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Decentralized automatic generation control of interconnected power systems incorporating asynchronous tie-lines

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Abstract

This Paper presents the design of decentralized automatic generation controller for an interconnected power system using PID, Genetic Algorithm (GA) and Particle Swarm Optimization (PSO). The designed controllers are tested on identical two-area interconnected power systems consisting of thermal power plants. The area interconnections between two areas are considered as (i) AC tie-line only (ii) Asynchronous tie-line. The dynamic response analysis is carried out for 1% load perturbation. The performance of the intelligent controllers based on GA and PSO has been compared with the conventional PID controller. The investigations of the system dynamic responses reveal that PSO has the better dynamic response result as compared with PID and GA controller for both type of area interconnection.

Keyword: Automatic generation control; Genetic algorithm; Particle swarm optimization; Ziegler and Nichols method asynchronous tie-line

1. Introduction

Modern Power system consists of large number of generating units interconnected by transmission lines. The interconnection of the power systems enhance the stability and become a viable tool to provide the almost uninterruptible power to load canters from generating stations. The two power system areas may be connected through synchronous/asynchronous tie-lines. To provide a good quality of power, the operation of power system must be maintained at the nominal frequency and voltage profile. And it is achieved by controlling of real and reactive powers. A modern power system is divided into a number of control areas and each area is responsible for its own load and power interchanges. If the input-output power balance is not maintained, a change in frequency will occur which it highly undesirable. In modern interconnected power system, automatic generation control (AGC) is used to maintain the system frequencies and tie-line power flows at the specified nominal values.

The automatic generations control of interconnected power systems has become more significant as size and complexity of the system is going on increasing to meet out power demand. A large number of control techniques have been proposed by the researchers for the design of AGC regulators. In the early era, the AGC strategies were proposed base on centralized control strategy (Quazza 1966; Elgerd & Fosha 1970; Aldeen & Trinh 1994; Fosha & Elgerd 1970). The limitation of AGC centralized control strategy is that it requires the exchange of information from control areas spread over distantly connected geographical areas along with their increased computational and storage complexities. The decentralized automatic generation control strategies deals the limitations of centralized power system very effectively (Kawabata and Kido 1982; Park & Lee 1984; Calovic 1984; Aldeen and Marsh 1990,1991; Aldeen 1991; Yang et al. 1998,2002). The researchers (Kumar et al. 1985) proposed the systematic distributed control design methods and achieved almost identical results

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as obtained with the centralized strategies. The design of decentralized load frequency controllers based on structured singular values and multiple control-structure constraints are discussed in (Kumar et al. 1987; Shayeghi et al. 2007). The decentralized AGC regulator design based on the structured singular value is designed for local area robust analysis, and an eigen value method is derived for tie-line robustness analysis (Tan & Zhou 2012). (Tan 2011) proposed a method to analyze the stability of multi-area power system by accounting the inherent structure of the multi-area power system. (Sudha and Vijaya Santhi 2011) proposed a Type 2 Fuzzy controller for decentralized two area interconnected power system with consideration of generation rate constraint.

2. Power system models

In this paper two power system models are considered for design of decentralized AGC regulators using PID, GA and PSO. The area interconnection in one power system model is only AC tie line and in the second model Parallel AC/DC link is considered

3. State space model

The linear time-invariant state space representation of interconnected power system is given by the following equations:

$$\dot{X} = AX + BU + \Gamma D \tag{1}$$

$$Y = Cx \tag{2}$$

Where A, B, Γ are system, control and disturbance matrices and x, u and d are system control and disturbance vectors.

Power system model–I:

$$[X_1]^T = [\Delta f_1 \Delta P_{t1} \Delta P_{g1} \Delta f_2 \Delta P_{t2} \Delta P_{g2} \Delta P_{tie12} ACE_1 ACE_2]$$

$$[U_1] = [u1 \ \ u2], \ \ [D_1] = [\Delta P_{d1} \ \ \Delta P_{d2}]$$

Power system model–II

$$[X_2]^T = [\Delta f_1 \Delta P_{t1} \Delta P_{g1} \Delta f_2 \Delta P_{t2} \Delta P_{g2} \Delta P_{tie12} ACE_1 ACE_2 \Delta P_{dc}]$$

$$[U_2] = [U_1], \ \ \ [D_2] = [D_1]$$

State equations:

From the transfer function block diagram shown in Figure 1, the following equations are obtained:

$$\dot{x}_1 = -\frac{1}{T_{p1}}x_1 + \frac{K_{p1}}{T_{p1}}\dot{x}_2 - \frac{K_{p1}}{T_{p1}}x_7 - \frac{K_{p1}}{T_{p1}}\Delta P_{d1} \tag{3}$$

$$\dot{x}_2 = -\frac{1}{T_{t1}}\dot{x}_2 + \frac{1}{T_{t1}}x_3 \tag{4}$$

$$\dot{x}_3 = -\frac{1}{R_1 T_{g1}}\dot{x}_1 - \frac{1}{T_{g1}}x_3 + \frac{1}{T_{g1}}u_1 \tag{5}$$

$$\dot{x}_4 = -\frac{1}{T_{p2}}x_4 + \frac{K_{p2}}{T_{p2}}x_5 + \frac{K_{p2}}{T_{p2}}x_1 - \frac{K_{p2}}{T_{p2}}\Delta P_{d2} \tag{6}$$

$$\dot{x}_5 = -\frac{1}{T_{t2}}x_5 + \frac{1}{T_{t2}}x_6 \tag{7}$$

$$\dot{x}_6 = -\frac{1}{R_2 T_{g2}}x_4 - \frac{1}{T_{g2}}x_6 + \frac{1}{T_{g2}}u_2 \tag{8}$$

$$\dot{x}_7 = 2\pi T^0 x_1 - 2\pi T^0 x_3 \tag{9}$$

$$\dot{x}_8 = B_1 x_1 + x_7 \tag{10}$$

$$\dot{x}_9 = B_2 x_4 - x_7 \tag{11}$$

From the above equations, System, control and disturbance matrices can be obtained as given below:

State matrix 'A', Control matrix 'B', and disturbance matrix Γ for power system model-I are as follows below. The same matrices can be obtained for the power system model-II.

$$A = \begin{bmatrix} -1/Tp1 & Kp1/Tp1 & 0 & 0 & 0 & 0 & -Kp1/Tp1 & 0 & 0 \\ 0 & -1/Tt1 & 1/Tt1 & 0 & 0 & 0 & 0 & 0 & 0 \\ -1/R1Tg1 & 0 & -1/Tg1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1/Tp2 & Kp2/Tp2 & 0 & Kp2/Tp2 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1/Tt2 & 1/Tt2 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1/R2Tg2 & 0 & 1/Tg2 & 0 & 0 & 0 \\ 2\pi T^0 & 0 & 0 & -2\pi T^0 & 0 & 0 & 0 & 0 & 0 \\ B1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & B2 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 1/Tg_1 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 1/Tg_2 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \quad \Gamma = \begin{bmatrix} -Kp_1/Tp_1 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & -Kp_2/Tp_2 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

The area control error for area-1 is defined as:

$$ACE_1 = \Delta P_{tie1} + B_1 \Delta f_1 \tag{12}$$

and the feedback control for Area-1 takes the form

$$u_1 = -K_1(s)ACE_1 \tag{13}$$

where $K_1(s)$ is the local LFC controller for area-1.

According to (Tan 2009,2010), a decentralized controller can be designed assuming that there are no tie-line power flows, In this case the local feedback control will be

$$u_1 = -K_1(s)B_1 \Delta f_1 \tag{14}$$

4. A control scheme for an interconnected power system
4.1 Tuning of AGC parameter
The AGC regulator has the objective to minimize area control error (Xue et al. 2007). The AGC regulators
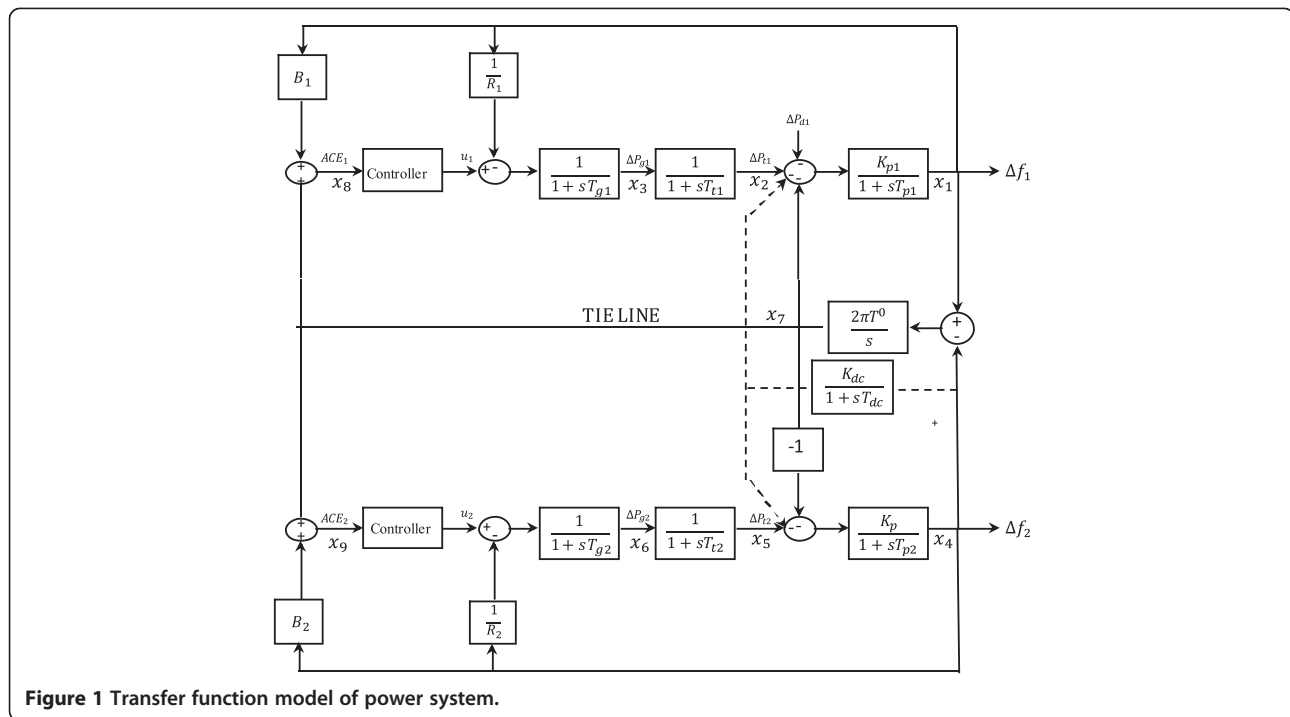
Figure 1 Transfer function model of power system.

having single output as a control signal based on PID is given below;

$$u(t) = K_P \left[e(t) + \frac{1}{T_i} \int_0^t e(\tau) d\tau + T_d \frac{de(t)}{dt} \right] \qquad (15)$$

where $u(t)$ is the control input for governor , e(t) the error , The tuning process of PID controller gain is done by Ziegler and Nichols (ZN) method (Asttrom & Hagglund 1995). The proportional, integral and derivative gains are calculated for the critical ultimate gain, Ku and oscillation of ultimate time period, Tu. These gains are shown below in Table 1.

4.2 Genetic algorithm

The genetic algorithm is a nature inspired optimization technique (Goldberg 1989). There are some sequential steps to be followed in developing the GA for automatic generation control. The Chromosomes Structure is built up with the initial set of random population in the form chromosomes which consists of genes as binary bits. These binary bits are then decoded to give proper string

Table 1 Gains of PID controller

Controllers	Proportional gain	Integral gain	Derivative gain
P	0.5 Ku		
PI	0.4 Ku	0.8 Tu	
PID	0.6 Ku	0.5 Tu	0.12 Tu

for optimization. The new population are regenerated which is to be converged at global optimum by the specified selection, crossover and mutation operators. Elitism is applied to save and use previously found best partner in subsequent fittest generation of population.

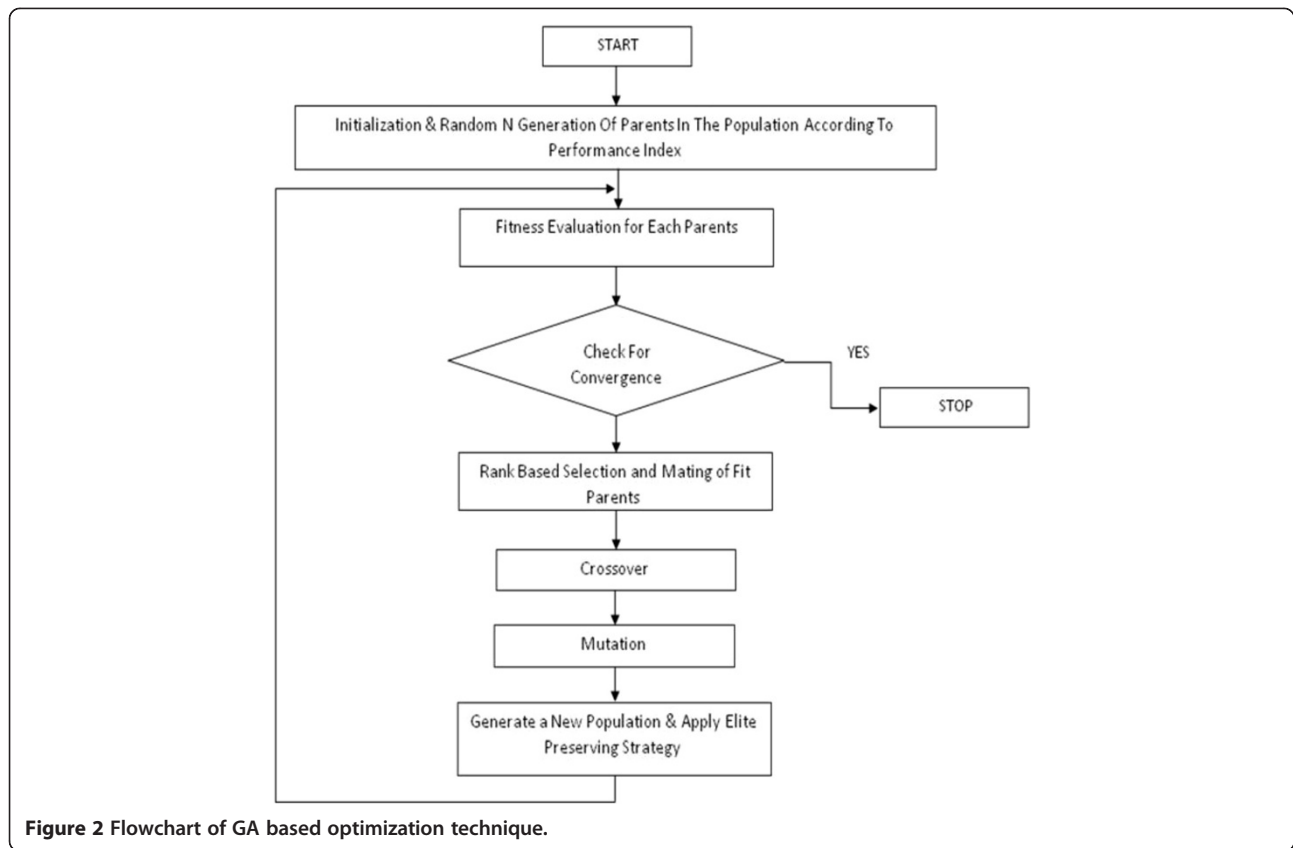The processes stop as soon as convergence criterion is satisfied.

The flow chart of the GA algorithm used in this work is shown in Figure 2.

4.3 Particle Swarm Optimization (PSO)

Particle swarm optimization (PSO) is a population-based stochastic optimization technique which is based on the social behavior of bird flocking, fish schooling and swarming theory (Kennedy & Eberhart 1995; Eberhart & Kennedy 1995). In the PSO method, a swarm consists of a set of individuals named as particles are specified by their position and velocity vectors $(x_i(t), v_i(t))$ at each time. In an n-dimensional solution space, each particle is treated as an n-dimensional space vector and the position of the ith particle is presented by $x_i = [x_i (1), xi(2), ..., xi(n)]$; then it flies to a new position by the velocity represented by $v_i = [v_i(1), v_i(2), ..., v_i(n)]$. The best position for i^{th} particle represented by $p_{best,i} = [p_{best,i}(1), p_{best,i}(2), ..., p_{best,i}(n)]$ is determined according to the best value for the specified objective function and this global best position is represented as $g_{best} = (g_{best},1, g_{best},2, ..., g_{best},n)$. For the next iteration, the position x_{ik} and velocity v_{ik} corresponding to

Figure 2 Flowchart of GA based optimization technique.

the kth dimension of ith particle are updated using the following equations:

$$v_{ik}(t+1) = w.v_{ik} + c_1.rand_{1,ik}\left(p_{best,ik}(t)\right)$$
$$+ c_2.rand_{2,ik}\left(g_{best,k}(t) - x_{ik}(t)\right) \qquad (16)$$

$$x_{i,k}(t+1) = x_{ik}(t) + v_{ik}(t+1) \qquad (17)$$

where i = 1, 2, ..., n is the index of particles, w is the inertia weight, $rand_{1,ik}$ and $rand_{2,ik}$ are random numbers in the interval [0 1], c_1 and c_2 are learning factors, and t represents the iterations.

The flow chart of PSO as implemented for optimization is shown in Figure 3.

## 5. Simulation results and discussion
The dynamic responses of various system states of interconnected decentralized power system are obtained for AGC regulators designed using PID, GA and PSO. The simulation work is carried out using MATLAB software with numerical data shown in appendix A. In this paper both AC tie-line and parallel AC/DC tie-line as area interconnection are considered for the investigations. The time responses are plotted for various system states

with implementation of designed AGC regulators considering 1% load perturbation in area-1. The Figures 4 and 5 show the dynamic responses of the frequency deviations in area-1 and area-2 respectively. The investigations of these plots inferred that with PSO controller, the oscillation, overshoot decreases as compared with GA and PID controller and also the settling time is faster in the case of time response with PSO with AC/DC tie-line compared to those offered by GA and PID. Figure 6 represents the tie-line power flow deviation between the two areas. The analysis reveals that the proposed controllers are capable to mitigate the deviations in tie-line power flows. The PSO controller has the superiority to the GA and PID in terms of over shoots and settling time. The Figures 7 and 8 are plotted for the area control error for area 1&2 respectively, the Figure 7 shows that the PSO controller has the best over shoot and settling time. The Figure 8 shows that the overshoot and settling time with GA controller is comparable with PSO and PID.

6. Conclusion
The AGC regulators are designed using PID, GA and PSO for two-area interconnected decentralized power

Figure 3 Flowchart of PSO optimization technique.

Figure 4 Dynamic response for Δf₁.
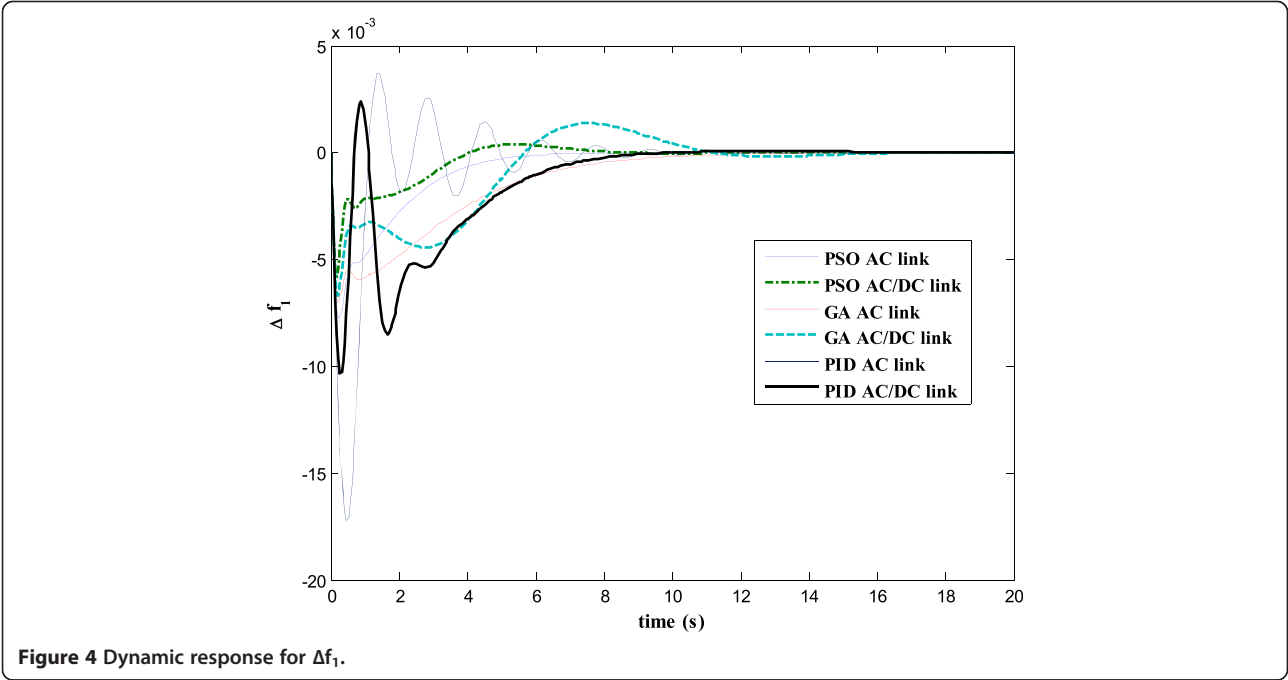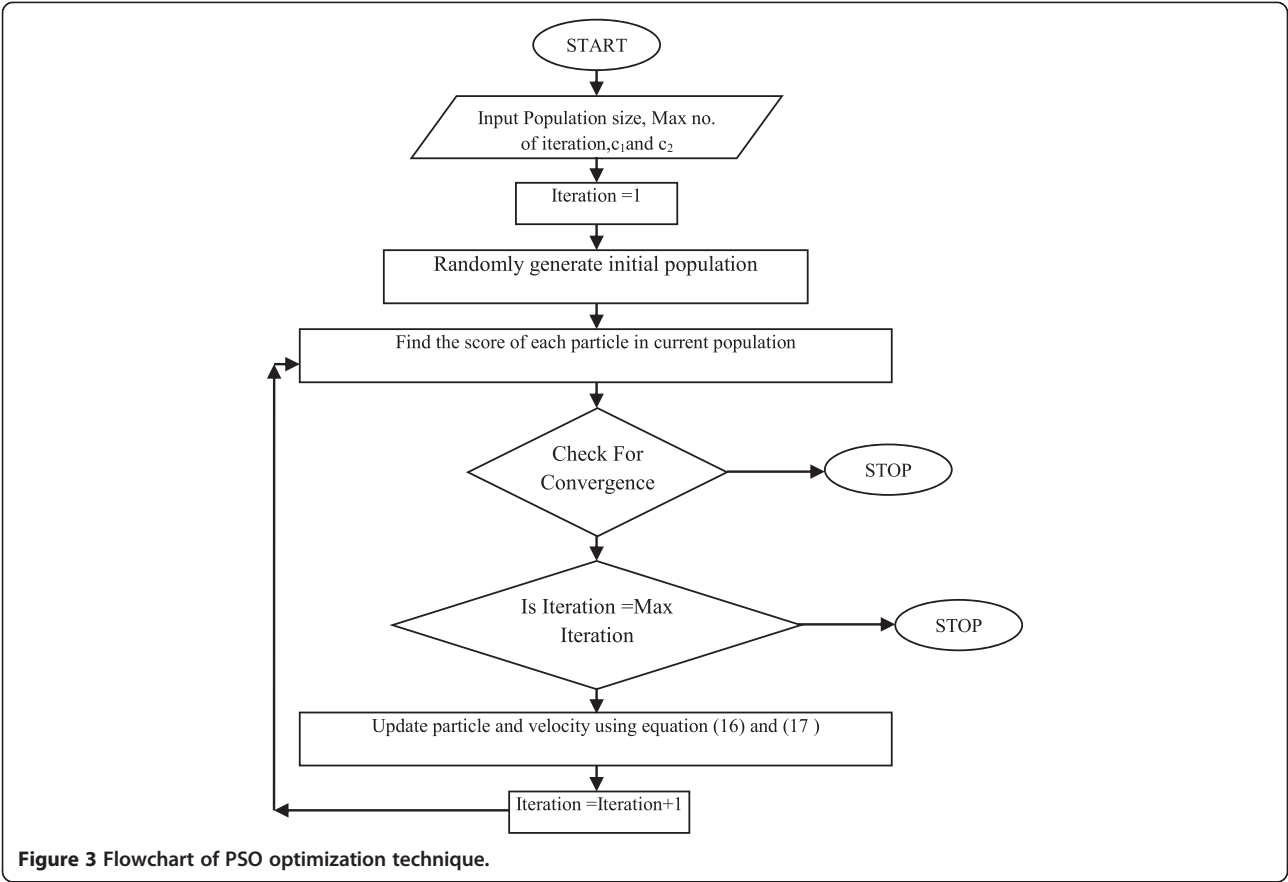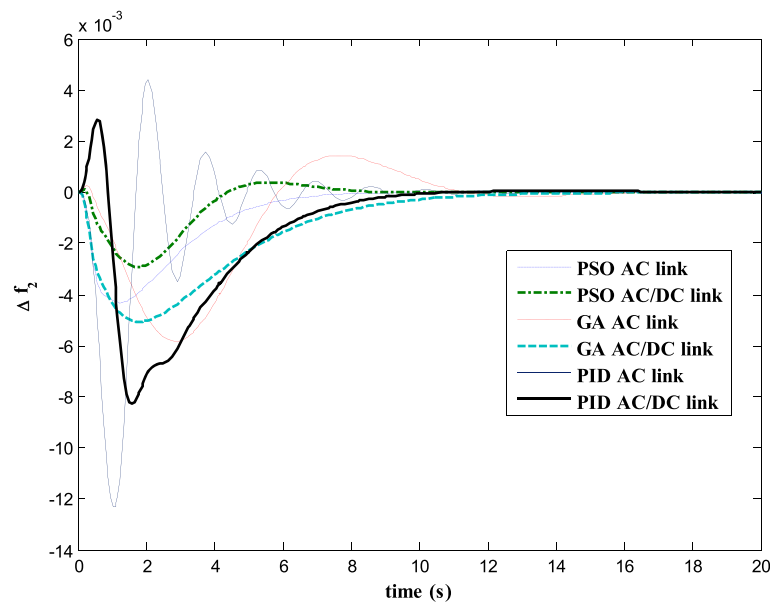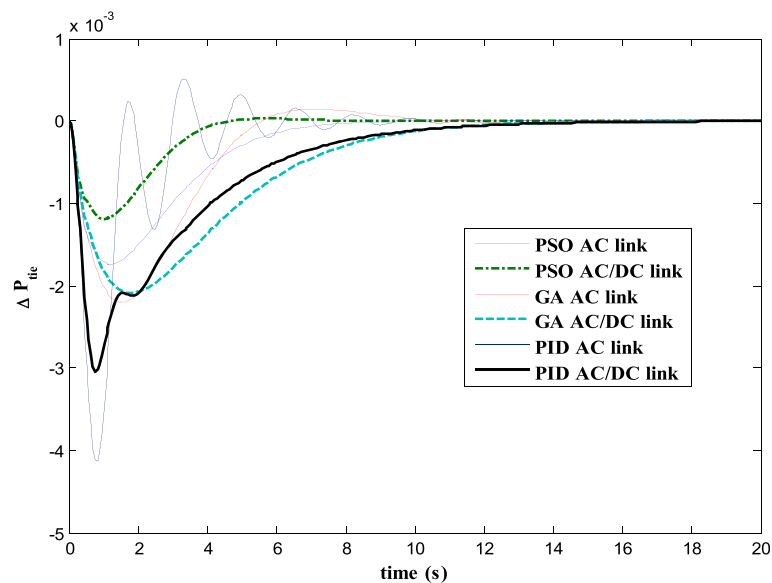
Figure 5 Dynamic response for Δf₂.

system. The area interconnections are considered as AC tie-line and parallel AC/DC tie-lines. Investigations of results are presented that inferred the superiority PSO controller in comparison to PID and GA. The comparisons have been made between the power system model-I and power system model-II consisting of AC tie-line and parallel AC/DC tie-line. The positive effect of DC link in parallel to AC tie-line is also clearly visible in the time response plots of all states with the designed regulators.
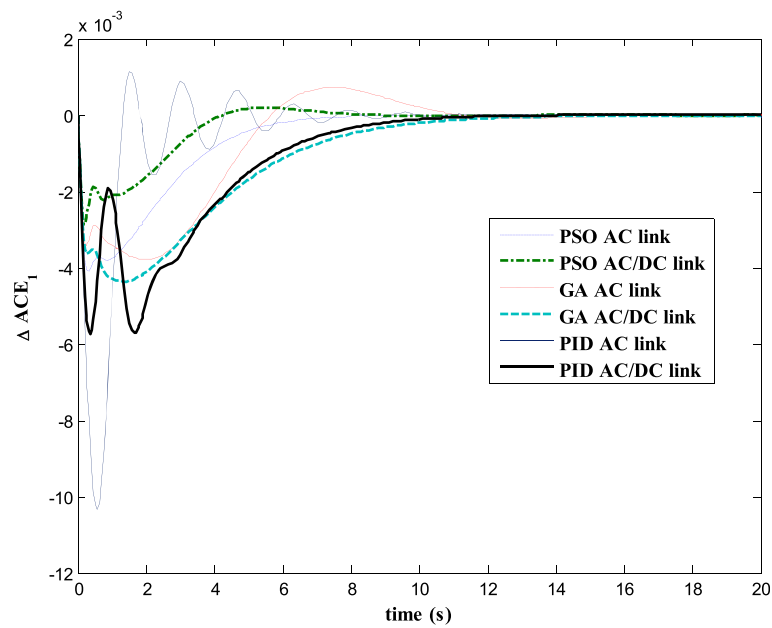
Nomenclature

i subscript referring to area i (i =1,2)
Δf_i frequency deviation of Area (Hz)

Figure 6 Dynamic response for P$_{tie12}$.

Figure 7 Dynamic response for ACE$_1$.

ACE_i area control error,
ΔP_{ti} incremental change in power generation,
ΔP_{gi} incremental change in governor valve position,
ΔP_{tie} tie-line power deviation,
T_{gi} governor time constant for the ith area subsystem (s),
T_{ti} turbine time constant for the ith area subsystem (s),
T_{pi} plant model time constant for the ith area subsystem (s),

T_{ij} synchronizing coefficient between the ith and jth area subsystem (p.u. MW),
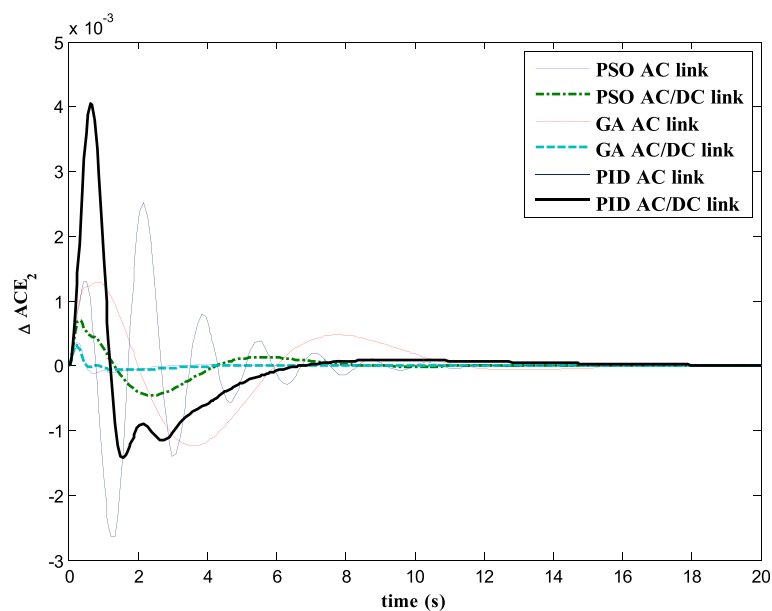K_{pi} plant gain for the ith area subsystem,
R_i speed regulation due to governor action for the ith area subsystem,
$\chi_i(t)$ states of the ith area subsystem,
$u_i(t)$ control input for the ith area subsystem.
ZN Ziegler and Nichols control method
ACE Area Control Error

Figure 8 Dynamic response for ACE$_2$.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

AAH has studied intelligent optimization techniques such as "GA and PSO" and implemented for Decentralized AGC of two area interconnected power system. NH has supervised and reviewed the work carried out here in this paper to the best for the good understanding of the researchers. IB has fine tuned the modeling of the decentralized interconnected power system and simulation results. The authors have read and approved the final manuscript.

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