

Load-Frequency Control of Three-Area Interconnected Power Systems with Renewable Energy Sources Using Novel PSO~PID-Like Fuzzy Logic Controllers

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Abstract—Modern era power systems may include not only traditional primary energy sources like hydro or thermal energy, but also a variety of Renewable Energy (RE) sources such as solar and/or wind power. This leads to the complexity of the electrical networks related to their design and construction as well as system stability and control issues. Considered to be one of the most crucial control issues, Load Frequency Control (LFC), must be continuously improved in order to ensure the control goals. For an interconnected power system, the control purposes are to maintain the net frequency at nominal value, e.g. 50 or 60Hz as well as to ensure that tie-line power flows are stable at scheduled values. This work proposes a novel LFC strategy applying Particle Swarm Optimization (PSO) ~ PID – like fuzzy logic-based controllers. PSO is one of the most effective optimization techniques. It is used to optimally determine four scaling factors for each LFC proposed in this study. A three-area power network consisting of a hydraulic station, a non-reheat plant, and a reheat unit along with RE sources such as wind and solar power are taken into consideration. The control performance of the proposed control strategy is compared to those of existing controllers, i.e. Genetic Algorithm (GA), Bacteria Foraging Optimization Algorithm (BFOA), Fractional Order-PID (FPID), and fuzzy logic-based PI controllers for the same interconnected power grid model with various case studies of load changes along with nonlinearities and different RE source conditions. Simulation results implemented in MATLAB/Simulink demonstrate the feasibility and applicability of the proposed control strategy.

Keywords—Load-Frequency Control (LFC); PSO~PID – like fuzzy logic controller; PID controller; RE sources; nonlinearities

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I. INTRODUCTION

The complexity and vastness of an interconnected power grid with hundreds of parameters needing to be managed have increased the difficulty of network control and stability. It is a fact that one of the most important control problems in power systems is controlling the generation capacity of plants. In [1], the authors proposed an effective integration between an artificial neural network model and a PD-like fuzzy logic inference system to control the frequency in six areas. A controller fuzzy-like PID was designed in [2] to stabilize frequency in an interconnected power system with nonlinearities and uncertainties. Controlling the output power of generating sub-stations such that transient difference in frequency of each region and power source variation between interconnected areas remains within the specified limits and ensuring zero-steady state error is called Load Frequency Control (LFC) [3–4]. The purpose of the authors in [5] is to present LFC using a GA-based robust controller in a multi-area interconnected power system with governor uncertainties. In [6], a robust H^∞ control technique for an islanded micro-grid in the presence of sudden changes in load conditions was proposed. In [7], the authors proposed the optimal sliding control method H^∞ load frequency (SMLFC) for power systems with time delay. A fractional order fuzzy PID is used to stabilize the frequency of the four areas in [8].

Smart grid is becoming an important issue at present and future power system network configuration [9]. New modern grids provide detailed information about the grid in real-time,

fast analysis of errors, and the ability to connect a large number of RE sources to the electrical system [10]. The rapid development of industry and business has caused a significant shortage of energy available in circumstances of excessive use of fossil fuels [11]. Security of sourcing concerns and environmental concerns invested in low-carbon power generation technology consist one of the priorities in the energy program of many countries [12, 13] Therefore, RE generation is a viable option that will not only meet the growing energy needs, but will also protect the environment [14]. The RE source integration poses additional uncertainties and challenges for power systems, since RE sources are discontinuous and their locations are geographically dispersed [15]. Penetration of different RE sources in modern power systems that are interconnected can greatly reduce the inertia of the system. When switching RE sources powering multi-area electrical systems using converters/inverters, such power electronic interfaces will reduce the total inertia of the system and the voltage/frequency stability. Therefore, a sufficient reduction of inertia will be a major limitation of grid connected RE sources. By increasing the penetration of the existing RE sources, the inertia of the interconnected power system may not be sufficient, creating dynamical problems for the stability of the system voltage and frequency, and cause negative effects on the stability/resiliency of the power system [16, 17]. If massive wind generation is faltered due to error, it may harm the power system's operation and lead to load frequency control issues [18]. An interconnected power system with additional RE sources is a practical need in modern life, but it reduces the inertia of the system and increases the frequency oscillations of the regions and at the same time increases the power fluctuations on power transmission lines. These include devices with nonlinear system components such as GDB (Governor Dead Band), GRC (Generation Rate Constraint), time delay in the system, changes of parameters of the electrical equipment, and varying operating loading conditions.

In traditional PID controllers, the controller parameters may not be updated when the system encounters the above problems. Therefore, a PSO~PID - like fuzzy logic – based controller is proposed in this paper to solve the LFC problem. The response results of the system are compared with the results of GA-tuned PI (GA PI) [19], BFOA PI [19], FPID [20], and fuzzy logic based – PI [21] controllers.

II. MATHEMATICAL MODELING OF INTERCONNECTED POWER SYSTEMS

The interconnected power system with high RE sources used in this study can be seen in [22]. The studied system comprises 3 areas that are interconnected by likely short transmission lines, called tie-lines. Each interconnected power system consists of several single areas. A single area usually includes a governor, a turbine, a load, and a generator. These elements are connected to be the core of a power plant.

A. Speed Governor

Governors are units used in power systems to sense the frequency bias caused by the load change and cancel it by varying the inputs of the turbines. A governor can be mathematically modeled as:

$$\Delta P_g(s) = \frac{1}{1 + sT_g} (\Delta P_c(s) - \frac{1}{R} f(s)) \quad (1)$$

where R is a speed regulation of the governor and T_g is the time constant of the speed of the governor.

B. Turbine Types

A turbine unit in power systems is used to transform the natural energy, such as the energy from steam or water, into mechanical energy that is supplied to the generator. There are three kinds of commonly used turbines: non-reheat, reheat, and hydraulic turbines, all of which can be modeled by transfer functions.

1) Non – Reheat Turbine

Non-reheat turbines are first-order units. A time delay, denoted by T_{ch} , occurs when switching the valve and turbine torque is produced. The transfer function for the non-reheat turbine is represented as:

$$G_t(s) = \frac{P_t(s)}{P_g(s)} = \frac{1}{1 + sT_{ch}} \quad (2)$$

2) Reheat Turbine

Reheat turbines are modeled as second-order units, since they have different stages. The transfer function of these turbines is:

$$G_t(s) = \frac{P_t(s)}{P_g(s)} = \frac{F_{hp}T_{rh}s + 1}{T_{ch}T_{rh}s^2 + (T_{ch} + T_{rh})s + 1} \quad (3)$$

where T_{rh} and F_{hp} are low pressure reheat time constant and high pressure stage respectively.

3) Hydraulic Turbine

Hydraulic turbines are non-minimum phase units due to the water inertia. In the hydraulic turbine, the water pressure response is opposite to the gate position change at first and recovers after the transient response. Thus, the transfer function of the hydraulic turbine can be described as:

$$G_t(s) = \frac{P_t(s)}{P_g(s)} = \frac{(-T_w s + 1)}{(0.5T_w s + 1)} \quad (4)$$

For stability concern, a transient droop compensation part in the governor is needed for the hydraulic turbine. The transfer function of the transient droop compensation part is given by:

$$G(s) = \frac{(T_r s + 1)}{(T_r \frac{R_I}{R^3} s + 1)} \quad (5)$$

where T_r , T_w and R_I are the reset time of the hydraulic unit and water star time and reset time respectively.

C. Wind Turbine (RE Source)

The wind turbine [23] consists of a turbine-generator shaft mechanism, which is used to convert the rotor rotation into electrical energy. Equation (6) represents the mechanical output of the wind turbine:

$$P_{WT} = \frac{1}{2} \rho A C_p (\lambda, \beta) V_w^3 \quad (6)$$

where λ , ρ , V_w , C_p are tip speed ratio, air density factor (Kg/cu.m), wind speed (m/s), and power coefficient respectively.

For small signal stability of the system, the rate of change of wind power output given in (7) has been considered for assessing the stability of the proposed systems.

$$\Delta P_{WT} = \begin{cases} 0, & V_w < V_{cut-in} \\ 0, & V_w > V_{cut-out} \\ 0, & V_{rated} \leq V_w \leq V_{cut-out} \\ \left[\begin{array}{l} 0.007872V_w^5 \\ -0.23015V_w^4 \\ +1.3256V_w^3 + 11.061V_w^2 \\ -102.2V_w + 2.33 \end{array} \right] \Delta V_w \end{cases} \quad (7)$$

The first-order transfer function model of the wind turbine is:

$$\frac{\Delta P_{wtg}(s)}{\Delta P_{wt}(s)} = \frac{1}{T_{wts}s+1} \quad (8)$$

D. Solar Power (RE Source)

The transfer function model of Solar power [24] is:

$$\frac{\Delta P_{spv}(s)}{\Delta P_{sp}(s)} = \frac{1}{T_{spv}s+1} \quad (9)$$

E. Generator - Load

A generator unit in power systems converts the mechanical power received from the turbine into electrical power. For LFC, we focus on the rotor speed output (frequency of the power systems) of the generator instead of the energy transformation. Since electrical power is hard to store in large amounts, balance has to be maintained between the generated power and the load demand. The mathematical model of generator – load is:

$$\Delta F(s) = \frac{1}{Ms+D} (\Delta P_l(s) - \Delta P_d(s)) \quad (10)$$

where M is the inertia constant of the generator and D is the load damping constant. Figure 1 shows a block diagram of a three-area interconnected power system with RE sources and GDB along with GRC established in Matlab/Simulink.

The control objectives of the LFC in multi-area interconnected power systems are mainly to control the frequency variation, and tie-line power deviation in the areas towards zero while the system has many nonlinear elements, varying operating load conditions, and different loads in RE sources.

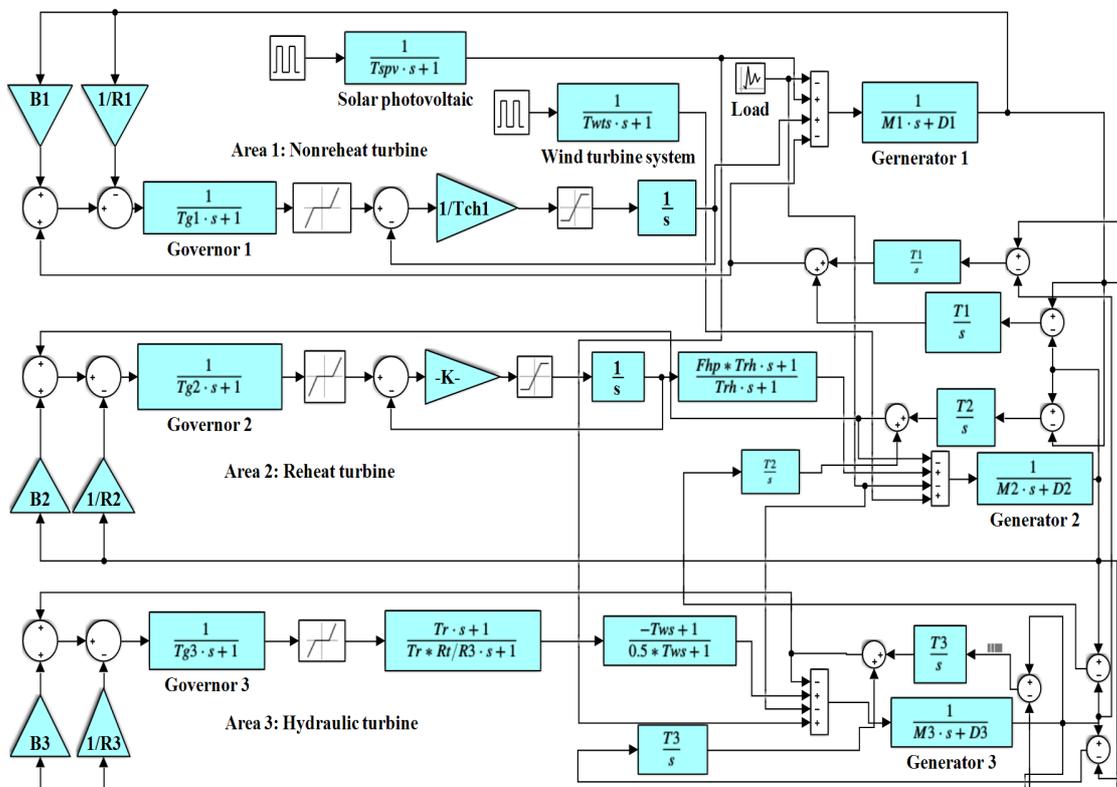


Fig. 1. A three-area interconnected power system model with RE sources, GDB, and GRC.

III. DESIGN OF THE PSO~PID FUZZY LOGIC CONTROLLER

PSO~PID - like fuzzy logic – based controllers are applied in each of the three areas. The structure of the proposed controller is shown in Figure 2. The error inputs to the controllers are the respective Area Control Errors (ACE_i) as shown in the following equations:

$$e_1(t) = ACE_1 = B_1\Delta f_1 + \Delta P_{tie} \quad (11)$$

$$e_2(t) = ACE_2 = B_2\Delta f_2 + \Delta P_{tie} \quad (12)$$

$$e_3(t) = ACE_3 = B_3\Delta f_3 + \Delta P_{tie} \quad (13)$$

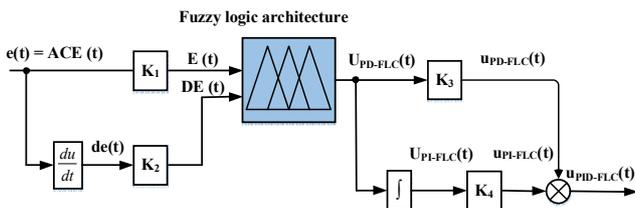


Fig. 2. The proposed structure of the fuzzy – PID controller

The PID-like fuzzy logic controller has two inputs: error $E(t)$ and derivative of error $DE(t)$. The output of the fuzzy controller u is the control input which must be taken to the governor. Each PID-like fuzzy logic controller designed with ACE , ΔACE as inputs and u as output has membership functions as illustrated in Figures 3 and 4. The fuzzy logic rules are presented in Table I.

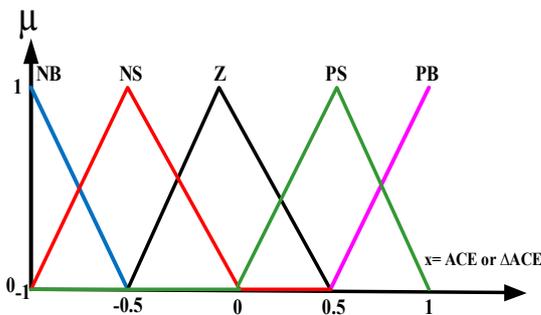


Fig. 3. Membership functions of ACE and ΔACE .

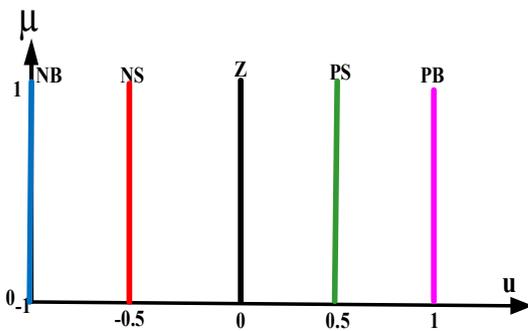


Fig. 4. Membership functions of u .

TABLE I. THE FUZZY RULES

		NB	NS	Z	PS	PB
ACE	NB	NB	NB	NB	NS	Z
	NS	NB	NB	NS	Z	PS
	Z	NS	NS	Z	PB	PB
	PS	NS	Z	PS	PB	PB
	PB	Z	PB	PS	PB	PS

In the design of a modern heuristic optimization based controller, the objective function is first defined based on the desired specifications and constraints. Performance criteria usually considered in the control design are the Integral of Time multiplied Absolute Error (ITAE), the Integral of Squared Error (ISE), the Integral of Time multiplied Squared Error (ITSE), and the Integral of Absolute Error (IAE). In this paper, ISE is used as the objective function to optimize K_1, K_2, K_3, K_4 in the PSO - PID - like fuzzy logic – based controller. The optimization technique uses the IATE objective function which is depicted in (14):

$$J = IATE = \int_0^{t_{sim}} \left(|\Delta f_1| + |\Delta f_2| + |\Delta f_3| + \sum_{i,k=1}^3 |\Delta P_{tie\ i,k}| \right) dt \quad (i \neq k) \quad (14)$$

where $\Delta f_1, \Delta f_2,$ and Δf_3 are the system frequency deviations, ΔP_{tie} is the incremental change in tie-line power and t_{sim} is the time range of simulation.

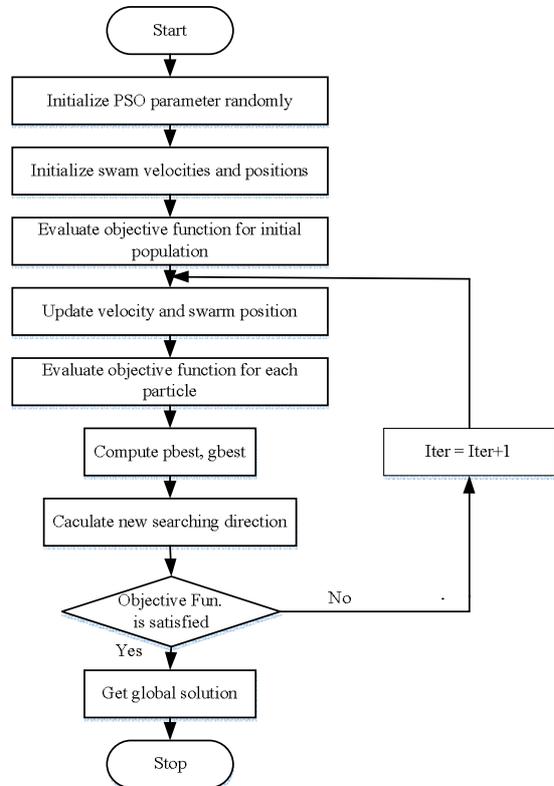


Fig. 5. A typical flowchart of the PSO algorithm.

The objective is to minimize the function J during changing conditions of the operating load with RE sources and GDB and GRC nonlinearities. Applying the objective function in (14), an effective optimization method can be used. In this study, the PSO [25] technique is chosen. PSO is a biological-inspired optimization mechanism. The computational optimization method mimics the activity of finding food of a flock of birds or fish. A typical flowchart of the PSO algorithm is illustrated in Figure 5. In this study, the PSO mechanism is executed with the parameter values indicated in Table II. N , c_1 , c_2 , and w are the population size, two acceleration coefficients, and the inertia weight factor of the PSO respectively. With these parameters, the PSO is able to optimally determine all scaling factors for the PID-like fuzzy logic controllers. Case studies of applying this optimization technique are presented below.

TABLE II. PSO PARAMETER VALUES

Parameter	N	c_1	c_2	w
Value	80	3	2.5	0.8

IV. CASE STUDIES

According to the control idea presented above, the PSO algorithm is employed to find the optimal coefficients K_1 , K_2 , K_3 , K_4 for the PID-based fuzzy logic controller based on the IATE objective function indicated in (14). After executing the PSO, the optimal coefficients given in Table III were obtained. The proposed controller is compared with GA PI [19], BFOA-PI [19], FPID [20], and Fuzzy PI [21] to verify its quality and feasibility. Five different case studies regarding load changes embedded in the 3 areas were considered (Table IV). In each simulation scenario of the load variations, the pulse loads in RE sources also affect the power network (Table IV). The obtained simulation results are shown in Figures 6-10 and Table V.

TABLE III. OPTIMAL FUZZY LOGIC-PID PARAMETERS USING PSO

Coefficient	K_1	K_2	K_3	K_4
Value	800.91	154.46	624.09	709.43

TABLE IV. SIMULATION CASE STUDIES

Case studies	Step load (pu)	Random load (pu)	Pulse load in RE sources (pu)
Case 1	$\Delta P_{d1} = \Delta P_{d2} = \Delta P_{d3} = 0.03$		$\Delta P_{spv} = \Delta P_{wts} = 0.03$
Case 2	$\Delta P_{d1} = \Delta P_{d2} = \Delta P_{d3} = 0.05$		$\Delta P_{spv} = \Delta P_{wts} = 0.03$
Case 3	$\Delta P_{d1} = \Delta P_{d2} = \Delta P_{d3} = 0.05$		$\Delta P_{spv} = \Delta P_{wts} = 0.05$
Case 4		$\Delta P_{d1} = \Delta P_{d2} = 0.05$ $\Delta P_{d3} = 0.05$	$\Delta P_{spv} = \Delta P_{wts} = 0.05$
Case 5		$\Delta P_{d1} = \Delta P_{d2} = 0.08$ $\Delta P_{d3} = 0.08$	$\Delta P_{spv} = \Delta P_{wts} = 0.05$

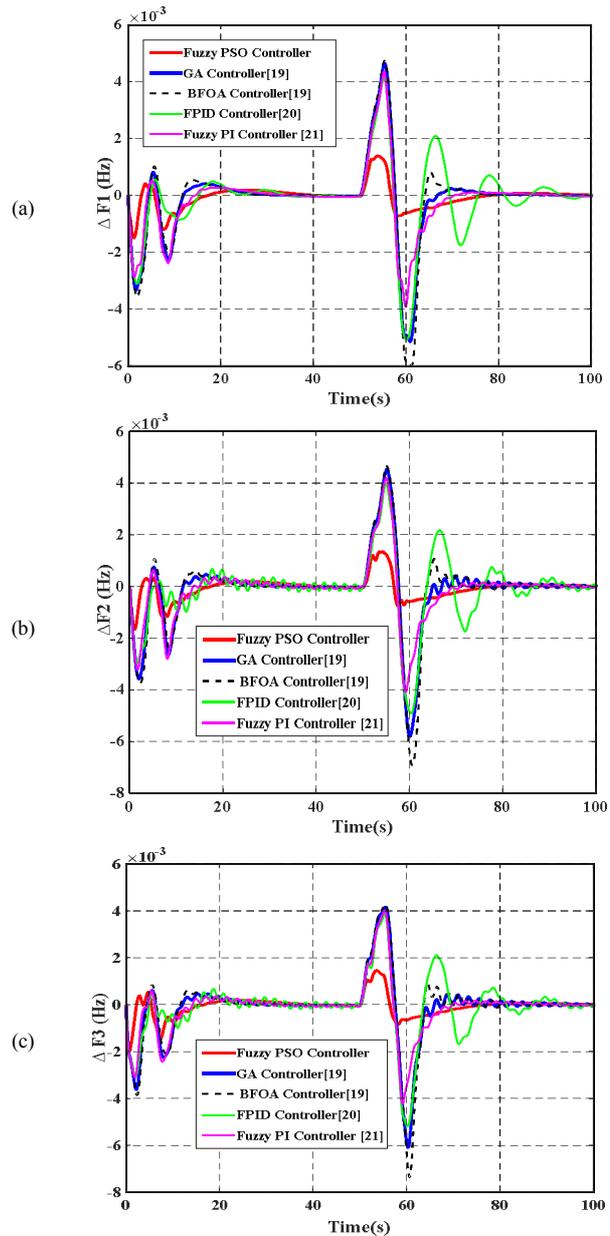


Fig. 6. Dynamic responses (case 1) in the three areas (a) Δf_1 , (b) Δf_2 , (c) Δf_3 .

TABLE V. IATE OBJECTIVES OF THE CONSIDERED CONTROLLERS

Techniques/parameters	ITAE (pu)	Peak time (s)		
		Δf_1	Δf_2	Δf_3
FPID [19]	68.02	55.25	55.04	59.13
GA PI [8]	67.55	61.16	60.59	60.62
BFOA PI [8]	69.60	60.13	60.34	60.16
Fuzzy PI [20]	62.09	60.88	60.09	60.34
Proposed	53.17	1.32	1.062	0.71

It can obviously be seen that the proposed PID-like fuzzy logic controller exhibits better control performance than the other controllers [19-21]. Major control indexes, such as overshoots and settling times, resulting from the proposed controller outperform the four existing controllers.

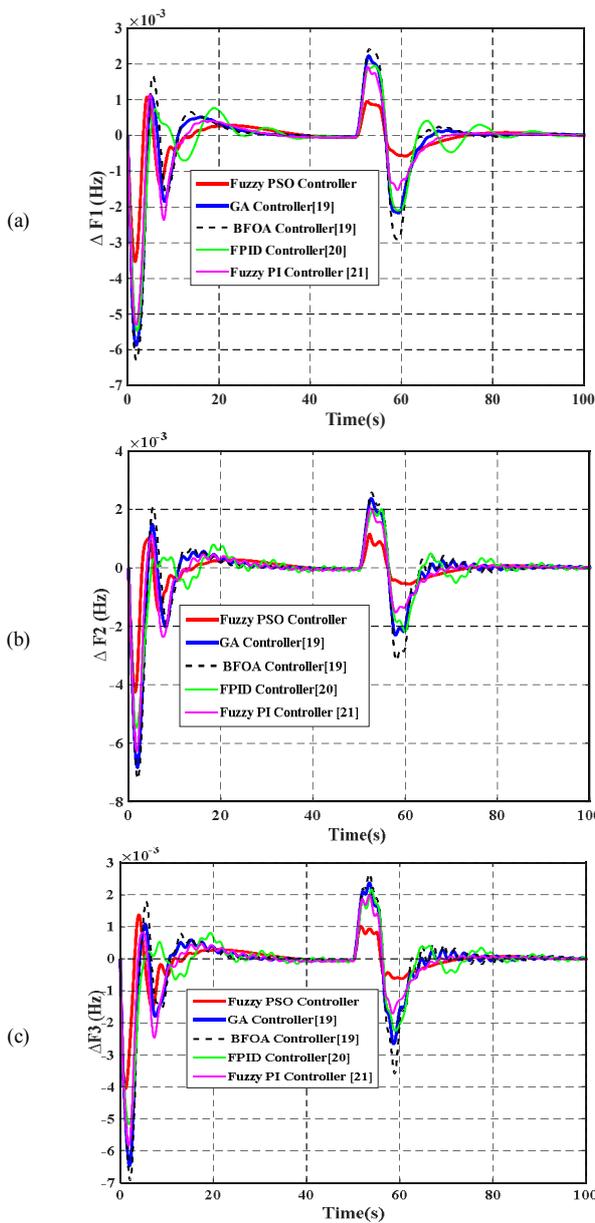


Fig. 7. Dynamic responses (case 2) in the three areas (a) Δf_1 , (b) Δf_2 , (c) Δf_3 .

The simulation results shown in Figures 6-10 illustrate that the output response of the frequency deviations in the three areas has settling times of about 20 to 30s, the overshoot is very low and frequency oscillation does not exist when using the proposed controller, proving its optimality. It is clear that when different types of load disturbances exist in the system, the undesirable effects will be minimized under the active capability of the proposed controller. In addition, from Table V, the minimum ITAE value is obtained with the proposed controller (ITAE = 53.17). Consequently, much better system performance in terms of minimum peak times in frequency deviations is achieved. It is extremely significant for the control of an interconnected power system with a huge number of electric equipment operating based strongly on the net

frequency. The shorter the peak times of the frequency deviation are, the better the obtained control quality of the power network can be. These illustrations demonstrate the applicability of the proposed fuzzy logic control strategy, which outperforms the other controllers in the LFC of an interconnected electric power grid, especially when considering uncertainties, nonlinearities, and RE sources.

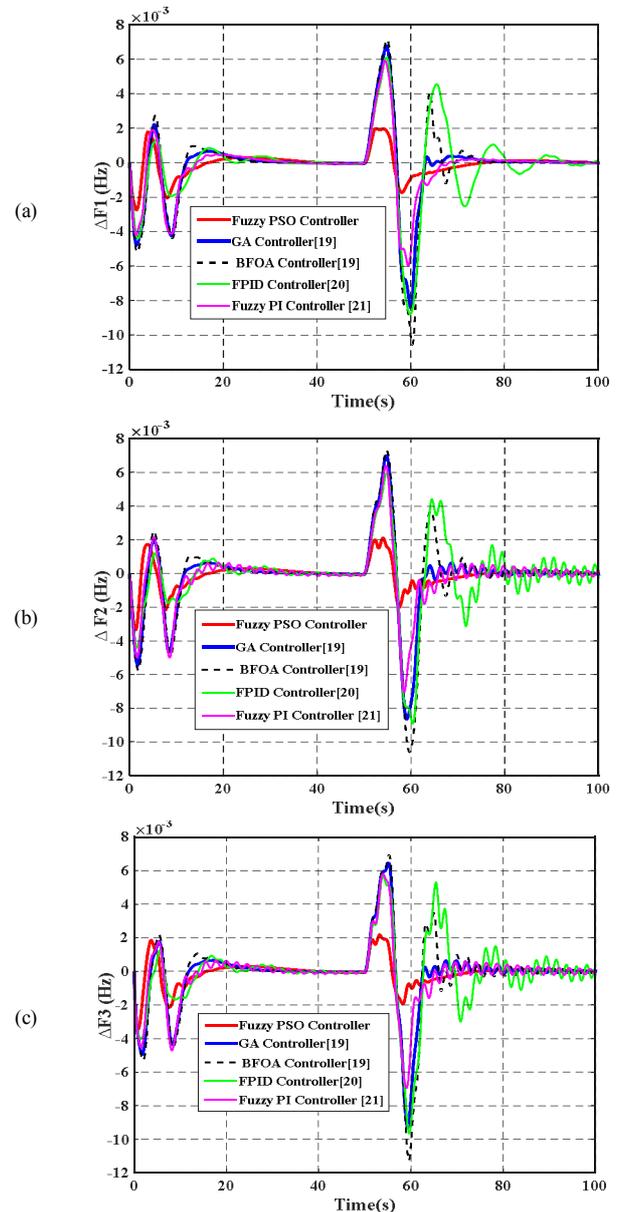


Fig. 8. Dynamic responses (case 3) in the three areas (a) Δf_1 , (b) Δf_2 , (c) Δf_3 .

V. CONCLUSION AND FUTURE WORK

In this paper, a novel PSO~PID-like fuzzy logic – based load-frequency control strategy has been proposed for a three – area interconnected power system with various RE sources and GRC and GDB nonlinearities. Such an electric power grid with

embedded various RE sources is highly complicated with different kinds of turbines used for generating stations as well as nonlinear parameters, making the control extremely challenging. It was also demonstrated from the numerical simulation results that the proposed PID-like fuzzy logic LFC controllers applying the PSO technique are completely able to solve the LFC problem, outperforming existing solutions.

practical power networks. In this aspect, the effectiveness of the studied intelligent LFC controllers will come to reality.

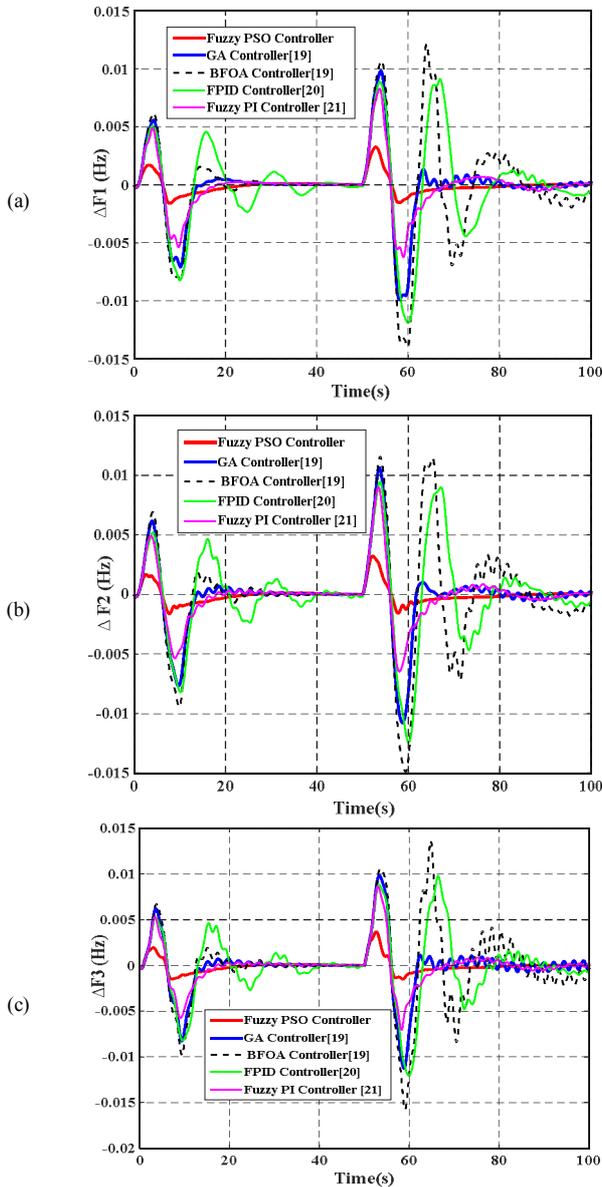


Fig. 9. Dynamic responses (case 4) in the three areas (a) Δf_1 , (b) Δf_2 , (c) Δf_3 .

Major control indexes of the proposed system, such as overshoot and settling time, obtained from the proposed LFC strategy were good enough, verifying this control scheme to be feasible and applicable.

Future work raised from this study will concentrate on step-by-step application of the theoretical control methodology to

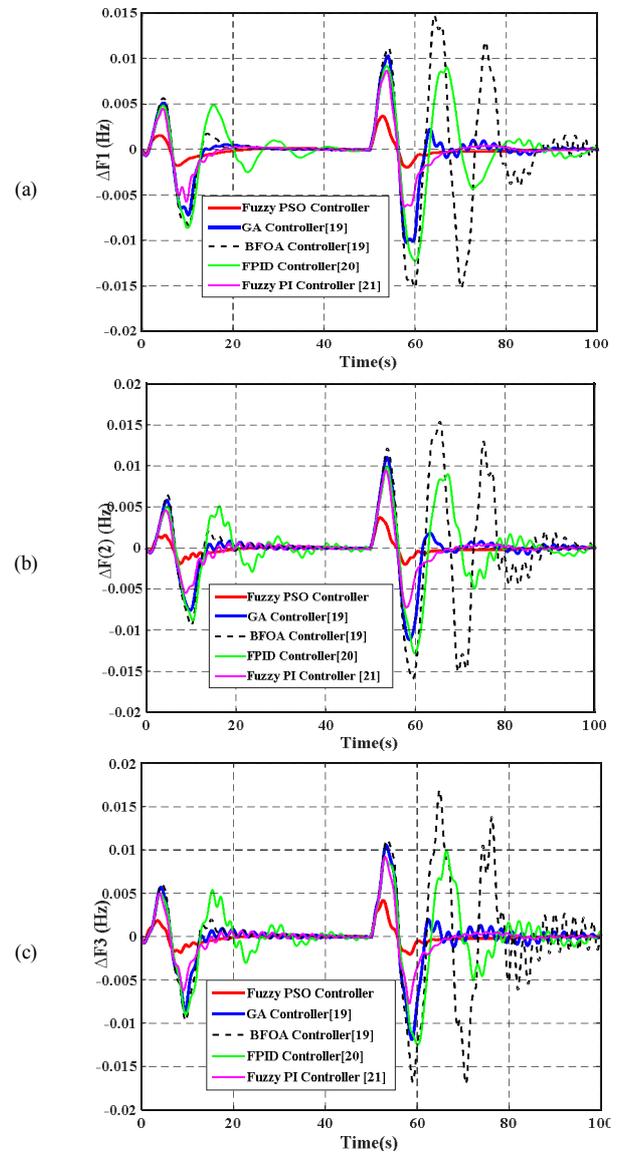


Fig. 10. Dynamic responses (case 5) in the three areas (a) Δf_1 , (b) Δf_2 , (c) Δf_3 .

APPENDIX

PARAMETERS OF THE THREE AREAS [19]

Area with non-reheat turbine	Value	Area with reheat turbine	Value	Area with hydraulic turbine	Value
M_1 (p.u.s)	10	M_2 (p.u.s)	10	T_w (s)	1
D_1 (p.u./Hz)	1	D_2 (p.u./Hz)	1	T_R (s)	5
T_{ch1} (s)	0.3	T_{ch2} (s)	0.3	F_{hp}	0.3
T_{gl} (s)	0.1	T_{g2} (s)	0.2	T_{rh} (s)	7
R_1 (Hz/p.u.)	0.05	R_2 (Hz/p.u.)	0.05	T_{spv} (s)	1.8
B_1 (p.u./Hz)	21	B_2 (p.u./Hz)	21	T_{ms} (s)	1.5
T_1 (p.u./rad.)	22.6	T_2 (p.u./rad.)	22.6		

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