BFOA Based FOPID Controller for Multi Area AGC System with Capacitive Energy Storage

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Abstract: This paper investigates how effectively a fractional order controller (FOPID) works for Automatic Generation Control (AGC) issues in a multi area power system. Fractional order controllers gives better dynamic response results than the widely used conventional integer order controllers like IOPI or IOPID controller. Optimal gain setting of the integer and fractional order controllers are obtained by using Bacterial Foraging Optimization Algorithm (BFOA) by minimizing an integral of time-weighted absolute error (ITAE) performance index. For the improvement of dynamic responses in a multi area power system, Capacitive Energy storage (CES) units are also implemented in its all control areas. The test system simulations are carried out in a Matlab/Simulink environment validates that BFOA based FOPID controller give better results than conventional controllers.

Keywords: Automatic generation control, Fractional order controllers, Capacitive energy storage, Bacterial foraging optimization

1. Introduction

To facilitate power generation, large interconnected power systems are mixed with thermal, hydro, nuclear, gas and renewable sources. This Load frequency control is one of the major control problems in power system operation. The major aim of Automatic Generation Control (AGC) is to maintain the frequency and tie-line power deviations within specified limits [1]. In case of a small load disturbance, frequency and tie-line power deviation persist for long time under supplementary control. To overcome this situation, an active power source with fast response can be implemented [2-7].More researchers are focused on short term energy storage systems like Superconducting Magnetic Energy Storage (SMES) unit, Battery Energy storage System, etc. are used [9-10]. The major disadvantage of SMES unit is maintenance and cost of the unit. But the low energy density capacitors are used for energy storage [8] because of their less maintenance and low cost.

In the literature survey, most research works are focused on different tuning methods for tuning the controller parameters in an AGC system [7-11]. Various control techniques for power system applications are classified as classical control approach, optimal control approach adaptive and self tuning approach etc. More researchers are focused on the area of soft computing techniques like Fuzzy logic Artificial neural network, Genetic algorithm are also used for various load frequency issues in a multi area power system. Nanda et al. explained the applications of conventional integer order controllers like proportional, integral, derivative and the combinations of these controllers for damping the power frequency oscillations [3-4]. Now a days more researchers focus on the various applications of Fractional order controllers [12-15]. Research results show that Fractional order controller is one of the suitable controller techniques for various power system applications [13]. It introduces two new additional parameters along with conventional controller. Literature survey shows that application of Fractional order controller in AGC systems is very less and no research papers available in the modeling of a six area power system along with CES unit. In the practical view point conventional PI controllers are more popular. So it is easy to convert a conventional Integer order controller to a Fractional order controller with less cost.

In this paper, an application of Bacterial Foraging optimization algorithm is used for tuning the various control parameters in a conventional and Fractional order controller. The proposed

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BFOA-FOPID controller is tested with a six area interconnected power system with CES unit. The frequency and tie line power outputs are compared with other conventional Integer order controllers and fuzzy logic controller. The test system simulations are carried using MATLAB/SIMULINK software and the Dynamic performance of the proposed BFOA-FOPID controller with CES unit is validated. It is observed that it effectively damps out the sudden load disturbance than other conventional controllers.

2. System investigated

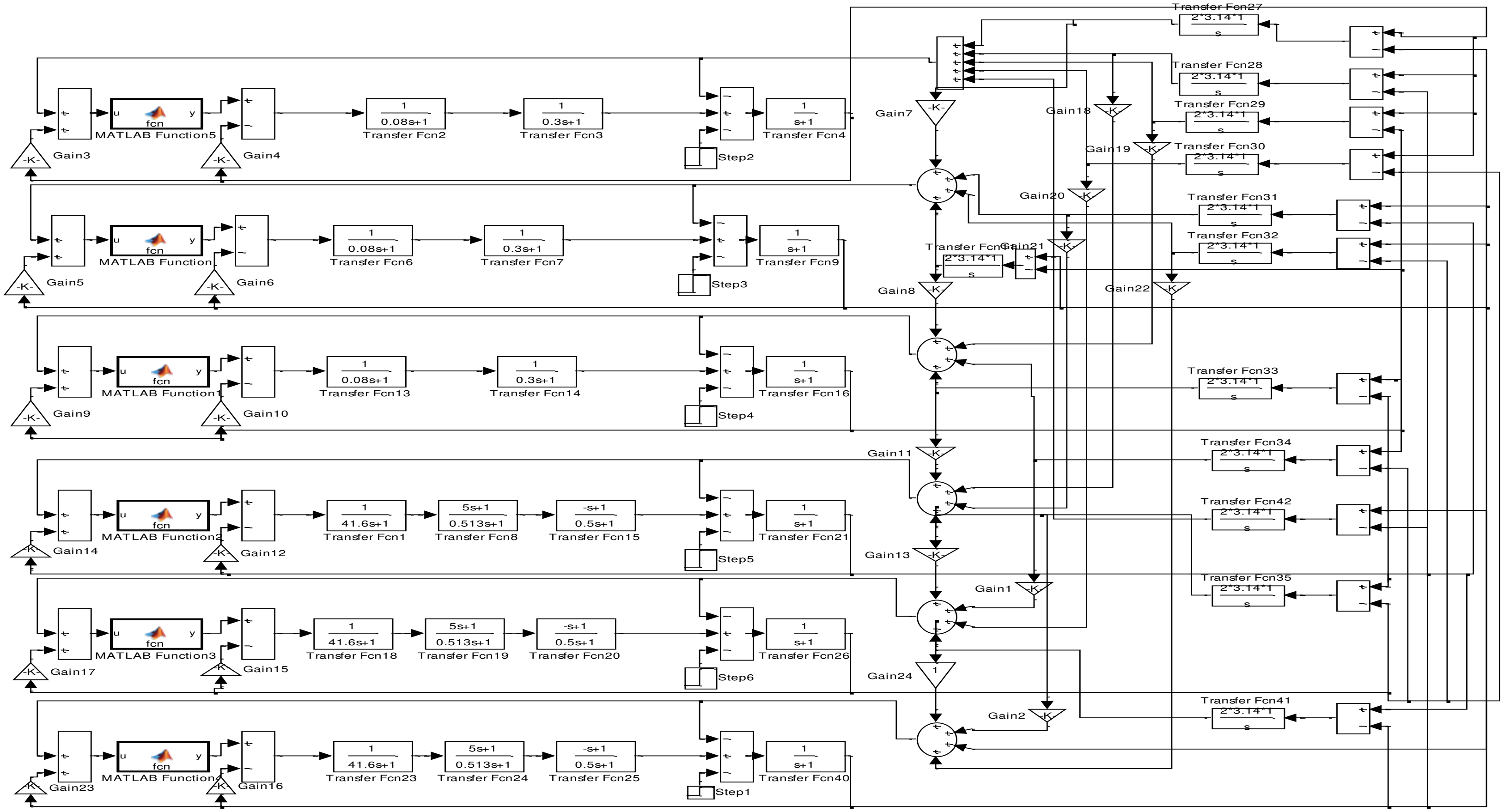


Figure 1. Transfer function model of six area hydro-thermal system

The AGC system investigated is composed of an interconnection of six different areas. The six generating areas consist of three thermal units and three hydro units with mechanical governor. The detailed transfer function models of speed governors and various types of turbines are explained in the IEEE Committee Reports [9].The transfer function model of six area hydro- thermal system is shown in figure 1. A 1% step load perturbation is applied for any two areas. The nominal parameters of the system are investigated and given in Appendix.1. [9].

3. Bacteria foraging optimization algorithm (BFOA)

Bacterial foraging optimization algorithm is widely accepted for power system applications and its control. The basic idea behind BFOA technique is the social foraging behaviour of *Escherichia coli.* Figure 2 Shows the formulation of BFOA technique, and it is further sub divided into four prime steps [14-20]:

A. Chemotaxis

This process denotes the two modes of movement of an *E.coli* cell through swimming and tumbling via flagella in a particular direction. It can change these two modes in its entire life time. Let $\phi(j)$denote the direction of movement after a tumble. In general [13]:

$$\theta^i(j+1,k,l) = \theta^i(j,k,l) + c(i)\frac{\Delta(i)}{\sqrt{\Delta^T(i)\Delta(i)}} \tag{1}$$

Suppose $\theta^i(j,k,l)$represents i^{th} bacterium at j^{th} chemotactic, k^{th} reproductive and l^{th} elimination-dispersal step. $C(i)$ is the step size taken in the random direction specified by the tumble (run length unit).

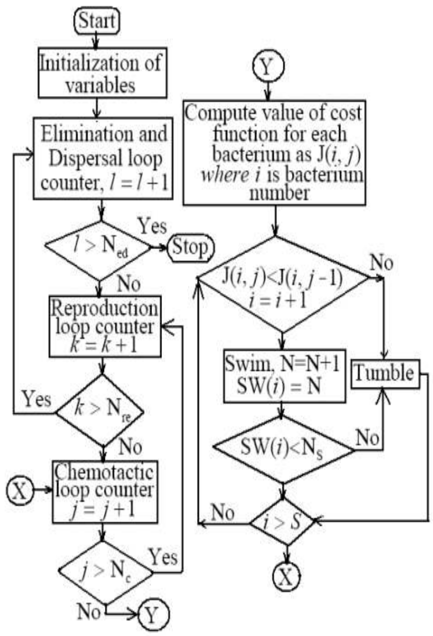


Figure 2. Flow chart for bacterial foraging optimization algorithm.

B. Swarming

It is a rapid and coordinated translocation of bacteria *E.coli* and *S. typhimurium*, forming stable swarms occurring across solid or semi-solid surfaces. The representation of cell-to-cell signalling in *E. coli* swarm is denoted as [16]:

$$J_{cc}(\theta, P(j,k,l)) = \sum_{i=1}^{s} J_{cc}\left(\theta, \theta^{i}(j,k,l)\right)$$
$$= \sum_{i=1}^{s}\left[-d_{attractant}\exp\left(-w_{attracted}\sum_{m=1}^{p}\left(\theta_m - \theta_m^i\right)^2\right)\right] + \sum_{i=1}^{s}\left[h_{repellant}\exp\left(-w_{repellant}\sum_{m=1}^{p}\left(\theta_m - \theta_m^i\right)^2\right)\right] \quad (2)$$

Where the objective function value $J_{cc}(\theta, P(j,k,l))$ is to be added to the actual objective function, which is to be minimized. *S* is the total number of bacteria, *p* is the number of variables to be optimized.

C. Reproduction

After the chemotaxis process, weak bacteria dies and the healthier bacteria fragments into two new bacteria, placed in the same location. In this way, population of bacteria remains constant.

D. Elimination and Dispersal

If elimination and dispersal events occur as a sudden rise in temperature, many bacterial groups vanish as bacteria in that region is killed or spread to a new location. From the evolutionary point of view, these changes affect the possibility of destroying chemotactic progress, but assisting in chemotaxis [19].

4. BFOA based Fractional order controller

A. Fractional order controller

Fractional order transfer function (FOTF) is given by the following equations [12]:

$$G_n(s) = \frac{1}{a_n s^{\alpha_n} + a_{n-1} s^{\alpha_{n-1}} + \cdots + a_1 s^{\alpha_1} + a_0 s^{\alpha_0}} \quad (3)$$

Where α_k, (*k=0, 1, 2…., n*) is an arbitrary real number

$$\alpha_n > \alpha_{n-1} > .... > \alpha_1 > \alpha_0 > 0$$

In the time domain sequence, the n-term fractional order differential equation (FDE) is

$$a_n D^{\alpha_n} y(t) + a_{n-i} D^{\alpha_{n-1}} y(t) + \cdots + a_1 D^{\alpha_1} y(t) + a_0 D^{\alpha_0} y(t) = 0 \quad (4)$$

The fundamental operator representing the non-integer order integration and differentiation is [11]:

$$_aD_t^{\alpha} = \begin{cases} d^{\alpha}/dt^{\alpha}, & \mathrm{Re}(\alpha) > 0, \\ 1, & \mathrm{Re}(\alpha) = 0, \\ \int_a^t (dt)^{-\alpha}, & \mathrm{Re}(\alpha) < 0, \end{cases} \quad (5)$$

Where α is the fractional order and a complex number. The constant *a* is associated with its initial conditions.

The Grun-wald-Letinikov (GL) definition is written as [11]:

$$ {}_aD_t^\alpha f(t) = \lim_{h\to 0}\frac{1}{h^\alpha}\sum_{j=0}^{\left[\frac{t-a}{h}\right]}(-1)^j\binom{\alpha}{j}f(t-jh) \tag{6}$$

In this equation, $\left[\frac{t-a}{h}\right]$ is the integral part of the number $\frac{t-a}{h}$, and $\binom{a}{j}$ is the binomial coefficient.

The Reimann-Liouville's (RL) definition is written as:

$$ {}_aD_t^\alpha f(t) = \frac{d^n}{dt^n}\frac{1}{\Gamma(n-\alpha)}\int_a^t\frac{f(t)}{(t-\tau)^{n-\alpha-1}}d\tau \tag{7}$$

Where, $0 \le n-1 < \alpha < n$, $\Gamma(\alpha)$ is the Euler's gamma function of α, a is the initial time instant which is normally zero.

The Caputo's definition is written as:

$$ {}_aD_t^\alpha = \frac{1}{\Gamma(n-\alpha)}\int_\alpha^t (t-\tau)^{n-\alpha-1} f^{(n)}(\tau)d\tau \tag{8}$$

Where $0 \le n-1 < \alpha < n, n \in N$

According to these three equations, we can conclude that GL definition is the base method and the other two methods are improvement versions. With these parameters, FOPID is more flexible than IOPID [12].

B. Design of BFOA based FOPID controller

FOPID controller has two more adjustable parameters than IOPID controller. The differential equation of FOPID can be written as:

$$u(t) = K_Pe(t) + K_ID_t^{-\lambda}e(t) + K_DD_t^{\mu}e(t) \tag{9}$$

Taking the Laplace transform of the above equation, the transfer function of FOPID is:

$$G_c(s) = K_P + K_Is^{-\lambda} + K_Ds^{\mu} \tag{10}$$

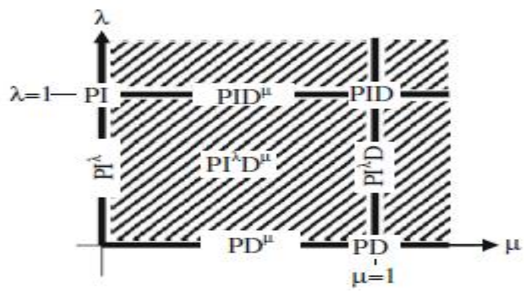


Figure 3. Description of FO and IO systems.

Putting $\lambda = \mu = 1$, the traditional IOPID controller is obtained. For P controller λ=μ= 0.For PID controller λ = 0,μ = 1.For PI controller λ = 1,μ = 0. Varying the parameters λ and μ, various types of integer and fractional order controllers are obtained as shown in Figure 3.

5. Design of Fuzzy based PID Controller

Fuzzy Logic Controller (FLC) technique is a widely used control technique for power system applications. In load frequency control, fuzzy logic rules give better results than conventional PID controller. The fuzzy logic controller is comprised of four main components: the fuzzifier, the inference engine, the rule base and the defuzzifier [6-7]. The fuzzifier transforms the two input signals Area Controller Error (ACE) and change in Area Controller Error (Δ ACE) to the fuzzy sets. This operation is called fuzzification. In this paper triangular membership functions are used because it is easier to intercept membership degrees from a triangle. The fuzzy logic rules for tuning the AGC control parameters are shown in Figure 6.

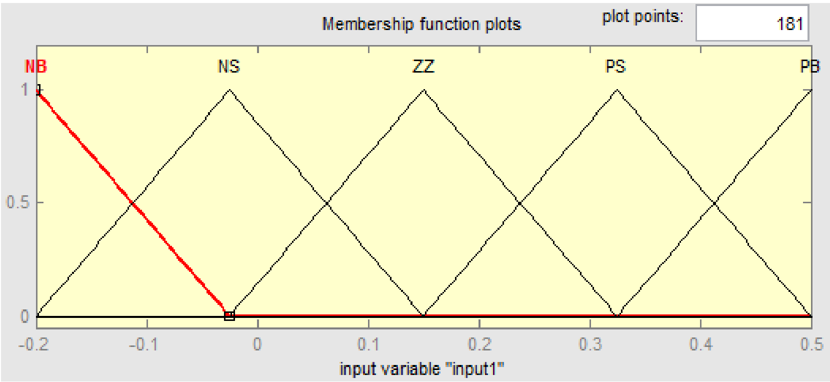


Figure 4. Membership functions of input signals

The fuzzy logic system is developed based on Mamdani's method. The input and output membership functions are shown in Figure 4 and Figure 7. The Simulink model of the fuzzy PID controller is shown in Figure 5.

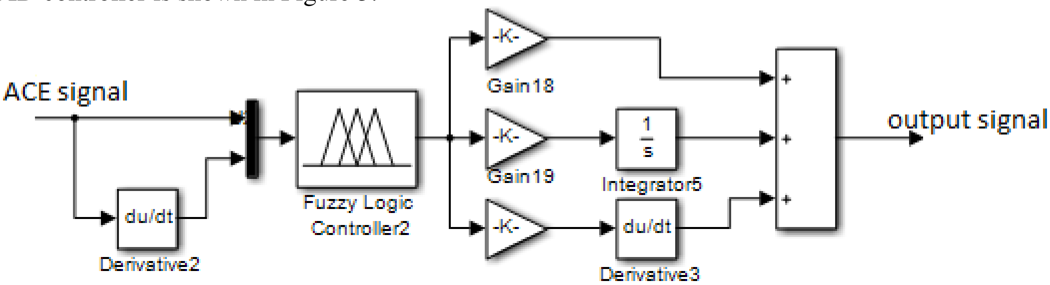


Figure 5. Fuzzy PID Controller structure

ΔACE →

ACE ↓

	NB	NS	ZZ	PS	PB
NB	ZZ	PS	PB	PB	PB
NS	NS	ZZ	PS	PB	PB
ZZ	NB	NS	ZZ	PS	PB
PS	NB	NB	NS	ZZ	PS
PB	NB	NB	NB	NS	ZZ

Figure 6. fuzzy rule based table

For the output variable singleton, membership functions are defined and the defuzzified output is the weighted average of the contributions from each rule. Figure 7 shows the membership function of the output signal.

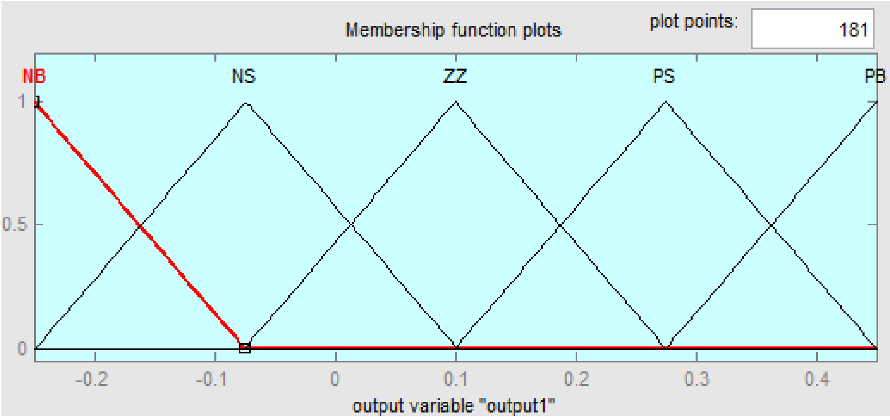


Figure 7. Membership function of output signal

6. Capacitive energy storage unit and its control strategy

Figure 8 shows the basic configuration of a CES unit. The main storage capacitor consists of a number of discreet capacitors arranged in parallel. A resistor R is connected across the capacitor bank to represent the leakage and dielectric loss. The CES system is connected to the grid via a power conditioning unit (PCU), which consists of a rectifier/ inverter unit.

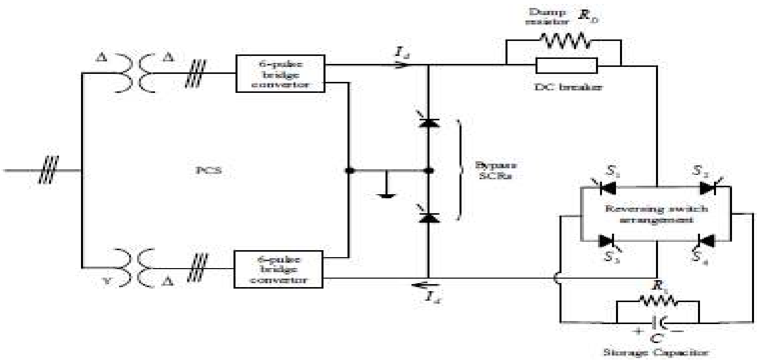


Figure 8. Basic configuration of a CES unit

To analyse the effect of AGC with CES unit, a 12.8MJ CES unit is taken. Under negligible loss condition, the circuit bridge voltage E_D is denoted as [8]:

$$E_D = 2E_{D0}\cos\alpha - 2I_d R_D \tag{11}$$

where α is the firing angle in degree and I_d is the current through inductor, R_D is the equivalent commutating resistor in kΩ and E_{D0} is the maximum bridge voltage in kV. By varying the firing angle α from 0 to 180 degree, the value of E_{D0} changes from its maximum positive to the maximum negative value [10].To overcome the effect of sudden load variation during charging, keep E_{D0} as 30% of the rated voltage. The control or input signal to CES unit is taken as the output of Area Control Error (ACE) signal. The general equation for ACE of entire area is represented as:

$$ACE_i = B_i \Delta f_i + \Delta P_{Tij} \tag{12}$$

Where B_i is the bias factor and Δf_i is the frequency deviation of i^{th} area. ΔP_{Tij} is the tie line power deviation between i^{th} and j^{th} area.

The change in current in the i^{th} area is given by

$$\Delta I_{Di} = K_{ACEi} ACE_i - K_{VD} \Delta E_{Di} \tag{13}$$

Where K_{ACEi} is the gain of i^{th} ACE signal. ΔE_{Di} is thechange in capacitor voltage.

For the i^{th} area, the change in capacitor voltage, ΔE_{Di} is represented as

$$\Delta E_{Di} = \left(\frac{1}{sC + \frac{1}{R}} \right) \Delta I_{Di} \tag{14}$$

Under sudden load disturbance, the sum of instantaneous power and initial power goinginto the CES is given as:

$$\Delta P_{CES} = \left(\Delta E_{Di} + E_{D0} \right) \Delta I_{Di} \tag{15}$$

7. Objective function formulation for AGC

The main objective of the AGC is to maintain the frequency and tie-line power within prescribed limits. A performance index is calculated using Integral Time-weighted Absolute Error (ITAE) [7] of the frequency and tie-line power deviation. Gain of the controller is tuned optimally for obtaining the area frequency and tie-line power exchange with minimum overshoot and less settling time. The objective function J is defined as

$$J = \int_0^\infty t\left(|\Delta f_1| + |\Delta f_2| + ... + |\Delta f_6| + |\Delta P_{tie}| \right) dt \tag{16}$$

Based on the objective function, Minimize J Subject to

$$K_P^{\min} \le K_P \le K_P^{\max}$$
$$K_I^{\min} \le KI \le K_I^{\max}$$
$$K_D^{\min} \le K_D \le K_D^{\max} \tag{17}$$

8. Simulation result and discussions

Simulation studies are carried out to investigate the performance of a six area hydrothermal system with CES unit under integer order and fractional order controllers whose gain parameters are tuned by BFOA technique. A step load disturbance of 1% of the normal loading is considered in thermal area (area-1). Optimal gain setting of integer order controllers (IOPID) and FOPID controller under BFOA technique is shown in Table 1. Figure 9 and Figure 10 shows the dynamic responses of frequency deviation in thermal and hydro area under 1% step load variation with different controllers in the presence of CES unit. Figure 11 shows the tie-line power deviation of each area. Analysis of settling time and peak overshoot under three different controllers are compared in Table 2.

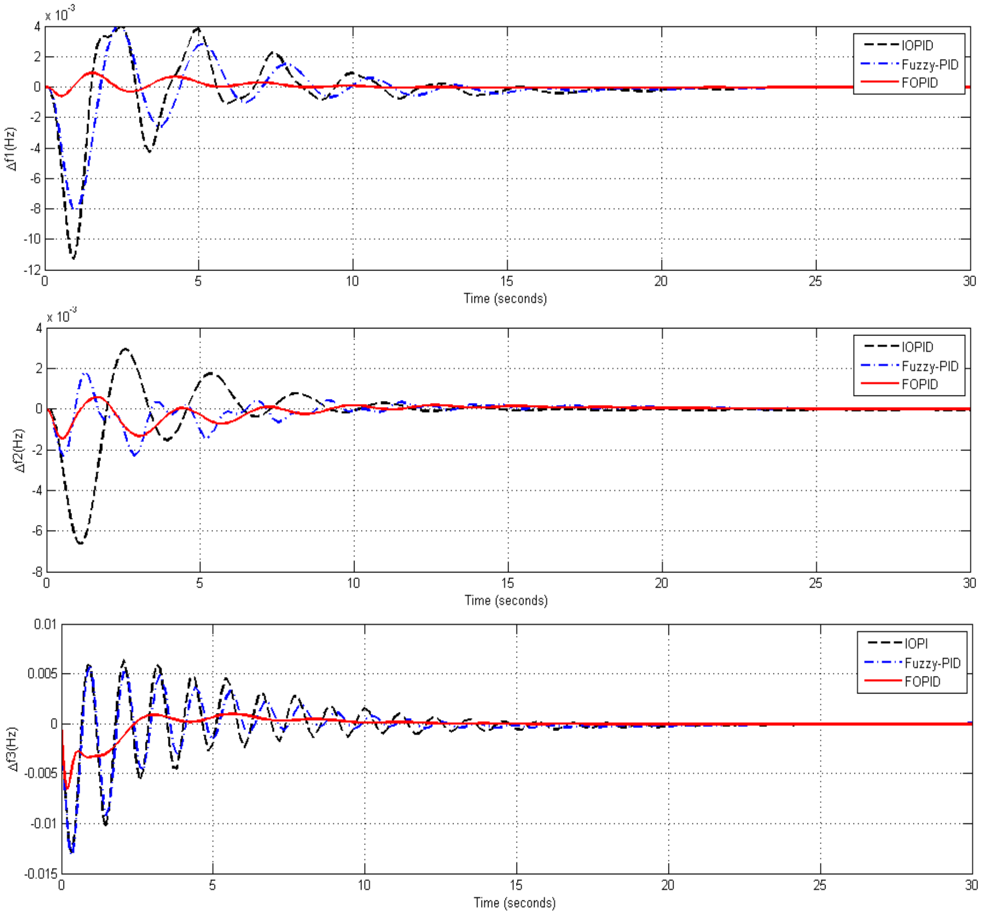
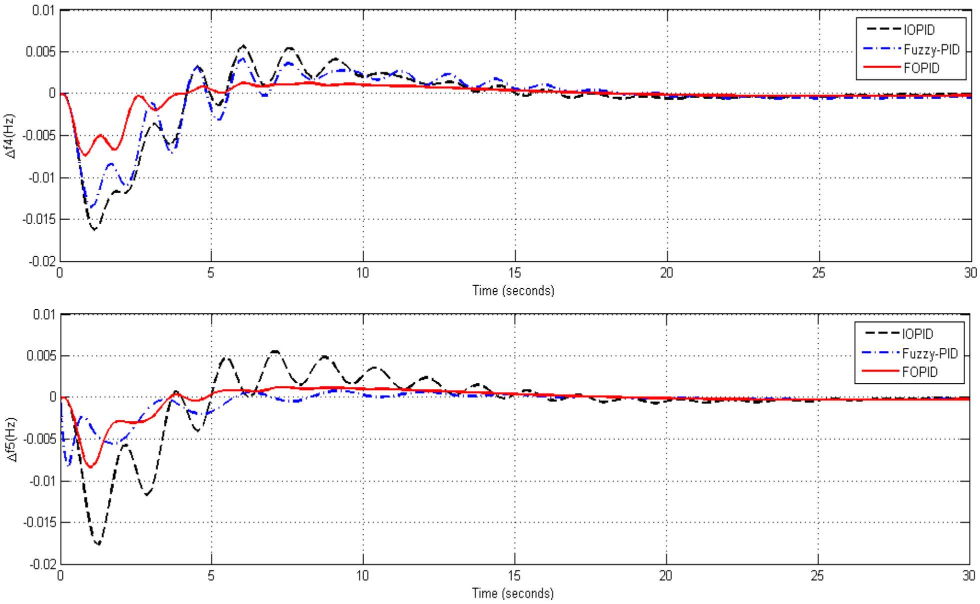


Figure 9. Frequency deviations in hydro area under1% of load disturbance.



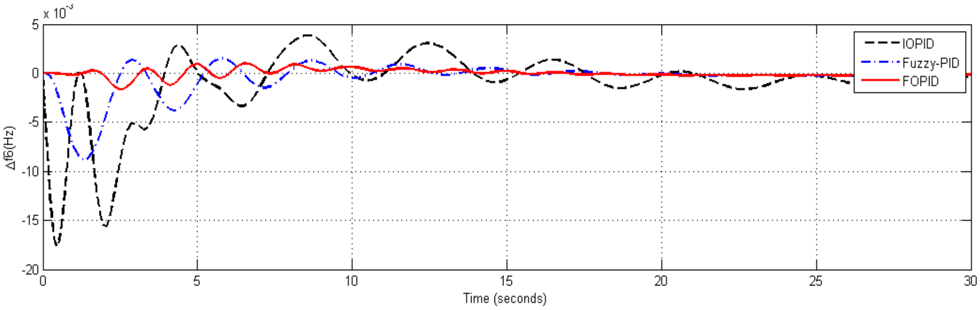
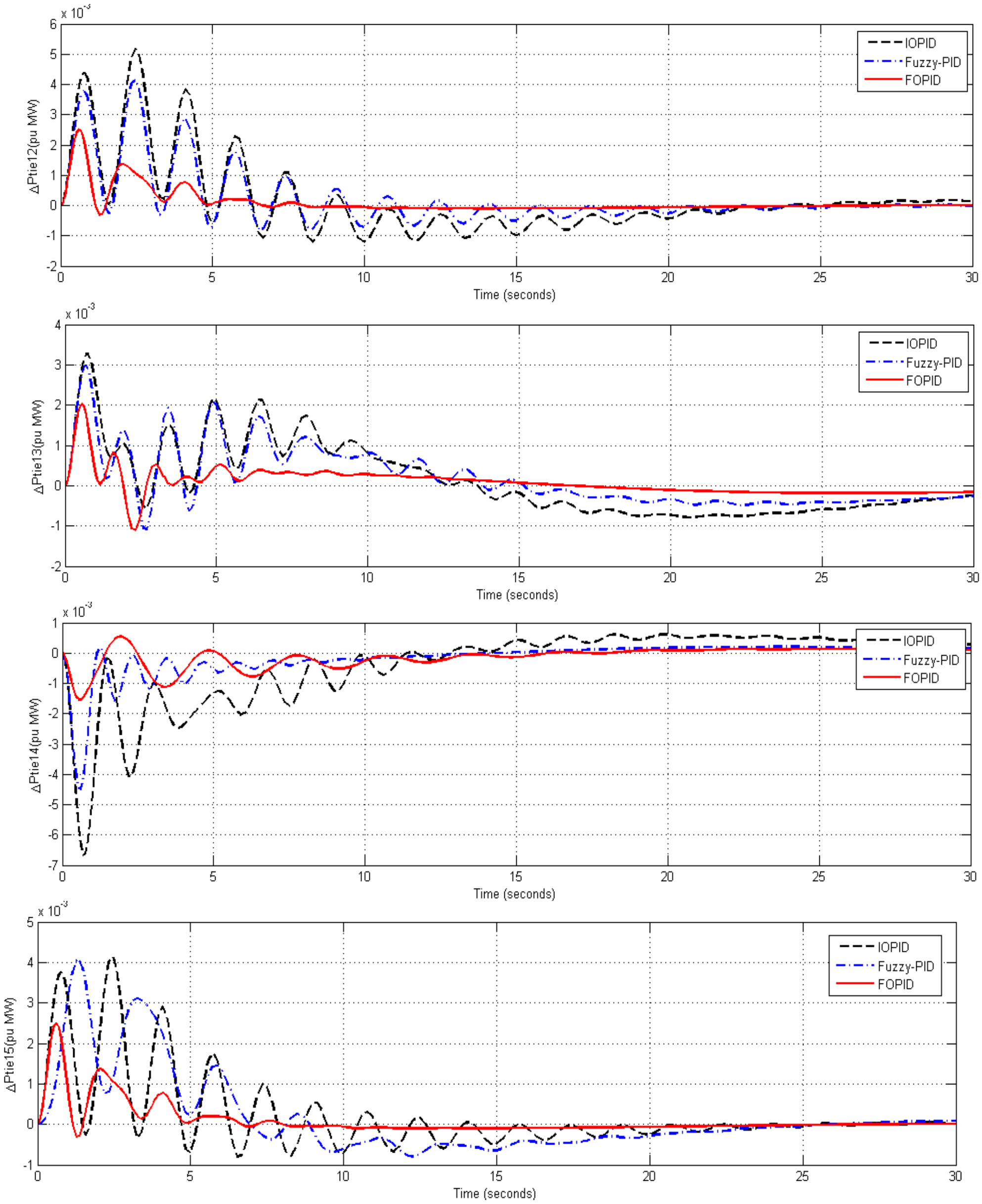


Figure 10. Frequency deviations in hydro area under1% of load disturbance.



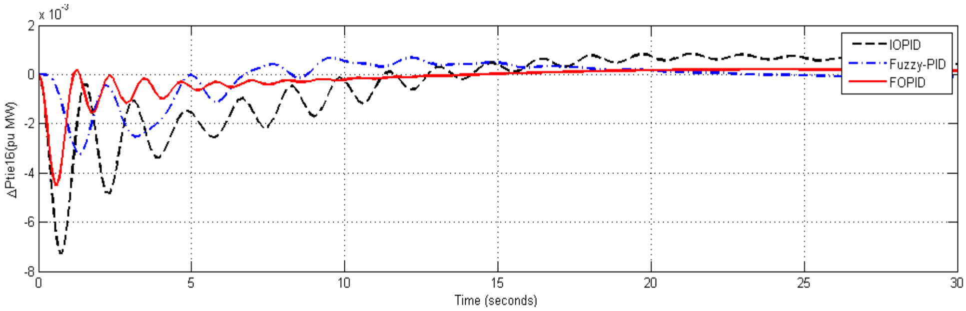


Figure 11. Simulation result shows the tie line power deviation of six area power system with CES.

Table 1. BF optimized gain values for controller

Controller Parameters		Area 1	Area 2	Area 3	Area 4	Area 5	Area 6
IOPID	K_P^*	0.0467	0.0866	0.08912	0.7568	0.7814	0.9964
	K_I^*	0.0957	0.0535	0.1352	0.0798	0.6812	0.7165
Fuzzy-PID	K_P^*	0.2033	0.4487	0.8016	0.6688	0.6115	0.7004
	K_I^*	0.3305	0.5194	0.3990	0.5219	0.7043	0.6167
	K_D^*	0.2718	0.9905	0.7109	0.8610	0.7609	0.7809
FOPID	K_P^*	0.5560	0.4090	0.5119	0.7994	0.5682	0.7196
	K_I^*	0.7097	0.5518	0.4984	0.4453	0.4102	0.5105
	K_D^*	0.5130	0.5906	0.7529	0.6123	0.6872	0.8019
	λ^*	0.9514	0.9226	0.9790	0.9067	0.9709	0.9177
	μ^*	0.4938	0.5859	0.7918	0.6489	0.7074	0.6469

Table 2. Comparison of dynamic responses with different controllers

Responses	IOPID		Fuzzy-PID		FOPID	
	M_P	T_S (sec)	M_P	T_S (sec)	M_P	T_S (sec)
ΔF_1	0.00418	20	0.00386	18	0.00021	11
ΔF_2	0.00302	16	0.00190	13	0.00056	10
ΔF_3	0.00552	18	0.00494	15	0.00058	10
ΔF_4	0.00512	20	0.00470	18	0.00016	10
ΔF_5	0.00528	23	0.00186	16	0.00021	09
ΔF_6	0.00492	30	0.00394	18	0.00058	11
ΔP_{TIE1-2}	0.00587	30	0.00384	23	0.00250	08
ΔP_{TIE1-3}	0.00345	35	0.00203	30	0.00201	08
ΔP_{TIE1-4}	0.00106	35	0.00118	20	00.0001	12
ΔP_{TIE1-5}	0.00557	34	0.00412	22	0.00250	08
ΔP_{TIE1-6}	0.00417	28	0.00218	23	0.00125	08

Under 1% of step load disturbance in area-1, performance of the three controllers in area1 reveals that, with peak overshoot as the performance index, the FOPID controller showed an improvement of 64% over conventional PID controller and 10% over fuzzy-PID controllers. In the case of settling time, the FOPID controller showed an improvement of 10 % over fuzzy-PID controller and 44 % over conventional PID controllers. Hence it is proved that, the performance of the FOPID controller is better than the fuzzy-PID controller and conventional PID controllers.

Hence from Figure 9, Figure 10, Figure 11and Table 2, it is seen that CES unit in both the control area under FOPID controller improves the dynamic performances significantly. However from the economic point of view, implementing CES unit is preferable.

9. Conclusion

The simulation studies are carried out on a six area AGC system along with CES unit in all control areas has been presented in the paper. The conventional and fractional order controllers gain parameters are tuned by BFOA technique. Dynamic responses show that FOPID gives distinctly better response than conventional and Fuzzy based PID controller. The system frequency and tie line power deviation can be effectively damped out in the presence of CES unit. The Investigation shows that ACE as the input to CES unit gives better performance and also adding CES unit improves the dynamic response of the system. Moreover CES units make the proposed BFOA-FOPID controller more effectively damp out the frequency related issues in an AGC system.

Appendix. (A)

Table 3. Numerical parameters for hydro and thermal generating units

data	Hydro area (1,2,3)	Thermal area (4,5,6)
Rating (MW)	1200	1200
Droop characteristic: R (Hz /pu MW)	2.4	2.4
Damping: D (pu MW/Hz)	8.33×10^{-3}	8.33×10^{-3}
Frequency bias factor:B (sec)	0.4249	0.4249
T_P(sec)	20	20
K_P(Hz / p.u MW)	120	120
T_R(sec)	10	10
T_T(sec)	0.3	0.3
T_G(sec)	0.08	0.08
Time constants(sec)	T_1=41.6	T_w=1
Time constants(sec)	T_1=0.513	T_R=1

(B) CES Data

C= 1.0 F, R=100Ω, T_{DC}= 0.05 sec, K_{ACE}= 70kA/MW, K_{VD}= 0.1 kA/kV, E_{d0}= 2kV

10. References

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