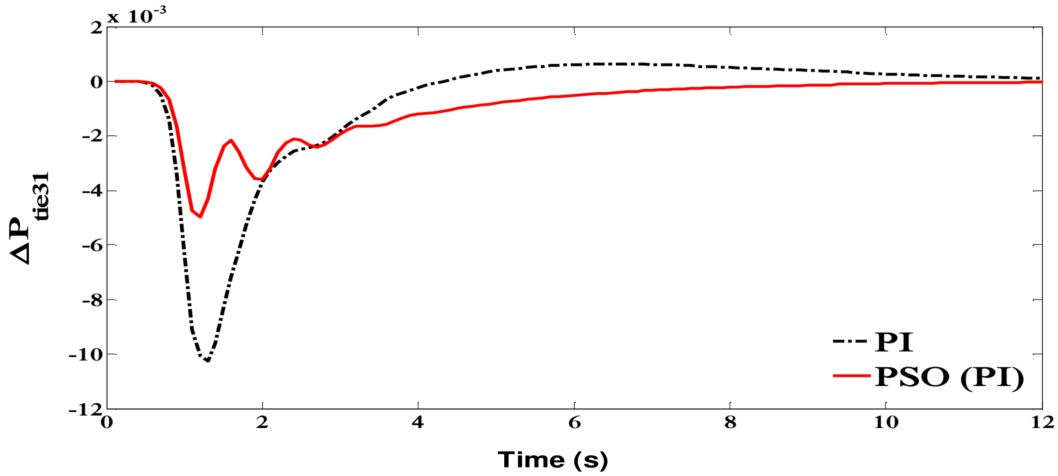

Figure 9. Dynamic response of ΔP_{tie31} for 1% load disturbance in Area-1.

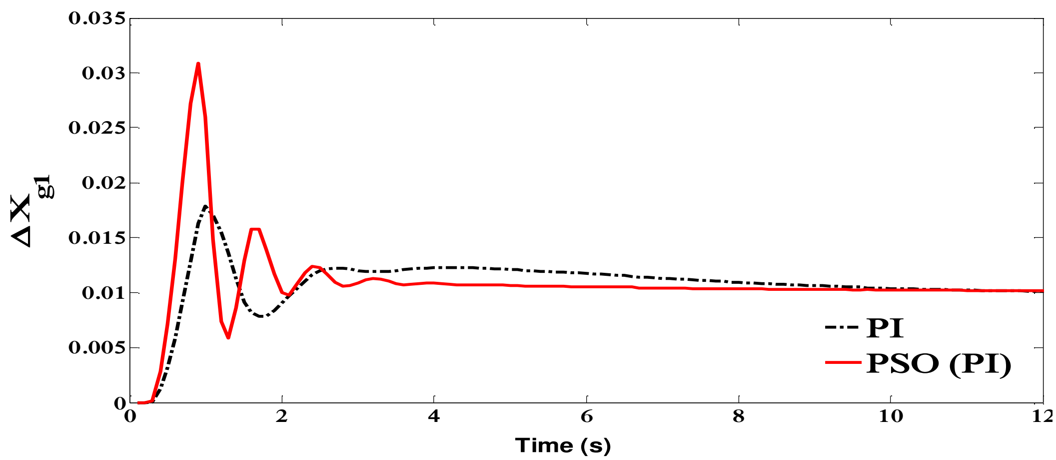

Figure 10. Dynamic response of ΔX_{g1} for 1% load disturbance in Area-1.

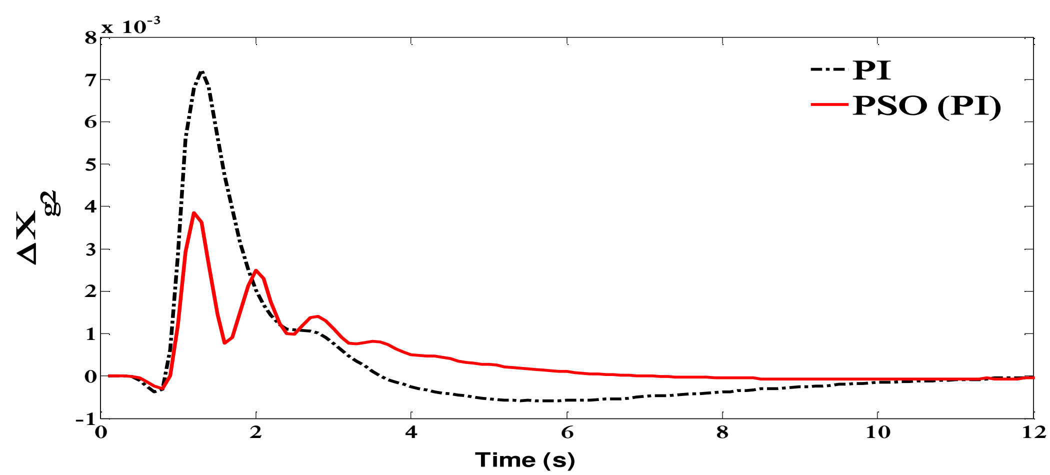

Figure 11. Dynamic response of ΔX_{g2} for 1% load disturbance in Area-1.

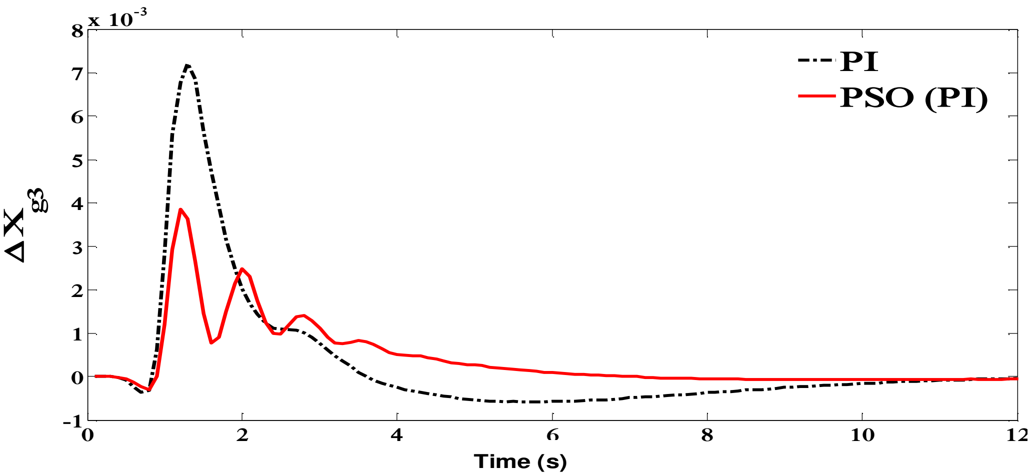

Figure 12. Dynamic response of ΔX_{g3} for 1% load disturbance in Area-1.

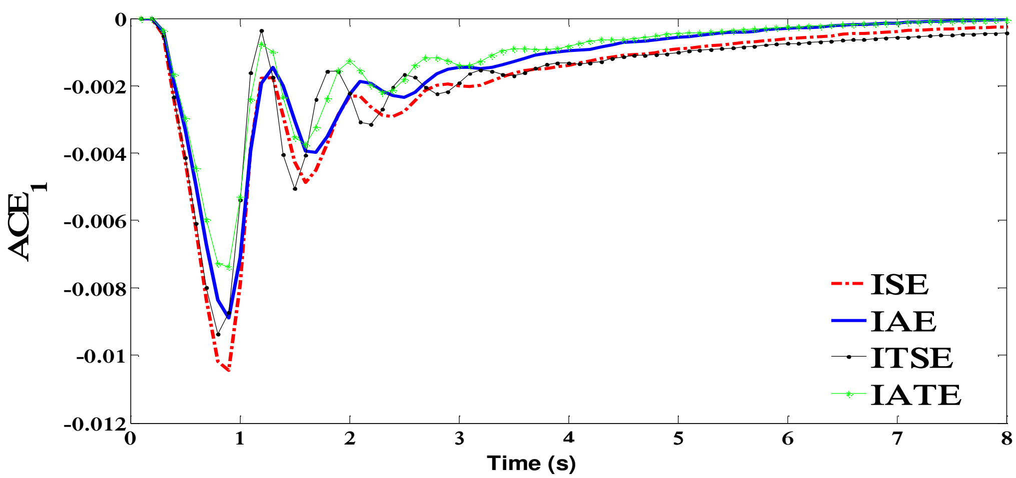

Figure 13. Dynamic response of ACE_1 for 1% load disturbance in Area-1.

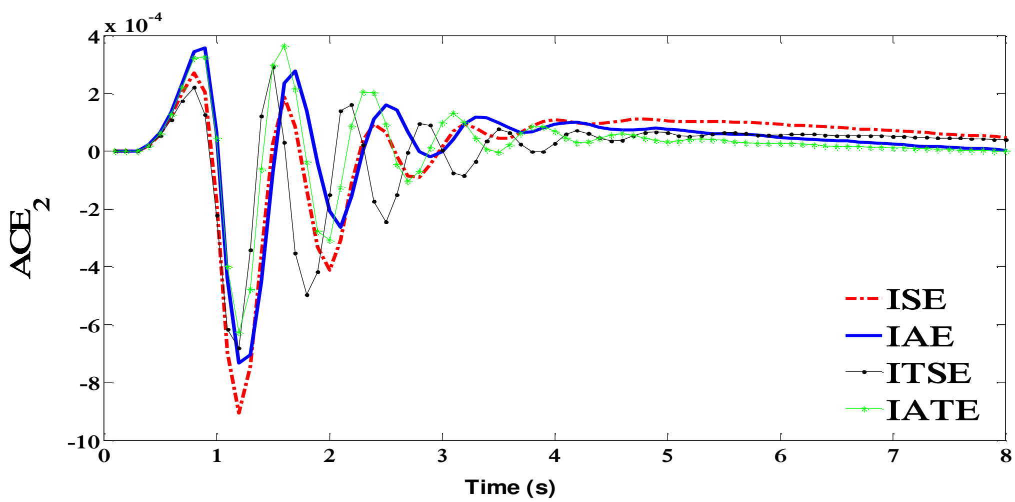

Figure 14. Dynamic response of ACE_2 for 1% load disturbance in Area-1.

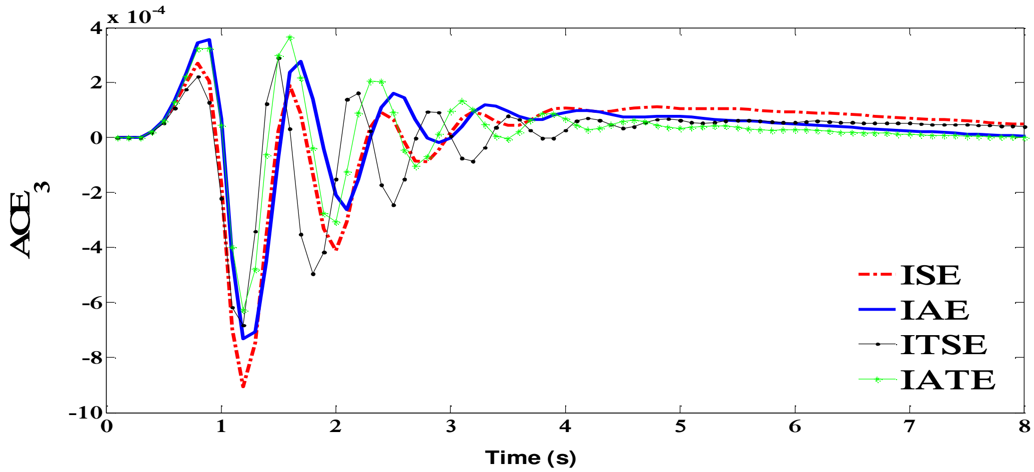

Figure 15. Dynamic response of ACE_3 for 1% load disturbance in Area-1.

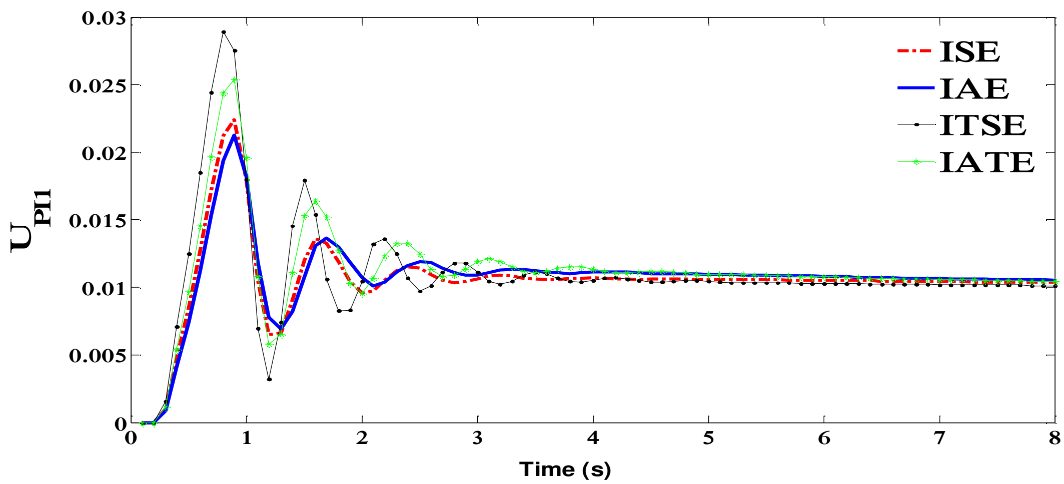

Figure 16. Dynamic response of U_{PI1} for 1% load disturbance in Area-1.

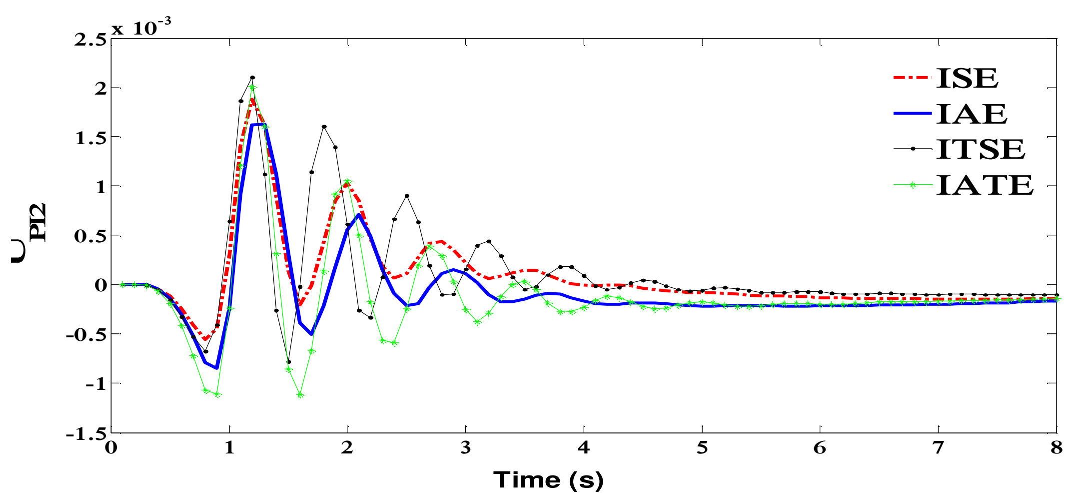

Figure 17. Dynamic response of U_{PI2} for 1% load disturbance in Area-1.

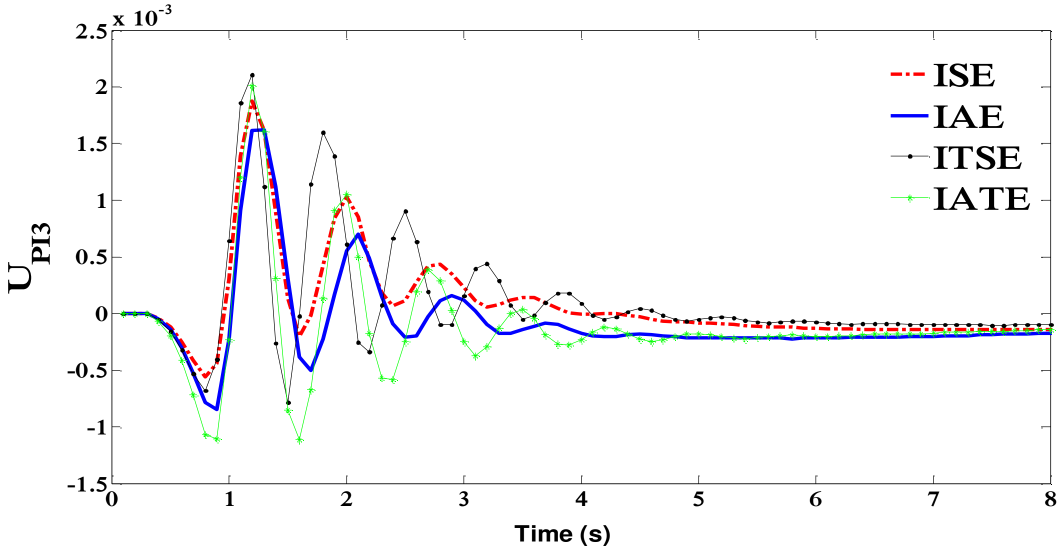

Figure 18. Dynamic response of U_{PI3} for 1% load disturbance in Area-1.

A comparison between the standard and optimal cost function revealed that the system performance can be improved. A different cost functions are also presented by its effectiveness in the model. Such proposed optimal PI controller has the advantage of being systematic, derivative-free and weakly dependent on the power systems model.

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