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Intelligent Load Frequency Control in a Deregulated Power Systems

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***Abstract*—One of the most important issues in interconnected deregulated power systems is frequency stabilization. Practically in deregulated power systems, the load and the power system parameters are variable, therefore the stability of the frequency is necessary. In this article, the PID controller is used to load frequency control (LFC) and its K factors are adjusted using PSO, DE, ICA, and fuzzy algorithms. The evolution algorithms such as PSO, DE, and ICA, according to the power system's transfer function, make constant K factors. Load changes and power system parameters change need variables K factors for accurate frequency control. In this study fuzzy parameters controller is proposed in order to create variable K factors for self-tuning. The results obtained from the MATLAB/Simulink show that in a single area deregulated power system, the Fuzzy-PID hybrid controller has reduced settling time and overshoot by 11.79% and 13.04% compared to the existing methods respectively and is a suitable solution for the LFC problem.**

Keywords— ***Multi-Source, Evaluation Algorithm, Fuzzy PID, Optimization Controller, Deregulated Power System***

I. INTRODUCTION

Power systems is going complex day by day therefore to solve LFC efficient methods are required. E. Nikmanesh *et al.* used a MUGA based method for optimizing the K-factors of the PI and PID controllers, then compared the results with BFOA, HBFOA-PSO and NSGA-II methods and achieved better results [1]. Jay Singh *et al.* used IMC-PID for LFC in single and two area power systems. In this paper decreasing model order with logarithm is studied to decrease the order of single and double area power systems. This method occurs better dynamic respond and disorder robust for the system [2]. Authors applied Fractional-Order Proportional-Integral-Derivative (FOPID) is used to control the load frequency of a multi-source power system and used SSO to optimize the parameters (including DGs effects) [3]. The considered DGs have diesel and wind units. The results show that DGs decrease the Standard deviation of the frequency of a power system network. Reference [4] studied a two-region power system. In this paper, FOPID and SSO are used to study the generation rate constraint limits. In addition, RFB Batteries and SMES energy storages are used in order to increase the LFC efficiency. The results show that optimizing the FOPID parameters using SSO algorithm is very effective.

V. Kumarakrishnan *et al.* have conducted a study on frequency deviation control in a single area, multi-source power network that includes hydro, thermal, and nuclear power plants and also photovoltaic systems (PV) with energy storage devices. In this study, the combination of PSO evolutionary algorithm with PID controller is used. The proposed method has greatly reduced the settling time [5]. In reference [6] LFC and AVR are studied simultaneously for a multi-area system. In this article, a PID controller in which the initial parameters are determined using Zeigler Nichol (ZN) is studied. The load change occurs massive changes in frequency and voltage, therefore Simulated Annealing (SA) is used as a second phase optimization for the PID parameters. The results show this type of optimization simplify the PID controller function and has a good response for the system against load changes.

In reference [7] The LFC problem for a single area, multi source power system has been performed using Grey Wolf Optimizer (GWO) algorithm. This electricity network, which is considered here, is consists of reheat thermal, gas, and hydroelectric power plants. In reference [8] for controlling the load frequency, a PI controller combined with a genetic algorithm is used. This paper concentrates on reducing the computations and increasing the controller's speed. AGC is done in a multi-source power system with plugin electric vehicles (PEV) using a PI/PID controller. In this paper for solving AGC at first, a multi-source power system using I controller which is optimized by stochastic fractal search (SFS) approach is studied. In the second study, the effect of PEV on the power network is considered for the system and the AGC is done with a PI-PD controller, and for optimizing the controller's parameters the HSFS-PS method is used. Configuring the PI/PD parameters using HSFS-PS makes the system's frequency more stable in complicated situations [9]. Reference [10] used PID controller to (LFC) of a single area power network. The optimization of controller parameters has been done by the evolutionary algorithm of mayfly (MF). This paper indicates that the proposed optimization method is more robust to sudden load changes than conventional methods such as GA and PSO.

Arya has studied the AGC in a power network which contains Redox Flow Batteries (RFB). He used a novel controller named as "A new functional order fuzzy PID (FOFPID)", and for optimizing the controller's parameters ICA is used. This method is highly robust against power system's parameters change [11]. Reference [12] suggests a Jaya algorithm for optimizing the parameters of the linear quadratic regulator for LFC in a single-source single-area power network. The proposed method has significantly reduced the settling time.

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Chang *et al.* used PI controller for LFC and applied fuzzy rules to tune the PI [13]. In this paper, frequency control is done using fuzzy controller. [14] a self-tune fuzzy PID controller is suggested for LFC. In this study, FPID controller acts like a controlling set and the input signals are used for optimizing the PID parameters. Kumar Sahu *et al.* proposed Fuzzy PID (FPID) for a deregulated Power system and used DE for optimizing the parameters. The advantage of this method is that wide variation in load and power system's parameters would not affect the FPID parameters [15].adaptive control technique is to make the system robust variate parameter when system is subjected to sudden disturbance. A novel adaptive controller is presented according to the unsupervised learning technique called feedback error learning (FEL) [6].

In this paper, the LFC problem for a deregulated power system with a poolCo contract is investigated. The PID controller is selected as a fast controller and also two different intelligent topologies are used to optimize the k-factors of the PID controller. The most important goal of this study is to investigate the performance of intelligent techniques that are connected to the PID controller. The proposed hybrid controller is responsible for keeping the power system stable when the power system is under severe load changes, Governor time constant (Tg), Turbine time constant (Tt), and System turbine reheat time constant (Tr).

II. SYSTEM MODELING AND LFC IN DEREGULATION

In a deregulated electricity market, according to the necessity of balancing GENCOs and DISCOs, contracts are signed between companies based on rules and relationships. These contracts can only be PoolCo [16, 17]. In the PoolCo contract, the electricity needed by each area is supplied only by the generators of its area [16, 18]. In the present study, a single area is considered in the deregulated power system. The area consists of 3-thermal generations and two distribution companies: GENCO1, GENCO2, GENCO3, DISCO1, DISCO2 are located in this area. The relationship between electricity producers and their distributors (GENCOS and DISCOS) is expressed as follows using the DPM matrix:

$$DPM = \begin{bmatrix} cpf_{11} & cpf_{12} \\ cpf_{21} & cpf_{22} \\ cpf_{31} & cpf_{32} \end{bmatrix} \tag{1}$$

In this matrix, the total number of DISCO present in a single area is equal to the number of matrix columns and the total number of GENCO in this area is equal to the number of rows in the DPM matrix. Each array of the DPM matrix represents the GENCO's participation factor for the DISCO's power supply. So cpf_{ij} is defined as the participation factor between $GENCO_i$ and $DISCO_j$ for total power supply. In Matrix DPM, equation $\sum_{i=1}^{N} cpf_{ij} = 1$ it should always be true as long as the PoolCo contract is in place. With the help of the DPM matrix, power generated and power planned by each generator can be as power requirements of $DISCO_j$ can be defined and represented by ΔP_{Lj}. The total power requirement of a single-area power system from a DISCO is equal to the sum contracted power in a PoolCo's contract. The DPM matrix is given in Eq. (4).

$$\Delta P_{Di} = \Delta P_{L1} + \Delta P_{L2} + \cdots + \Delta P_{Ln} \tag{2}$$

Total power generated is given as:

$$\Delta P_{gi} = \sum_{j=1}^{n} cpf_{ij} \Delta P_{Lj} \tag{3}$$

$$DPM = \begin{bmatrix} 0.2 & 0.4 \\ 0.4 & 0.3 \\ 0.4 & 0.3 \end{bmatrix} \tag{4}$$

III. CONTROLLERS DESIGN

A. PID Controller

The PID controller is one of the easiest, most reliable, and widely applied control methods in the power industry. In general, PID controllers stabilize the system by adding poles and zeros to its transform function. The proper operation of a PID controller depends on the tuning of its parameters [19]. A single-area deregulated power system with three sources is used to evaluate the proposed method. Therefore, to obtain the optimal values for the PID controller parameters, the transfer function of the power system must be calculated. The transfer function of the single area deregulated power system is connected to a PID controller for frequency stability. The transfer function of the deregulated power system is G(s) which shown in Eq. (5) in the Appendix. For the better efficiency, PID controller should change its parameters with change of load and power system parameters immediately. To achieve this target, the fuzzy inference system (FIS) is connected to the PID controller. The fuzzy system optimizes the controller parameters simultaneously with changes of load and system parameters. The performance of the fuzzy PID controller is compared with the performance of the PID controller optimized by ICA, DE and PSO in a single-area power system. H. Shayeghi *et al.* presented a decentralized Radial Basis Function Neural Network (RBFNN) for LFC in a restructured power grid using the generalized of LFC according to the existing contracts. This technique has advantage of a ANN and mixed control technique to provide robust performance with a flexible controller and a simple structure that is easy to implement [29]. MA Kamarposhti *et al.* a Fuzzy PID controller is proposed for AGC of a wind farm connected to the two-area power system with hydro-thermal power plants. [30].

PolCo contract has been simulated using Simulink MATLAB. The optimization model of PID controller parameters with a fuzzy inference system and evolutionary algorithms are shown in Fig. 1 (a) and (b), respectively. [13, 14, 20-22].

B. Evolution Algorithms

One of the most successful population-based optimization algorithms is the differential evolution (DE) technique. [23, 24]. Since the DE algorithm is very similar to the GA, its coding is very simple. On the other hand, floating point coding is used in this method, while binary coding is used in GA.

The mentioned items come from the advantages of the DE.

GA and DE algorithms have differences in the Selection Operators. The selection operator in the GA algorithm is such that the chance of being selected as one of the parents depends on its value, but in the DE algorithm, all responses have an equal chance of being selected. After creating a new response using the crossover operator and the mutation operator, the new response is compared with the previous value and replaced if it is better. The steps of the algorithm are given in Fig. (2) of the appendix.

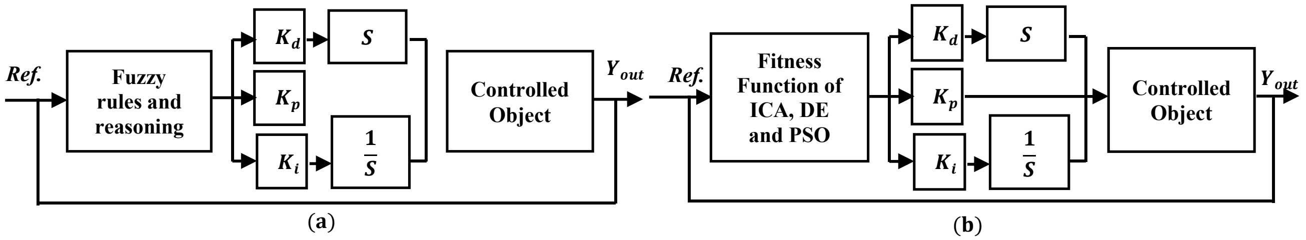

Fig. 1. Optimization of the PID controller parameters. (a) Fuzzy rules inference, (b) Evolution algorithms.

Step 1: Initial Population

Creating a population with constant size and uniform distribution.

Step 2: Mutation

$$V_{iG+1} = X_{r1G} + F_1(X_{r2G} - X_{r3G}) \quad (6)$$

$$V_{iG+1} = X_{bestG} + F_1(X_{r2G} - X_{r3G}) \quad (7)$$

$$V_{iG+1} = X_{r1G} + F_1(X_{r2G} - X_{r3G}) + F_2(X_{bestG} - X_{r1G}) \quad (8)$$

Where, $i = 1, \ldots, NP$, $r_1, r_2, r_3 \in \{1, \ldots, NP\}$ are chosen randomly. $r_1 \neq r_2 \neq r_3 \neq i, F \in [0,1]$, F is the mutation factor proposed by Storn and Price [25].

Step 3: Crossover or Recombination

Combining the successful solutions of the previous generation with the current generation. $V\_(iG+1) = (v\_(1, iG+1), \ldots, v\_(n, iG+1))$ and the current population member, $X\_iG = (x\_(1, iG), \ldots, x\_(n, iG))$ are subject to a crossover operation, that eventually creates a population of candidates or "trial" vectors. $U\_(iG+1) = (u\_(1, iG+1), \ldots, u\_(n, iG+1))$ as follows:

$$U_{i,jG+1} = \begin{cases} V_{i,jG+1} & if\ rand_{i,j} \leq CR \ \ or\ j = I_{rand} \\ X_{i,jG} & otherwise \end{cases} \quad (9)$$

With $rand_{i,j} \sim U(0,1), I_{rand}$ an integer random variable is from one to D, and d is the dimension of the solution.

Step 4: Selection

The selection operator is used to keep the population size constant in the next generations; in this operation, two target and trial vectors are compared and the preferred vector is transferred to the next generation, as follows:

$$X_{iG+1} = \begin{cases} V_{iG+1} & if\ F(U_{iG+1}) < F(X_{iG}) \\ X_{iG} & otherwise \end{cases} \quad (10)$$

The PID controllers are one of the most popular controllers in industries due to their stability and fast response. The proper performance of the PID controller depends on the calculation of the optimal values of K_p, K_i, and K_d. The ISD criterion is considered the performance index of the objective function, which is given below.

$$ISE = \int_0^{t_{sim}} (\Delta f^2 + \Delta P_{tie}^2) dt \quad (11)$$

Δf is the frequency deviation in the power system in Eq. (11), ΔP_{tie} is the exchange power in tie-line between areas, and t_{sim} is the simulation time range. Fig. (3) shows the flowchart of the proposed method (DE-PID). Here the problem is formulated as an ISE optimization problem as shown below.

$K_{pmin} \leq K_p \leq K_{pmax}$; $K_{imin} \leq K_i \leq K_{imax}$ and $K_{dmin} \leq K_d \leq K_{dmax}$. Where K_{min}, K_{max} are the min and Max values of the control parameters. [31].

C. Fuzzy Gain Scheduling Optimization

Power system whose transfer function change non-linearly with changes of load or systems parameters conditions, the best way of controlling systems are used the self-tuning fuzzy PID [20]. The method has taken here used to fuzzy inference system to generate controller parameters. The application of fuzzy inference to PID controller design used the "K" factors of PID controllers are tuned real-time from the knowledge base and fuzzy inference and therefore the PID controller produces the control signal [14]. Parameters of the PID controller are $K_p, K_i$and K_d which, normalized them are$K'_p, K'_i$and α. Those parameters determined by a set of fuzzy rules [20].

In these studies, the calculation of K parameters of the PID controller has been done according to the change of frequency error and error difference as shown in Fig. 1(a). The membership functions is shown in Fig. 3(a, b, and c) respectively.

It is also defined that K_p and K_i are in the destine ranges $[K_{p,min}\ K_{p,max}]$and $[K_{i\,min}\ K_{i\,max}]$. K_p andK_i are normalized with following linear transformation and called K'_p and K'_i which shown in Eq. (12) and (13) respectively.

$$K'_P = (K_p - K_{p\,min})/(K_{p\,max} - K_{p\,min}) \quad (12)$$

$$K'_i = (K_i - K_{i\,min})/(K_{i\,max} - K_{i\,min}) \quad (13)$$

T_i is the time constant of the integral and T_d is the time constant of the derivative, which is given in Eq. (14).

$$T_i = \alpha T_d \quad (14)$$

The set rules used in fuzzy inference for K'_p, K'_d and α are the same as reference [17]. Fuzzy PID controller changes k factors as real-time and has not constant value in the duration of the simulation. These changes affect to growth speed of convergence and increase of overshoot and undershoot, also decrease the time of settling time. K factors are shown in Fig. (4).

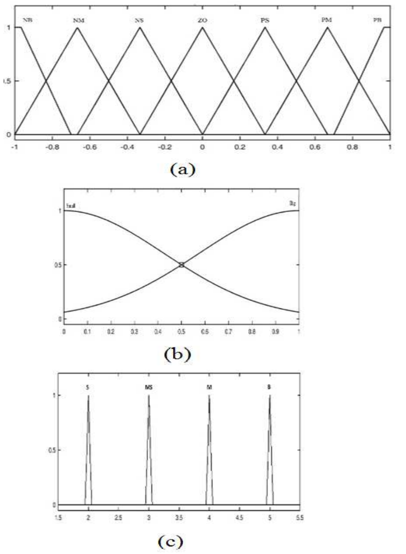

Fig. 3. Membership function of the fuzzy inference.

(a) Membership functions for error and difference of error,

(b) Membership functions for K_p', K_i', (c)Membership functions for α.

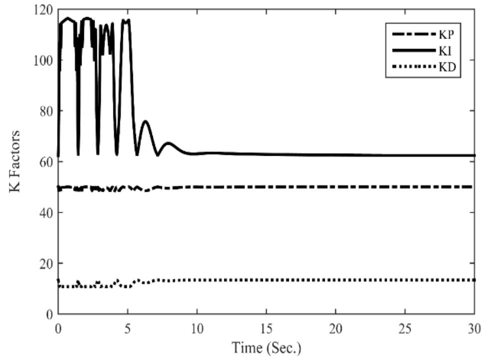

Fig. 4. K factors changes in the fuzzy PID controller.

IV. SIMULATION AND RESULTS

The block diagram model of the single-area deregulated power system that has been studied includes three generators (one non-reheat thermal generator and two reheat thermal generators) simulated in Simulink MATLAB, which is given in Fig. (5)-appendix. The simulation has been carried out for all possible contracts (PoolCo) in the deregulated electricity market with a PID controller in which the PID parameters are optimized using fuzzy inference and evolutionary algorithms such as DE, ICA, and PSO. Single-area multi-source deregulated power system parameters are given in table (1). epf_k, is the k_{th} factor of generator economic participation [26]. In this article, the factors of generators' economic participation are considered as follows: $epf_1 = 0.3$ ، $epf_2 = 0.32$ ، $epf_3 = (1 - (epf_1 + epf_2)) = 0.38$ respectively. In the PoolCo contracts, the required power of each DISCO is considered equal to $0.05\ pu$. Fig. (6) is related to change in frequency in a single area. The controller is designed using the fuzzy inference and evolution algorithms according to "OS" overshoot, "ST" settling time, and "US" undershoot.

TABLE I. COMPARISON OF TRANSIENT CHARACTERISTICS.

$T_{g1} = 0.08\,s, T_{t1} = 0.35\,s, R_1 = 0.3333\frac{HZ}{pu}.MW, k_{g1} = k_{t1} = 1$
$T_{g2} = 0.875\,s, T_{t2} = 0.375\,s, k_{r2} = 0.3113, T_{r2} = 10.6\,s, R_2 = 0.32\frac{HZ}{pu}.MW, k_{g2} = k_{t2} = 1$
$T_{g3} = 0.06\,s, T_{t3} = 0.3\,s, k_{r3} = 0.5, T_{r3} = 10\,s, R_3 = 0.33\frac{HZ}{pu}.MW, k_{g3} = k_{t3} = 1$
$k_{p1} = 20\frac{HZ}{pu}.MW, T_{P1} = 120\,s, B_1 = 0.532\frac{pu}{MW}.HZ$

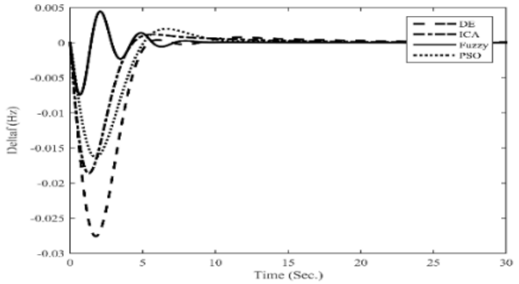

Fig. 6. Frequency deviation in the normal state for all controllers

The details of the transient dynamic response of the Fuzzy-PID, ICA-PID, DE-PID, and PSO-PID controllers are listed in Table (2).

TABLE II. POWER SYSTEM PARAMETERS.

Δf	OS (10^{-3})	US (10^{-3})	ST (Sec.)
Fuzzy PID	0.0044	-0.0073	5.46
ICA PID	0.0008	-0.0014	14
DE PID	0.00055	-0.018	20
PSO PID	0.00255	-0.019	17

PoolCo Based Transactions

In the PoolCo contract, each DISCOs supplies its power demand only from the GENCOs of its own area. These demands are determined by the DPM matrix and are given in Eq. (4).

The output response of the generator power is given in Fig. (7). Two types of experiments were performed in comparing the controllers. Firstly, the change in the load of the single-area deregulated power system. It is assumed that the total power required by the DISCOs in each area changes between $\pm 50\%$ (with a band f ± 0.05).

The results are also compared with the fuzzy inference PID controller and evolution algorithms with a PID controller in Table (3). From the obtained results, it is clear that the performance of the fuzzy PID hybrid controller is better than the performance of the PID hybrid controllers optimized with evolutionary algorithms in the PoolCo contract. Therefore, the PID fuzzy hybrid controller can be considered a suitable candidate for controlling the dynamic stability of the deregulated power system against load severe changes.

The basic power system parameters such as the "Tg" governor time constant, "Tt" turbine time constant, and "Tr" turbine reheat time constant are presented in the appendix, table (4). According to Table (4), Tt, Tr, and Tg parameters have been changed by ±25% and compared with their nominal values for evaluating the performance of the proposed controller against possible changes in system parameters. The results show that OS, US, and ST indicators of frequency deviation have fluctuated within an acceptable range (according to 0.05% changes in power system parameters). The proposed controller can have a proper dynamic performance against the changes in power system parameters.

TABLE III. COMPARISON OF FREQUENCY DEVIATION FOR DIFFERENT LOADING CONDITIONS.

Ctrl.	%change in load	Δf		
		OS(10^{-3})	US(10^{-3})	ST(Sec.)
Fuzzy	-50%	0.0027	-0.0047	5.46
	-25%	0.0035	-0.0060	5.49
	+25%	5.325	-8.760	7
	+50%	6.205	-10.14	7.31
ICA	-50%	0	-0.0093	4.38
	-25%	0.0005	-0.00116	6.54
	+25%	0.962	16.27	19.86
	+50%	1.179	-18.61	20.97
DE	-50%	0	-0.0137	7.91
	-25%	0	-0.0171	8.06
	+25%	0.183	-24.07	6.49
	+50%	0.389	-27.58	6.78
PSO	-50%	0.00145	-0.0132	9.28
	-25%	0.0020	-0.0163	9.82
	+25%	3.084	-22.62	22.39
	+50%	3.641	-25.80	23.55

To validate, the proposed controller has been compared with existing control methods and is shown in Table (5). By comparing the results, we find out the robustness and high speed of the response in the proposed controller against other methods.

TABLE V. COMPARISON OF US, OSAND ST WITH OTHER STUDIES.

Method	Δf		
	$US(*\,10^{-3})$	$OS(*\,10^{-3})$	$ST(Sec.)$
DE-I[27, 31]	-64	-	10.35
hSFS-PS-PI [9]	-63.8	-	10.48
ICA-FOFPID[11]	-29.6	-	6.57
PSO-PI [5]	-10	10.5	94
Fuzzy [14]	-24	22	21
Fuzzy PID [30]	-5.36	5.06	6.19
SSO-PID [19]	-9.6	8	10
FOPID [28]	-27	7.6	17
Proposed methods.	**-7.3**	**4.4**	**5.46**

V. CONCLUSIONS

In this article, an intelligent controller is designed in a deregulated power system. An extensive analysis of the proposed LFC system controller is performed in the deregulated power system with a PoolCo contract. The results clearly show that the Fuzzy-PID controller adjusts the frequency deviation.

In order to show the superiority of the proposed controller (Fuzzy-PID), the results of the dynamic behavior (frequency deviation) are compared with obtained results of the DE, ICA, and PSO algorithms. Results proved that Fuzzy-PID has a better OS, US, and ST in the PoolCo contract as compared to DE-PID, ICA-PID, and PSO-PID. In addition, the simulation results show that the proposed controller is not affected by load changes and uncertainty in power system parameters, and the controller has satisfactory dynamic performance.

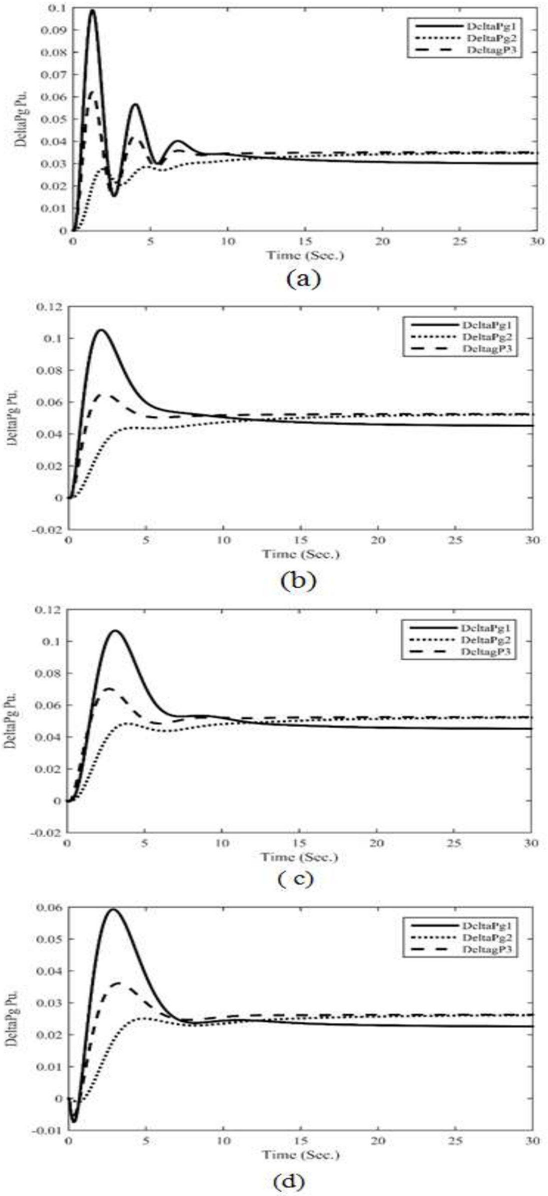

Fig. 7. (a), (b), (c) and (d) generator power outputs response in fuzzy PID, ICA-PID, DE-PID and PSO-PID controllers respectively.

According to the results obtained from the Fuzzy-PID hybrid control system, it is suggested to use this technique for the LFC issue in multi-area deregulated power networks. Also, due to load changes, it is suggested to use Fuzzy (Type-II)-PID.

APPENDIX

$$G_{(s)} = \frac{-0.171\,S^7 + 2.655\,S^6 + 79.92\,S^5 + 424.8\,S^4 + 863.7\,S^3 + 699.9\,S^2 + 166.3\,S + 10.27}{S^9 + 31.37\,S^8 + 353.1\,S^7 + 1810\,S^6 + 4799\,S^5 + 6892\,S^4 + 5376\,S^3 + 249\,S^2 + 446\,S + 26.37} \tag{5}$$

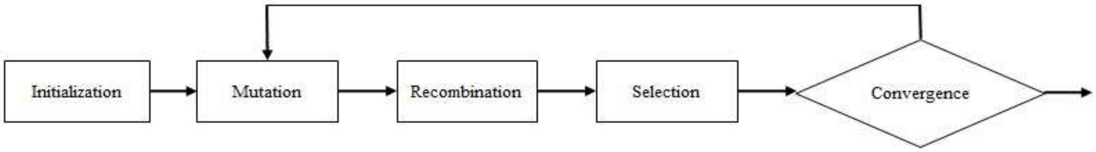

Fig. 2. Simple cycle of DE

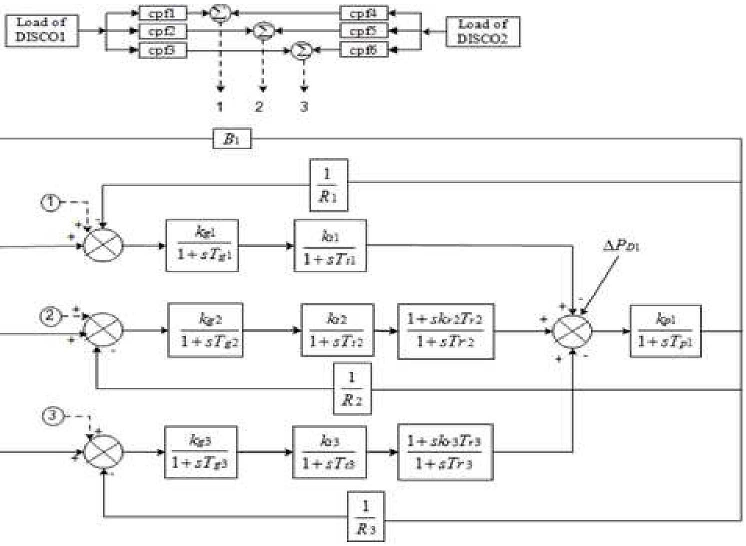

Fig. 5. Single area multi-source power system model

TABLE IV. OVERSHOOT, UNDERSHOOT AND SETTING TIME OF Δf FOR DIFFERENT VALUES OF SYSTEM PARAMETERS.

System par.	method	%change	Δf			%change	Δf		
			OS	US	ST		OS	US	ST
$\boldsymbol{T_t}$	Fuzzy	-25 %	0.00448	-0.00945	6	+25%	0.00855	-0.0109	14
	ICA		0.00112	-0.0177	17		0.00148	-0.0196	17
	DE		0.00095	-0.0227	23		0.00084	0.0246	22
	PSO		0.00173	-0.0158	14		0.00243	-0.017	16
$\boldsymbol{T_r}$	Fuzzy	-25 %	0.00765	-0.0103	11	+25%	0.0091	-0.0114	14.8
	ICA		0.00057	-0.0184	13		0.00205	-0.0205	19
	DE		0.00034	-0.023	17		0.0014	-0.0257	26
	PSO		0.0012	-0.0158	10		0.00253	-0.0168	17
$\boldsymbol{T_G}$	Fuzzy	-25%	0.0040	-0.0071	5.44	+25%	0.0048	-0.0075	5.49
	ICA		0.0009	-0.0182	11.23		0.0013	-0.0189	11.14
	DE		0.0007	-0.0275	15.3		0.0008	-0.0249	16.29
	PSO		0.0017	-0.0161	10		0.0022	-0.0165	9.72

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