State Feedback Load Frequency Controller Design Using Artificial Bee Colony Algorithm

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Abstract: Load Frequency Control (LFC) is one of the major issues in the power system design and operation. In this paper a new method to solve load frequency control problem is proposed using the state feedback controller based on Artificial Bee Colony (ABC) Algorithm. For this, the designing problem is restructured as an optimization problem and an objective cost function is used to design the gains of the state feedback matrix. The proposed cost function decrease the frequency deviation and power flow variations. In this paper the ABC algorithm is employed to minimize the proposed cost function. For the purpose of the proposed method's evaluation, the design controller is applied to a two area power system with considerations regarding governor saturation and the results are compared to the one obtained by a classic PI controller. Moreover, the robustness of the proposed method is tested against change of parameters. The simulation studies show that the designed controller by suggested method has a very desirable dynamic performance, better operation and improved system parameters such as settling time and step response rise time even when the system parameters change.
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1. Introduction

With the development of extensive power systems, especially with increasing size, changing structure and complexity of these interconnected systems, the Load Frequency Control (LFC) has become one of the important criterion in electric power system design and operation and has received a great deal of attention [1].

An interconnected modern power system with commercial and industrial loads, require operating at constant frequency with stable and reliable power. The fundamental goals of the LFC in an interconnected power system are to hold reasonably uniform frequency at each area and to maintain the tie-line power interchanges in a predefined tolerance in the presence of modeling uncertainties, system nonlinearities, area load disturbances and sudden changes in load demands [2].

During the past decades, several control approaches have been proposed and applied to the LFC design problem including; optimal control, adaptive control, model predictive control, sliding mode control and robust control which can be found in [2–6], respectively. Each of these techniques has their own advantages and disadvantages.

In [2] the optimal control strategy is presented for dealing with parameter variations. These controllers are based on state-space approach and require the full data related to the system states, whose measurement or estimation is not simple or might be impossible. The authors in [3] presented an implementation of adaptive technique for LFC controller design. Due to requirement of the prefect model, it is rather difficult to apply these techniques to the LFC in practical implementations.

In [4], a linear model predictive control is present to solve LFC problem. Power systems have a wide range of operating conditions that change frequently. So, MPC linear model will not be able to handle the dynamic behavior of them and nonlinear model must be used for better control performance. The sliding mode control is another approach that is used in LFC problem [5], the disadvantage of sliding mode control is sudden and large change of control variables during the process which leads to high stress for the system. Some authors have been employed robust control methodologies [6] to the solution of LFC problem. Although proposed methods gave good dynamical responses, but robustness in the presence of large modeling uncertainties was not considered and stability of the overall system was not guaranteed.

More recently, there has been a growing concern in Artificial Intelligence (AI) techniques, such as fuzzy logic control (FLC) [7], Artificial Neural Network (ANN) [8] and Biologically Inspired (BI) algorithms [9, 10] to design of load frequency controller in a power system by the researches around the world.

State feedback control method is one of the most commonly used techniques in the wide area of control problems and applications. The difficulty of this approach consists essentially in the determination of the state feedback control gains so that the performance specifications, such as rise time, settling time, overshoot, and steady state error is well understood, are satisfied.

The computation of state feedback control gains is conventionally handled by pole placement method or LQR method via Riccati equation. Unfortunately, they still possess trial-and-error approach in choosing their parameters. Therefore, an intelligent method to resolve this problem is proposed by adopting ABC-based optimization.

ABC algorithm is a population-based stochastic optimization algorithm inspired from the particular intelligent behavior of honeybee swarms when searching for food source and proven its superior capabilities, such as faster convergence and better global minimum achievement [11].

This paper investigates the ability of ABC method to design and evaluation of a state feedback load frequency controller of power system. The design problem of state feedback load frequency controller is formulated as an optimization problem according with the time domain based objective function which is solved by the ABC technique that has fewer parameters and stronger search capability as well as is easy to implement. The proposed approach is implemented to a two-area interconnected power system with considerations regarding governor saturation. The results obtained by proposed approach are compared with those obtained by classic PI controller reported in the literature. Simulation studies show that the dynamic performance of the proposed controller is considerably desirable.

2. Overview of ABC algorithm

ABC algorithm, originally developed by Karabog in 2005 [11] which simulates the foraging behaviour of a bee colony. Due to the advantages of the ABC algorithm, such as simple in concept, easy for implementation, and fewer control parameters, it is being researched and utilized to solve different kinds of optimization problems by researchers around the world since 2005, such as data clustering [12], leaf-constrained minimum spanning tree problem [13], designing IIR filters in [14] and designing optimal parameters of power system stabilizer.

In ABC algorithm, the colony of artificial honey bees consists of three types of bees: employed bees, onlookers and scouts, which half of the colony population are employed bees and the remaining of them form the onlooker bees [11]. Each solution of optimization problem is called a food source in the search space. On the other word, the searching process of bees for the food source stands for the finding process for the optimum solution of problem to be optimized. The fitness of solution corresponds to the profitability of food source. Also, the related profitability (fitness) of a food source (solution) is calculated by evaluation of the fitness function of the corresponding variables considering the related objective function. The number of solutions is known as SN and is considered equal to the number of employed bees or the onlookers. The employed bee whose food source has been abandoned by the bees becomes a scout [11, 12].

The main procedures of the ABC algorithm can be written as follows:

Step 1: Initialize population.

Step 2: Send the employed bees onto their food sources and evaluate their nectar amounts (fitness).

Step3: Place each onlooker bee on a food source according to her nectar amounts (quality of her solution), based on the information provided by employed bees

Step4: Determine the source to be abandoned and assign its employed bee as scout for searching area for discovering new food sources.

Step5: Memorize the best food source (solution) found so far.

Step6: Until the termination criterion is satisfied, repeat steps 2-5.

Similar to other evolutionary algorithms, this algorithm begins with an initial population of “SN” food source positions created randomly within the feasible space. Each food source corresponds to a solution in the search space. For D-dimensional problems (D variables), the position of the ith food source is represented as $Xi=[x_{i1},x_{i2},...,x_{iD}]T$. Initial population of artificial bees are generated randomly within the range of the boundaries of the parameters, as follow.

$$X_{ij} = X_j^{min} + rand(0,1)\left(X_j^{max} - X_j^{min}\right) \quad (1)$$

Where, $i\in\{1,2,\ldots, SN\}$ and, $j\in\{1,2,\ldots, D\}$ which, D is the number of optimization parameters. X_j^{min} and X_j^{max} are the lower bound and upper bound of the parameter j, respectively. Also, rand () is a random number in rang of [0, 1].After initialization, all food sources (solutions) are subjected to repeat cycles of the search processes of the honeybees. The search process is continued until the termination criterion is met. The termination criterion could be maximum cycle number (MCN) or when an error tolerance (ε) is met [12].

In step 2, employed bees produce a modification on the position of the food sources (solutions) in their memories depending on local information (visual information) and produce new food source positions (new solutions), V_{ij}, in the neighbourhood of old food source position (old solutions), X_{ij},using the following equation:

$$V_{ij} = X_{ij} + r_{ij}(X_{ij} - X_{kj}) \quad (2)$$

Where, $j \in \{1,2,\ldots, D\}$ is a random integer in the interval [1, D]. $k \in \{1,2,\ldots, SN\}$ is a randomly chosen index that $k \neq i$. Moreover, r_{ij} is a uniformly distributed real random number in the range [-1, 1]. It is an adaptively control parameter that controls the production of neighbour food sources around X_{ij} and determine the comparison of two food positions visually by a bee. As can be seen from (2), as the difference between X_{ij} and X_{kj} reduced, the perturbation on the position X_{ij} gets decreased, too. Thus, as the search find better solution, the step length is steadily decreased.

If this repositioning process produces sources (solutions) with higher nectar amounts (better fitness's) than that of the previous ones, the bees replace the position of new sources with the previous ones. Otherwise they keep the position of the previous sources food in their memories.

At third step, after all the employed bees complete their searches process, they communicate their information related to the nectar amounts (fitness's) and the positions of their sources food (solutions) with the onlooker bees. Then, the onlooker bees calculate the nectar information taken from all employed bees and select food sources by using a selection probability that depends on the fitness values of the solutions in the population. As the fitness of solution increases, the probability of that solution chosen also increases [13].

This probabilistic selection scheme might be a roulette wheel, stochastic universal, rank selection, disruptive selection, tournament selection or another selection method. The basic ABC algorithm uses the roulette wheel selection mechanism in which, the probability value associated with a food source, Pi, can be expressed by the following expression:

$$P_i = \frac{fitness_i}{\sum_{i=1}^{SN} fitness_i} \quad (3)$$

Where fitnessi is the fitness value of the ith food source (solution) and is proportional to the nectar amount of the food source in the ith position. Also, SN denotes the number of food sources which is equal to the number of employed bees or onlooker bees.

After selecting the food source, as in the case of the employed bee, onlookers start to carry out the exploitation process and produce some modifications on the positions in their memories by using (2). Here, new positions V_{ij} are produced for the onlookers from the solutions X_{ij}, selected depending on Pi. Once again, if this repositioning process produces sources food (solutions) with higher nectar amounts (better fitness's) than that of the previous ones, the bees replace the position of new sources with the previous ones. Otherwise they keep the position of the previous sources food in their memories [12, 13].

In ABC algorithm, there is a control parameter which is called "limit" for abandonment. Limit is a predetermined number of cycles that controls the times of updates of a certain solution and is used to determine if there is any exhausted source to be abandoned. For this, after all employed bees and onlooker bees complete their searches; the algorithm checks the counter value which has been updated during search. If the value of the counter is greater than the limit value and there is no improvement becomes possible in the food source position, then the source associated with this counter is assumed to be abandoned and the employed bee becomes a scout. Then scout starts to search a new food source to be replaced with abandoned one.

This is simulated by generating a site position randomly and replacing it with the abandoned one. If the abandoned source is Z_i, then the scout randomly discovers a new food source to be replaced with Z_i. This operation can be expressed as in (4). In basic ABC, it is assumed that only one source can be exhausted in each cycle, and only one employed bee can be a scout. These steps are repeated through maximum cycle number (MCN) or until a termination criterion is satisfied.

$$Z_i^j = Z_{min}^j + rand(0,1)\left(Z_{max}^j - Z_{min}^j\right) \quad (4)$$

3. Power System Model

In actual power system operations, the load is varying randomly and continuously throughout the day. As a result, both frequencies in all areas and tie-line power flow between the areas are affected by these load changes at operating point. These changes create a mismatch between generations and demand that result in exact forecast of real power demand cannot be assured. Therefore, for good and stable power system operation, both the frequency and tie-line power flow should be kept constant against the sudden area load perturbations, system parameter uncertainties and unknown external disturbances. Therefore, to ensure the quality of power supply, a load frequency controller is needed to restoring the system frequency and the net interchanges to their desired values for each control area, still remain.

The area frequency deviation (Δf) and tie-line power deviation (ΔP_{tie}) are two important parameters of interest. The linear combinations of them are known as area control error (*ACE*). The measurements of all the generation and all load in the system for computation of the mismatch between the generation and obligation in one area is so hard. The mismatch is measured at the area control center by using *ACE*. The *ACE* for the *i*th area is defined as:

$$ACE_i = P_{tie_i}^{act} - P_{tie_i}^{s} - 10B_i(f_i^{act} - f_i^{s}) = \Delta P_{tie_i} - 10B_i\Delta f_i \quad (5)$$

Where $P_{tie_i}^{act}$ and $P_{tie_i}^{s}$ are the actual and scheduled (manually set) interchange of ith area with neighboring areas, respectively. Also, f_i^{act} and f_i^{s} are the area's actual and scheduled frequency, in ith area, and B is the frequency bias coefficient of ith area that is a negative number measured in MW per 0.1Hz. However, the ACE signal often is calculated using the area frequency response characteristic β instead of B: as follows:

$$ACE_i = \Delta P_{tiei} + \beta_i \Delta f_i \quad (6)$$

$$\beta_i = \frac{1}{R_i} + D_i \quad (7)$$

In which (D_i) is the damping ratio or the frequency sensitivity of the i^{th} area's load and R_i is the regulation due to governor action in the i^{th} area, or droop characteristic. Also, β_i is frequency bias constant and should be high enough such that each area adequately contributes to frequency control [1].

The frequency and interchanged power are kept at their desired values by means of feedback of area control error containing deviation in frequency and error in tie- line power, and controlling the prime movers of generators. The main objective of control system is to damp these variations to zero as fast and smooth as possible and following a change in the load demand values.

A two-area interconnected power system with considering governor limiters is investigated in this study. Each area consists of three major components, which are turbine, governor, and generator. The detailed transfer function block diagram of uncontrolled two-area system is shown in Fig. 1.

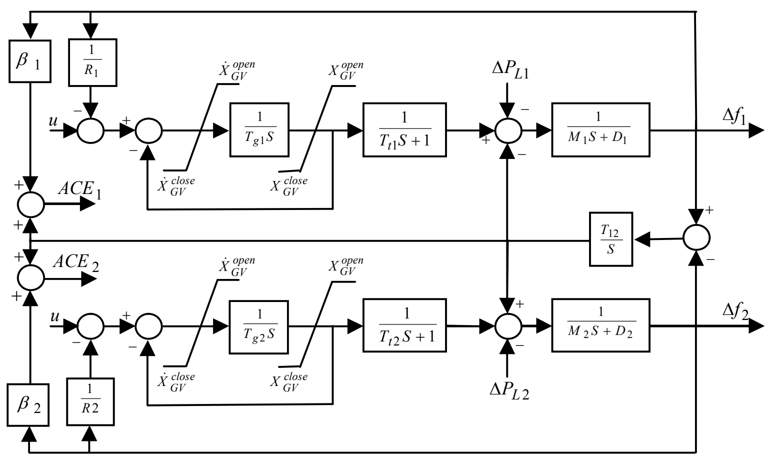

Figure 1. Two-area interconnected power system

Table 1.Two Area Interconnected Power System Parameters

Area	Parameters
Area# 1	M=10, D_1=0.8, T_g=0.2, T_t=0.5, R_1=0.05, $\dot{X}_{GV}^{open}=0.4$, $\dot{X}_{GV}^{close}=1.5$, $X_{GV}^{open}=1.2$ $X_{GV}^{close}=0.4$, T_{12}=2
Area# 2	M=8, D_2=0.9, T_g=0.3, T_t=0.6, R_2=0.0625, $\dot{X}_{GV}^{open}=0.4$, $\dot{X}_{GV}^{close}=1.5$, $X_{GV}^{open}=1.2$, $X_{GV}^{close}=0.4$, T_{12}=2

Where Δf_1 and Δf_2 are the frequency deviations in area 1 and area 2 respectively in Hz. Also ΔP_{L1} and ΔP_{L2} are the load demand changes in areas 1 and 2 respectively in per unit (p.u.). Moreover, T_{gi}, T_{ti} and M_i are speed governor time constant (s), turbine time constant (s), and power system time constant (s) of i^{th} area, respectively. The detailed transfer function models of the speed governors and turbines are discussed in [1]. Typical data for the system parameters and governor limiters, for nominal operation condition, are adopted from [1] and presented in Table 1.

The state-space model of foregoing power system can be modeled as multivariable system as the following equation:

$$\dot{x} = Ax(t) + Bu(t) + \Gamma d \qquad (8)$$

Where *x(t), u(t)* and *d* are state, control and load changes disturbance vectors, respectively and represented as following form:

$$u = [\Delta\Delta_{ref1}\ \ \Delta P_{ref2}]$$
$$d = [\Delta\Delta_{L1}\ \ \Delta P_{L2}] \qquad (9)$$
$$x = [\Delta\Delta_{v1}\ \ \Delta P_{m1}\ \ \Delta\omega_1\ \ \Delta P_{Tie}\ \ \Delta P_{v2}\ \ \Delta P_{m2}\ \ \Delta\omega_2\ \ \Delta E_1\ \ \Delta E_2]$$

Also, *A*, *B* and *Γ* are given in (10) and are respectively the system state, control input and disturbance constant matrixes of appropriate dimensions associated with above vectors. The corresponding coefficient matrices are given in Table 1.

$$A = \begin{bmatrix} \frac{-1}{\tau_{g1}} & 0 & \frac{-1}{R_1\tau_{g1}} & 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{1}{\tau_{T1}} & \frac{-1}{\tau_{T1}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \frac{1}{M_1} & \frac{-D_1}{M_1} & \frac{-1}{M_1} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & T_{12} & 0 & 0 & 0 & -T_{12} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{-1}{\tau_{g2}} & 0 & \frac{-1}{R_2\tau_{g2}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{\tau_{T2}} & \frac{-1}{\tau_{T2}} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{M_2} & 0 & \frac{-1}{M_2} & \frac{-D_2}{M_2} & 0 & 0 \\ 0 & 0 & B_1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & B_2 & 0 & 0 \end{bmatrix} \qquad (10)$$

$$B = \begin{bmatrix} \frac{1}{\tau_{g1}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{\tau_{g2}} & 0 & 0 & 0 & 0 \end{bmatrix}^T$$

$$C = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \end{bmatrix} \quad \Gamma = \begin{bmatrix} 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}^T$$

In equation (9), ΔPref1 and ΔPref2 are output of state feedback controller that obtained from following equation:

$$u = \begin{bmatrix} \Delta P_{ref1} \\ \Delta P_{ref2} \end{bmatrix} = -Kx \qquad (11)$$

Where *K* is state feedback matrix. To provide a reasonable dynamic performance for the system, tuning of feedback matrix parameters is done in the optimization process by using ABC.

4. Design of State Feedback Load Frequency Controller Using ABC

The goals are control of frequency and inter area tie- line power with good oscillation damping, also obtaining a good performance. Here, our task is to determine the state feedback control gains (*K* in Eq. 11) to satisfy performance specifications such as rise time, settling time, overshoot, and steady state error. So, the design problem is converted to an optimization problem and ABC is employed to solve this problem. Here, the state space model and available states are considered as (9) and (10), respectively. The ABC is used to optimize the gains of state feedback controller with a fitness function based on integral of the square of the error (ISE) and the integral of time-multiplied absolute value of the error (ITAE) [1], which are respectively given by:

$$ISE = \int_0^{tf} (ACE_1^2 + ACE_2^2)dt \qquad (12)$$

$$ITAE = \int_0^{tf} t(|ACE_1| + |ACE_2|)dt \qquad (13)$$

The simulations are carried out with the feedback gains obtained from ABC with a fitness function as follow.

$$Fitness = w_1 \times ISE + w_2 \times ITAE \qquad (14)$$

Where w_1 and w_2 are constant coefficient. A digital simulation is used in conjunction with the ABC optimization process to determine the optimum parameters of state feedback controller for the performance index considered. The first step to implement the ABC is generating the initial population where is considered to be 100. The number of employed bees and onlooker bees are considered 50. Also, the predetermined limit is set to 20.

5. Simulation Studies

A two-control area power system, shown in Fig. 1 is considered as a test system. The typical data for the system parameters and governor limiters for nominal operation condition can be given as Table 1.

In order to show the ability and effectiveness of the proposed method, a conventional PI controller by using the approach adopted from [1] is applied for comparison, too. It was found that $K_{I1}=K_{I2}=0.3$ were the best selections for having the best performance. Using ABC method for LFC design, the following results were obtained for state feedback controller parameters:

$$K = \begin{bmatrix} 0.2646 & 1.766 & 27.8879 & -24.6821 & -0.1778 & -0.4892 & -11.2231 & 5.1120 & -3.9871 \\ -0.1560 & -0.3998 & -14.9952 & 35.9892 & 0.8733 & 3.1873 & 51.8614 & -4.7656 & 5.5638 \end{bmatrix}$$

To show the effectiveness of the designed controllers, a time domain analysis is performed for the case study. To test the proposed method, a sudden small load perturbation which continuously disturbs the normal operation of the power system is applied to the system. Here we use a step load change of 0.01 p.u., (i.e. $\Delta P_{L1} = \Delta P_{L2} = 0.01$). The frequency deviation of both areas and tie-line power variation in nominal condition of the closed loop system are obtained and shown in Figs. 2, 3 and 4 respectively.

To show the robustness of the proposed approach and to investigate the effect of changing the system parameters on system performance, the system parameters is considered as 25% increase for all system parameters. Figs 5-7 show response system for upper bound parameters condition including frequency deviation of areas 1 and 2, and also, tie-line power deviation.

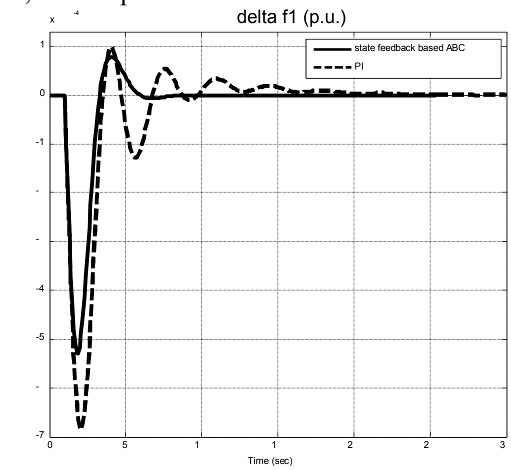

Figure 2. Frequency deviation of area 1

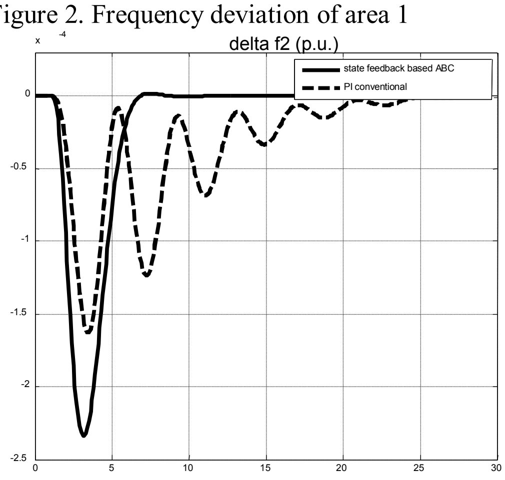

Figure 3. Frequency deviation of area 2

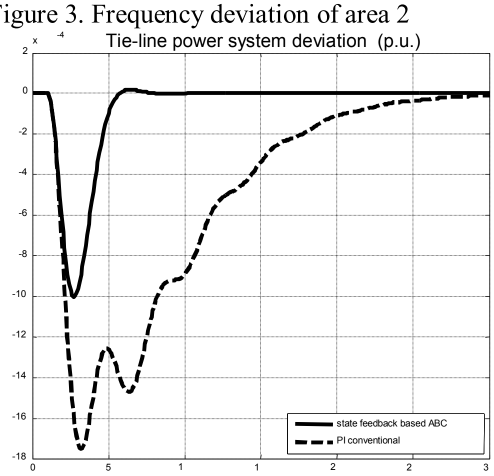

Figure 4. Tie-line power deviation

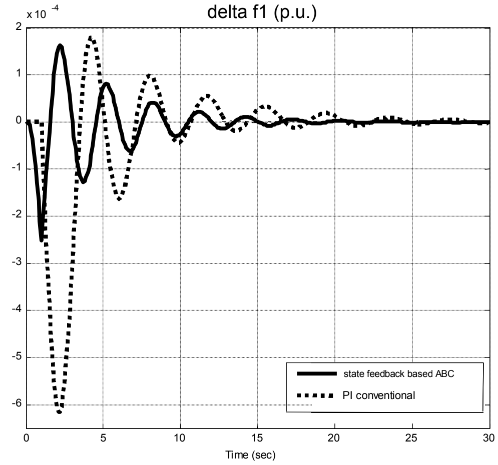

Figure 5. Frequency deviation of area 1 for upper bound of parameters

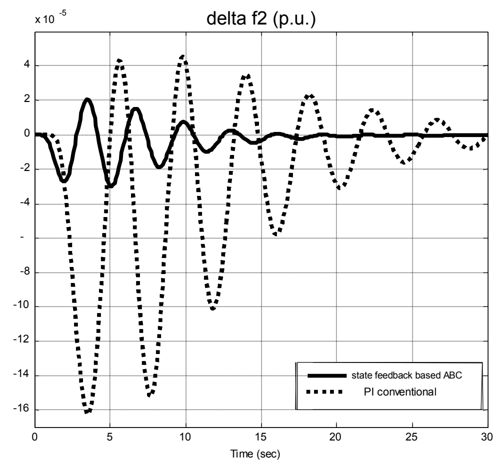

Figure 6. Frequency deviation of area 2 for upper bound of parameters

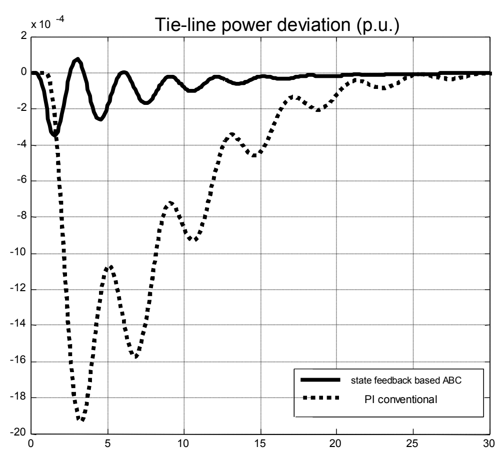

Figure 7. Tie-line power deviation for upper bound of parameters

From the comparing curves it can be seen, using the proposed method, the frequency deviation and tie-line power variation of two areas following the load changes and are quickly driven back to zero. It should be mentioned that although the overshoot of frequency response of classical PI controller shown in Fig. 4 is better than the proposed approach, but the settling time of the latter is better than the former. Generally, by looking at Figs. 4-6 it can be oncluded that the proposed method gives a better performance than the classical LFC.

Conclusions

In this paper a new control system incorporating the state feedback control and artificial bee colony algorithm is used for control of frequency and damping inter area tie-line power variation in a multi-machine power system. The performance of designed controller is tested on a two-area power system with considering governor limiters and the results obtained are compared with the classical PI controller. The simulation studies show that the designed controllers by proposed method have a very desirable dynamic performance over the PI controller in terms of settling time and step response rise time, even when the system parameters change.

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