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Tuning of Optimal Classical and Fractional Order PID Parameters forAutomatic Generation Control Based on the Bacterial Swarm Optimization

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Abstract: Particle Swarm Optimization algorithm converges rapidly during the initial stage of a global search, but around global optimum, the search process slows down. In order to overcome this problem and to further enhance the performance of Particle Swarm Optimization, this paper implements a hybrid algorithm, Bacterial Swarm Optimization, combining the features of Bacterial Foraging Optimization and Particle Swarm Optimization.The PID parameters of classical and fractional-order controllers are optimized with Bacterial Swarm Optimization for load frequency control of a two area power system. Simulation results show fractional-order PID controller has less settling time and less overshoot than the classical PID controller for most of studies.

Keywords: Power system control, automatic generation control, bacterial swarm optimization, fractional calculus, fractional-order PID controller.

1. INTRODUCTION

Although the amount of electrical energy consumption per capita indicates the developmental level of countries, the quality of the energy consumption is also an important criterion from now on. System frequency and system voltage are the most important two parameters, which determine the power quality. Frequency is a predominant parameter in a power system, which needs to be controlled with priority. A load change, which occurs in any areain an interconnected power system, causes other areas connected to be affected in terms of frequency and power. Furthermore, the characteristic of tie-line between the regions in the interconnected system is another factor affecting the frequency deviation. When the deviation, which occurs in the frequency of the power system, exceeds the limits, this can cause serious instability problems; power plants connected to the system to tripand the system to collapse (black-out) at a later stage. On such occasion, aregion fed from the system will remain without energy and there will be huge economic losses. System crashes affecting 150 million people in Bangladesh and 620 million people in India are the examples of this situation. Consequently, load-frequency control is an important subject when the area it affects is taken into consideration at the present day.

The most significant point in control applications is to determine the controller parameters to provide required performance, which is an optimization problem. Heuristic methods, which are commonly used in control and optimization problems, are inspired from the behaviours of systems/livings in nature (Akyol and Alataş, 2012). Particle Swarm Optimization (PSO), Bacterial Foraging Optimization (BFO) and Bacterial Swarm Optimization (BSO), which is a hybrid structure in which the advantages of PSO and BFO are combined (Biswas et al., 2007), are recently used in load-frequency control (Korani, Dorrah and Emara, 2009). In these studies, advantages of BSO algorithm have been demonstrated against PSO and BFO.

Controllers used commonly in industry are classical PID (CPID). Inparallel with the developments in computer technologies, fractional-order calculus has been used intensely by the fractional-order controllers in control of linear systems (Vinagre et al.,2002; Valério and Costa, 2005). One of the fractional-order controllers is the fractional-order PID (FOPID) controller. This controller was not only used in control of linear systems (Podlubny, Dorcakand Kostial, 1997; Podlubny, 1999; Hamamci, 2008), but also in control of nonlinear systems (Çelik and Demir, 2010) and its efficacy was demonstrated in comparison with CPID.

In this study, the parameters of the CPID and the FOPID, which control the frequency of two area power systems with single-machine, were optimized using BSO. To the best of authors' knowledge, BSO algorithm is used for the first time for tuning of the FOPID of two area load frequency control (LFC) system. Integral of Time multiplied by Absolute Error (ITAE), Integral of Absolute Magnitude of the Error (IAE), Integral of the Squared Error (ISE), and Integral of Time multiplied by the Squared Error (ITSE) cost functions were used in the optimizations as performance indices. The main contribution of this paper is to show that the FOPID controller performance is better than the CPID controller for

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the investigated system. The frequency deviations in two areas for each performance index and the power variation in the tie-line for ISE index were obtained in the simulation. The mathematical model and block diagram of a two-area power system were givenin Section 2. The fractional calculus and the FOPID controller were introduced in Section 3 and, in Section 4, the BSO algorithm, which is a hybrid structure, was given. Simulation results were presented in Section 5 and the results were discussed in the last Section.

2. POWER SYSTEM MODEL

Potential/Kinetic energy is converted into mechanical energy by means of turbines and then the mechanical energy is converted into electrical energy via generators in a power plant, which has rotating machines. Simplified equation of motion belonging to this principle is written:

$$T_m - T_e = J\frac{d\omega}{dt} \quad (1)$$

where, T_m is mechanical momentum, T_e is load moment, J is the moment of inertia and ω is angular velocity.

Turbine, generator, and load can be expressed as main components of the power system. There are much studies onthe multi-area power systems. In a power system, which has two or more control areas, automatic load frequency control ensures that power exchange between the areas is among the desirable values as well as helping frequency control by providing the required active power output from the generators.

An interconnected power system consists of areas connected to each other with tie-line. It is assumed that generator groups, which exist in each of the areas, have a composite structure. The frequency deviations can occur in some areas of the power system. Deviations cause a variation in power flow in tie-line. In the present case, the variation and area frequency are required to be controlled.

Each area provides its own users with energy and tie-line allows inter-areas power flow. Therefore, when there is a sudden load change in an area, frequency in other areas and power flow in tie-lines are affected. Controllers need information about transient state of each area to return the system to the required steady state. Thus, it could return frequency of the system to the required steady state. If losses in tie-line are ignored, the power flow in tie-line can be written as

$$P_{line12} = \frac{|V_1|\cdot|V_2|}{X_{12}}\sin(\delta_1 - \delta_2) \quad (2)$$

WhereV_1 and V_2 are voltage amplitude of the 1st and 2nd areas, respectively, δ_1 and δ_2 are corresponding phase angles, and X_{12} is impedance of tie-line between the two areas. When the phase angle deviation for each area is written as

$$\Delta\delta = 2\pi\int\Delta f dt \quad (3)$$

Power flow deviation between areas will be

$$\Delta P_{12} = \frac{|V_1|\cdot|V_2|}{X_{12}}\cos(\delta_1 - \delta_2)(\Delta\delta_1 - \Delta\delta_2) = T_{12}(\Delta\delta_1 - \Delta\delta_2) \quad (4)$$

where the synchronizing moment coefficient of the tie-line is

$$T_{12} = \frac{|V_1|\cdot|V_2|}{X_{12}}\cos(\delta_1 - \delta_2) \quad (5)$$

When the moment coefficient is written in its place in (4), the power deviation of the tie-line will be:

$$\Delta P_{tie} = T_{12}(\Delta\delta_1 - \Delta\delta_2) \quad (6)$$

In consequence of power deviation ΔP_L of the system, frequency deviation, power deviation and control error (Area Control Error – ACE) are as follows:

$$\Delta f = \frac{-\Delta P_{L1}}{\frac{1}{R_1} + \frac{1}{R_2} + D_1 + D_2} \quad (7)$$

$$\Delta P_{tie} = \frac{-\Delta P_{L1}(\frac{1}{R_2} + D_2)}{\frac{1}{R_1} + \frac{1}{R_2} + D_1 + D_2} \quad (8)$$

$$ACE_1 = \Delta P_{tie} + B_1\cdot\Delta f_1 \quad (9)$$

$$ACE_2 = B_2\cdot\Delta f_2 + a_{12}\cdot\Delta P_{tie} \quad (10)$$

Block diagram of the power systemwith two interconnected areas is shown in Figure 1.

Transfer function of each block is given below:

Governor:

$$G_{g1}(s) = G_{g2}(s) = \frac{K_h}{T_h\cdot s + 1} \quad (11)$$

Re-heater:

$$G_{rh1}(s) = G_{rh2}(s) = \frac{(K_{r12}\cdot T_{r11})\cdot s + 1}{T_{r1}\cdot s + 1} \quad (12)$$

Turbine:

$$G_{t1}(s) = G_{t2}(s) = \frac{K_t}{T_t\cdot s + 1} \quad (13)$$

Power system:

$$G_{ps1}(s) = G_{ps2}(s) = \frac{K_g}{T_g\cdot s + 1} \quad (14)$$

Tie-line:

$$G_{tl}(s) = \frac{2\pi\cdot T_{12}}{s} \quad (15)$$

The system under investigation consists of two-area interconnected power system of reheat thermal plant. Each area has a rating of 2000 MW with a nominal load of 1000 MW. The system is widely used in the literature for the design and analysis of automatic load frequency control of interconnected areas (Yalcin,Çam and Lüy, 2010;Sathya and Ansari, 2015). In Fig. 1, B_1 and B_2 are the frequency bias parameters; ACE_1 and ACE_2 the area control errors; R_1 and R_2 the governor speed regulation parameters in pu Hz; K_h and T_h the speed governor time constants in *sec*; ΔXG_1 and ΔX_{G2} the governor output command (pu); T_{t1} and T_{t2} the turbine time constant in *sec*;

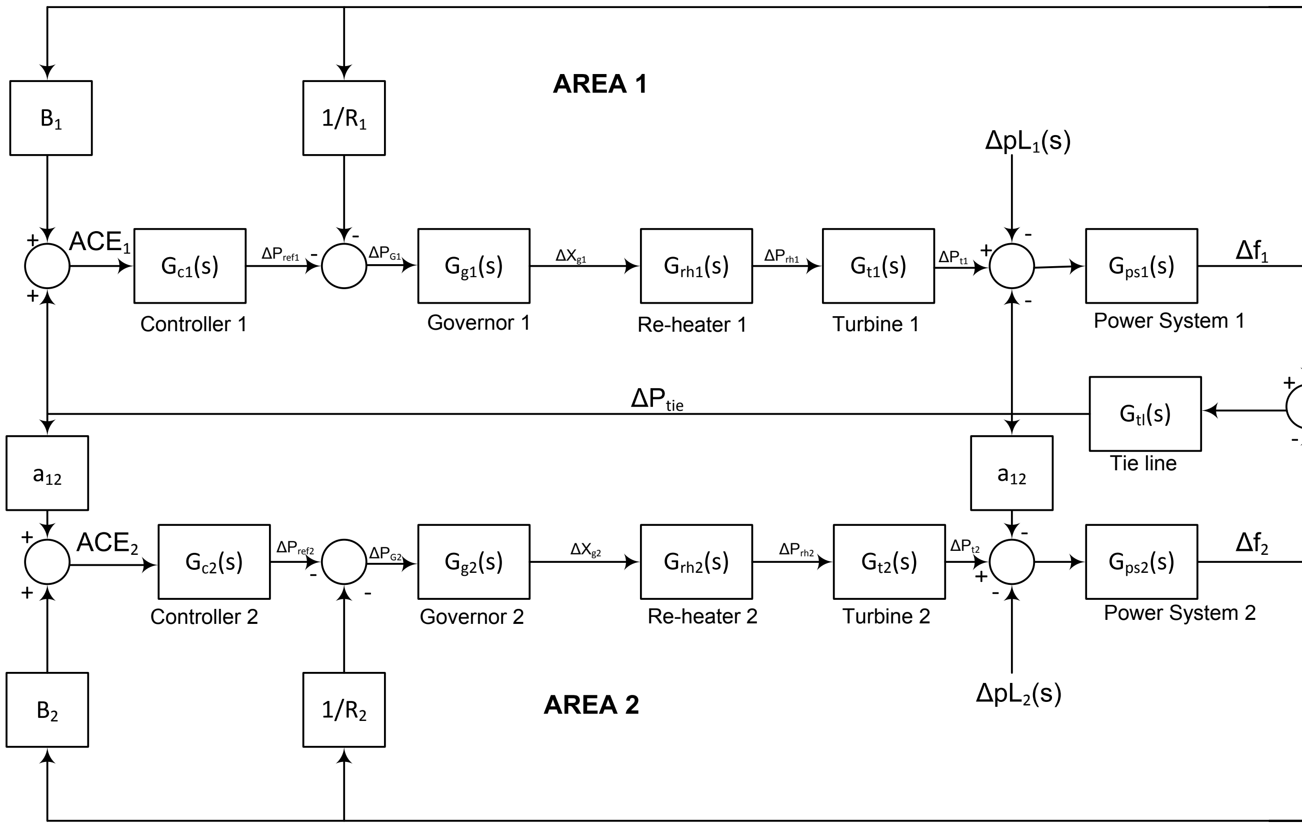

Fig. 1.Two-area power system model.

ΔP_{t1} and ΔP_{t2} the change in turbine output powers; ΔP_{L1} and ΔP_{L2} the load demand changes; ΔP_{tie} the incremental change in tie-line power (pu); K_g the power system gains; T_g the power system time constant in s; T_{12} the synchronizing coefficient and Δf_1 and Δf_2 the system frequency deviations in Hz. Parameter values of the system examined in this study are shown in Appendix.

3. FRACTIONAL CALCULUS AND FRACTIONAL-ORDER PID CONTROLLERS

Liouville, Riemann, and Holmgren are examples of the researchers executed the first systematic studies related to fractional calculus (Oldham and Spanier,1974). Many approaches were suggested about fractional-order integral or derivative in these studies (Podlubny,1999). In general, fractional-order integral and derivative operator can be expressed in the form of differ-integral:

$$ {}_bD_t^{\alpha} = \begin{cases} \dfrac{d^{\alpha}}{dt^{\alpha}} & R(\alpha) > 0, \\ 1 & R(\alpha) = 0, \\ \displaystyle\int_b^t (d\tau)^{-\alpha} & R(\alpha) < 0. \end{cases} \quad (16) $$

Where b is initial value, α is a complex fractional order and $R(\alpha)$ is the real part of the fractional order. Controllers, which contain fractional order derivative and/or integral operator, can roughly be described as the fractional-order controllers.

$PI^{\lambda}D^{\mu}$, which is one of the fractional-order controllers, is represented by transfer function

$$ G_c(s) = K_p + K_i s^{-\lambda} + K_d s^{\mu} \quad (17) $$

Here λ and μ are real numbers ($0 < \lambda, \mu < 2$). K_p is proportional gain, K_i is integrator gain and K_d is a derivative gain.

The presentation of the CPID and the FOPID controller on λ-μ plane are shown in Figure 2. While the integer-order controller is being represented with 4 points on the plane, the fractional order controller can be represented with infinite points in the shaded area. This situation means that the order of the fractional integral and derivative, as additional two parameters, will have an effect on the dynamics of system to be controlled, and the controller will perform a more flexible intervention on the system.

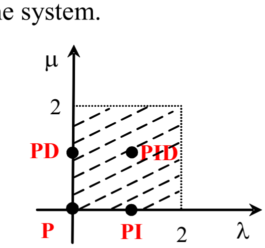

Fig. 2. CPID and FOPID on the λ-μ plane.

4. BACTERIAL SWARM OPTIMIZATION ALGORITHM

The PSO is an optimization algorithm based on swarm intelligence inspired from the behaviours of foraging of flies andschool of fish (Eberhart and Kennedy,1995). The PSO algorithm starts with taking parts of all particles randomly in the search space and the positions of the particles are updated according to the best coordinates of its neighbours and the best coordinates of itself in each step. Searching process continues in this manner to find the best result.

The BFO technique is another heuristic optimization technique, where *Escherichia coli* bacteria taken as references are microorganisms, which realize the nutrition activities spending energy at the optimum level and using the abilities of limited perception and motion (Passino, 2002). Optimization cycle of the BFO algorithm consists of three events, chemotaxis, reproduction, and elimination-dispersal. These three events are as follows:

Chemotaxis: Microbiological studies demonstrate that *Escherichia coli* bacteria move using their flagella. If all flagella turn counter clockwise, the bacterium swims forward. When the flagella turn clockwise, the bacterium slows down and tumbles. Foraging of the bacteria depends on the changes between the last two behaviors.

The rotation of the flagella in foraging process of the bacterium takes place according to the value of the environment at that moment and then it is decided whether the position will be changed or not and how the next movement (the direction and step length) will be changed. The formula of bacterium position in BFO algorithm is as follows:

$$\theta^i(i+1,k,l) = \theta^i(i,k,l) + C(i)\varphi(j) \quad (18)$$

where $\theta^i(i+1,k,l)$, *i* shows position of the bacterium; *j, k,* and *l*, show the indices of the chemotaxis, reproduction and elimination events; $\varphi(j)$ expresses the direction movement depending on the flagella movement, and $C(i)$ corresponds to the step length. Furthermore, when the bacterium reaches the food substance, it releases a chemical substance, which has a stimulatory effect on the other bacteria. This substance ensures the other close *Escherichia coli* bacteria to move to the place where the bacterium, which finds nutrition, is.

Reproduction: Since the foraging strategies of some bacteria fail to be successful clearly after a foraging period, these bacteria are removed from the population. Bacteria whose foraging strategy is good are duplicated in the same amount to replace the removed ones with the aim of pegging the number of the population. This process is an imitation of the segmentation of the bacteria in some way.

Elimination-Dispersal: Extreme temperature increase, fast water courses and other factors likewise in the environment where bacteria live affect the behaviors of the bacteria substantially. All these factors can cause sudden or slow changes in the population. These changes can occur in the form of deaths of all bacteria in that area or dragging of some parts of them to another area or immigration. Elimination-dispersal event is performed in order to imitate these biological processes. As this application can affect negatively the performance of the chemotaxis event, it can also affect positively there by dragging the bacteria close to where a better food area is. This application means that the bacterium moves to a new position.

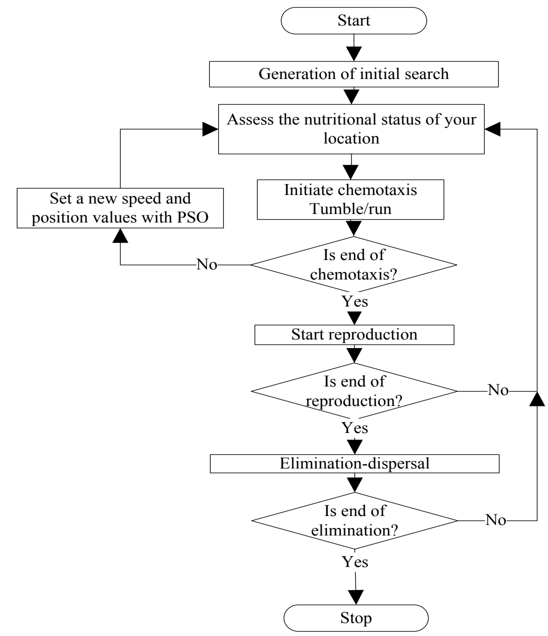

Fig.3.Flow chart for BSO algorithm.

The BSO, which is a hybrid optimization technique, features as a more effective optimization technique benefiting from the positive properties of PSO such as transferring the social studies and BFO such as determining a new rotation in the elimination and dispersal process (Korani,Dorrahand Emara, 2009).

Basic steps of the BSO algorithm are as follows:

Step 1: Form the population.

Step 2: Evaluate the individuals according to the evaluation function.

Step 3: Three cycles for the optimization:

Inner loop: Chemotaxis

Calculate the information of speed and position (PSO)

Mid-loop: Reproduction

Outside loop: Elimination- Dispersal

Step 4: Decode the optimal bacterium to determine the last solution.

The direction movement of a bacterium gets rid of randomness by using the PSO technique in the BSO technique. Thus, process of the reaching a solution, which occurs due to the movement direction which the BFO determines randomly, will be shortened. The flow chart belonging to the program to be used in optimization of the controller parameters in next chapter with BSO algorithm is shown in Figure 3.

5. SIMULATION RESULTS

As performance indices for CPID and FOPID controllers, ITE, ISE, ITAE and ITSE were used when the load changed is $\Delta P_{L1} = 0.01$ at *t*=0 in simulations. The simulation model were created in m-files on MATLAB R2009. Fractional-order controller structure was performed by using Fractional Variable Order Derivative Simulink Toolkit from the website http://www.mathworks.com Controller gains K_p, K_i and K_d were restricted between 0-10 and λ-μ values ware restricted between 0-2. Controller parameters optimized according to the indexes are shown in Table 1.Figs. 4-7 show the simulation results performed with the optimized controller parameters for each performance index.

Table 1.Optimal parameters of the CPID and FOPID controllers for different cost functions.

		ITAE	IAE	ISE	ITSE
CPID	***Kp***	7.3735	6.5354	7.3967	5.8565
	Ki	9.8284	9.0122	9.2515	6.4575
	Kd	1.2864	1.4901	4.236	7.8269
FOPID	***Kp***	4.8752	6.1157	9.9095	9.8220
	Ki	9.8420	9.8741	7.6365	9.3656
	λ	0.7929	0.8294	0.7889	0.927
	Kd	2.4312	2.3772	9.7293	2.0155
	μ	1.0277	1.3829	1.1075	1.4208

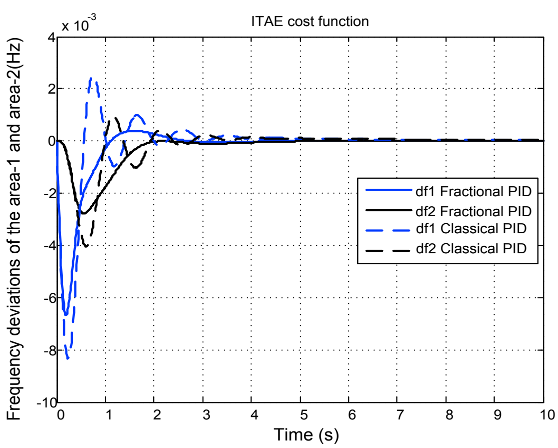

Fig.4.Change in frequency of areas: ITAE cost function.

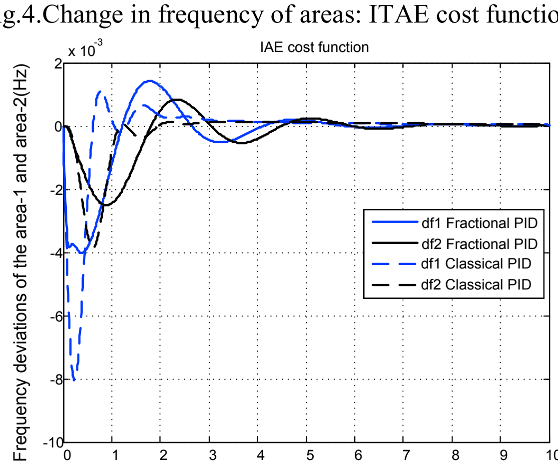

Fig.5.Change in frequency of areas: IAE cost function.

Fig. 5 shows the simulation result optimized for performance index IAE and frequency deviation in two areas. It is seen that fractional-order controller results are better than conventional controllers when the maximum overshoot and settling time are taken into consideration.

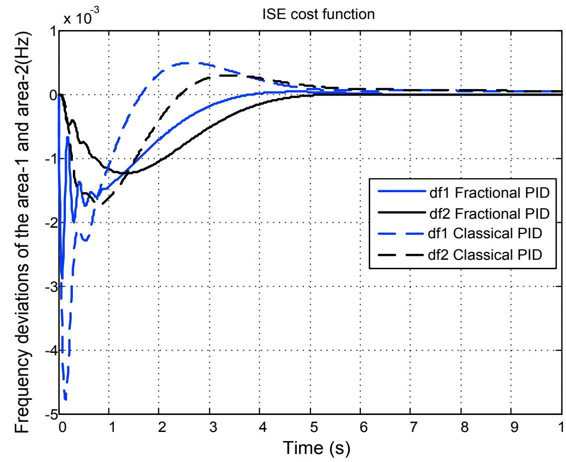

Fig.6.Change in frequency of areas:ISE cost function.

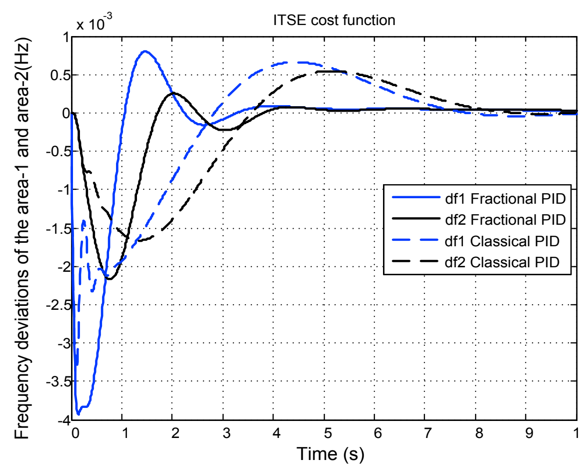

Fig.7.Change in frequency of areas: ITSE cost function.

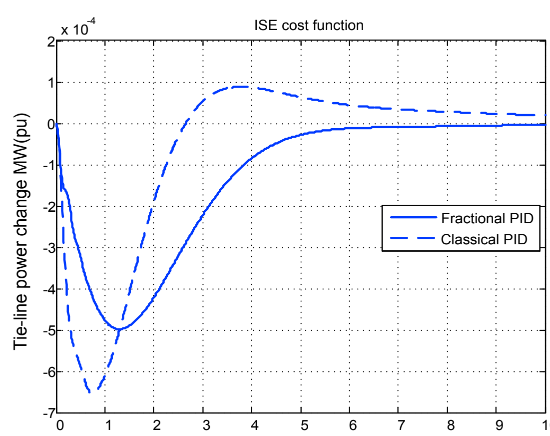

Fig.8.Change in tie-line power for ISE cost function.

It is seen that the FOPID controller is superior to the CPID controller in terms of maximum overshoot and settling time in Figs. 5 and 6. It is seen in Fig. 7 that CPID controller performance is a little better than FOPID controller only in terms of maximum overshoot. Fig. 8 shows the power deviation between the two areas, with CPID and FOPID. As it is seen that FOPID out performs in terms of power deviation.

Results obtained by using controller parameters, which are optimized in Table 1, are respectively given for areas 1 and 2 in Tables 2 and 3. Apart from the results of ITSE index, the FOPID performs better than the CPID.

Table 2.Maximum overshoots and settling times of the frequency deviation of the control area-1

		ITAE	IAE	ISE	ITSE
CPID	Max. oversht.	8.3276 e-3	8.0351 e-3	4.7843e-3	3.385 e-3
	Settling times	7.7821	8.21854	8.2979	9.2925
FOPID	Max. oversht.	6.6580e-3	4.0261 e-3	2.8803 e-3	3.9262e-3
	Settling times	3.3209	6.3908	3.5511	6.8903

Table 3. Maximum overshoots and settling times of the frequency deviation of the control area-2

		ITAE	IAE	ISE	ITSE
CPID	Max. oversht.	4.0649e-3	3.8784e-3	1.7415e-3	1.6713e-3
	Settling times	8.7639	9.1592	9.1703	8.2281
FOPID	Max. oversht.	2.8001 e-3	2.5181 e-3	1.2428 e-3	2.1774 e-3
	Settling times	4.0854	8.2671	4.6410	7.0784

6. CONCLUSIONS

In this study, the BSO algorithm is presented as a hybrid of PSO and BFO algorithms. The BSO is applied to optimize the controller parameters for load-frequency control of a two-area power system. The performances of the automatic generation controllers with optimized parameters are examined for both CPID and FOPID controllers. It is observed that FOPID is preponderantly superior for 4 different performance indices when the system was optimized under certain constraints. Especially, the parameters optimized for ISE cost function show the best performance in terms of maximum overshoot and settling time.

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Appendix A

Two-area power systemparameters: Rating of each area = 2000 MW, base power = 2000 MVA, Pr1 = Pr2 = 1000 MW, Kg= 120 Hz/p.u. MW, Tg = 20.0 s, Kr12 = 0.5, Tr1 = Tr2 = 10.0 s, Tg1 = Tg2 = 0.086 s,Tt1=Tt2 =0.3 s, R1 = R2 = 2.43 Hz/p.u. MW,B1 = B2 = 0.425 p.u. MW/Hz, a12 = −1, ΔPL1 = 0.01 p.u. MW.

Appendix B

BSO parameters: Number of bacteria = 10; Number of chemotatic steps = 5;Number of elimination and dispersal events = 6;Number of reproduction steps = 4;Probability of elimination and dispersal = 0.25.