Comparative Evaluation of Different Hybrid Intelligent Load-Frequency Controllers for Interconnected Electric Power Grids

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ABSTRACT

Network frequency is considered to be one of the most crucial parameters that strongly affect the stability and economic achievements of interconnected electric power grids. System frequency usually fluctuates and deviates from the nominal values due to random and continuous load changes over time, affecting the electric equipment to significantly decrease efficiency and increase instability. A Load-Frequency Control (LFC) strategy has been proposed to solve this problem. This study compared several different control strategies, namely Fuzzy Particle Swarm Optimization (Fuzzy-PSO), Proportional Integral Derivative (PID), Fuzzy-PID, Fuzzy- Proportional Integral (PI), PSO-PI, and FPID to investigate the effectiveness of intelligent hybrid LFC controllers. The above controllers were simulated on a three-area interconnected power network with the participation of renewable energy sources. Taking into account different load cases, the Fuzzy-PSO-PID controller obtained frequency deviations in the range of 0.0015 to 0.002 Hz. The settling time was about 10 s to reach zero frequency error in each area. With the above controller quality parameters, the Fuzzy-PSO-PID controller provided better quality than the other controllers. A comparative numerical simulation in MATLAB/Simulink for various load change scenarios revealed the effectiveness of hybrid smart controllers, such as the Fuzzy-PID-PSO, outperforming the traditional ones.

Keywords-Load-Frequency Control (LFC); Fuzzy-PSO-PID; Fuzzy-PID; Fuzzy-PI; PSO-PI; FPID; RE sources

I. INTRODUCTION

Interconnected power networks are typically complex systems with many parameters that need to be observed and controlled. Among them, system frequency and voltage are the most vital parameters. Frequency deviation from the rated one occurs due to the time-by-time imbalance between the production and consumption of electricity. This negatively affects consumers, especially those dealing with electrical equipment that is designed and optimized to work at rated frequency. When the frequency changes, it leads to a decrease in the performance of the equipment, reducing operation performance. When operating below 49.5 Hz, some steam turbines and rotors vibrate excessively. Excessive frequency attenuation in the system will increase the magnetization current in induction machines and transformers. Therefore, it is highly necessary to design frequency-stabilizing controllers in interconnected power systems. Many studies have used different algorithms for frequency stabilization in interconnected power systems.

In [1], an online controller that combined BIA and fuzzy algorithms to control the frequency stability of four areas was presented. In [2], a Linear Controller (LQ) was proposed based on the Genetic Algorithm (GA) to control frequency stability for a system consisting of two non-reheat turbine areas. In [3], the design of a neural controller for a system consisting of three areas with non-reheat, reheat, and hydraulic turbines was studied. In [4], the ANFIS controller combined neural network and internal fuzzy control to ensure the frequency stability of a system consisting of two areas of reheat and hydraulic turbines with frequency overshoots ranging from 0.01 to 0.08 Hz. The BBO controller in [5] was designed for frequency stabilization in a system of two areas, each consisting of three power sources. In [6], the model predictive-design controller aiming to improve the frequency stability of a four-area system was examined, considering factors for nonlinear systems, such as Governor Dead Band (GDB) and Generation Rate Constraint (GRC). In [7-9], focus was given to frequency and power stability studies in multi-connected power systems. The power stability of the line is one of the additional requirements for frequency stability [10-13]. In [14], the design of a Load Frequency Control (LFC) component was investigated in a four-area interconnected power system.

The PID controller has been optimized using the Particle Swarm Optimization (PSO) and JAYA optimization methods. In [15], a fuzzy logic controller based on the PID principle was proposed to completely solve the LFC problem in a two-area interconnected power system. Currently, due to high electricity demand, renewable energy sources are being increasingly used in power systems. In addition to the advantages of renewable energy sources, there are also inherent disadvantages. Renewable energy sources in interconnected power systems increase the non-linearity of the system. Solar power sources have no rotational inertia, but wind power sources have low rotational inertia and have a dynamic response that depends on the characteristics of the inverter. Therefore, when solar and wind power account for a high proportion of power production, they will reduce the inertia and vibration resistance coefficient of the grid, leading to an increased risk of destabilizing the power system. Therefore, increasing the frequency deviation in each region, reduces the working capacity of the system equipment, changes the power flow, and augments the losses on the power transmission lines.

In [16], an adaptive model predictive controller for systems with renewable energy sources of wind power was explored. In [17], a hybrid controller (DEPSO) was proposed to optimize the parameters of the fuzzy-PID controller. In [18], the frequency of a power system was stabilized using a combination of PSO and ANFIS hybrid controllers to adjust the PID parameters. In [19], the PSO control method was used to optimize the FOC design for a system that integrated additional wind power sources. In [20], an algorithm based on the cuckoo search method was employed to ensure the frequency stability of power systems with nonlinear factors. The cuckoo search algorithm was utilized in [21] for frequency stabilization of thermal and wind power systems. In [22], a fuzzy PID controller, whose parameters were optimized by the Cuckoo Search algorithm, was proposed to stabilize frequency. In [23], the BFOA method was used to optimize the PID controller parameters and thus stabilize the frequency of two regions with renewable energy. In many studies, the power networks embedded with renewable energy sources are highly difficult to control in a successful operation and distribution. An interconnected power system with nonlinear elements and renewable energy sources is an extremely complex system. The system's frequency stability control will not be effective if classical controllers are used. This study investigated and compared the ability to stabilize the frequency of several efficient load-frequency controllers, including Fuzzy-PSO-PID, Fuzzy-PID, Fuzzy-PI, PSO-PID, and FPID regulators. A system can be improved with intelligent hybrid controllers. The three-area power system was studied, having a non-reheat turbine, a reheat turbine, and a hydraulic turbine. This study considered nonlinear factors and the participation of renewable energy sources, such as wind and solar energy.

II. MODELING OF INTERCONNECTED POWER SYSTEM IN LFC

A single power system consists of the following basic components: a speed governor, a turbine of three types (non-reheat turbine, reheat turbine, and hydraulic turbine), and a generator. Figure 1 shows the structure of a basic single-area power system. A typical three-area electrical system comprises three single-area systems connected via interconnection lines. Each area has its own generating unit(s) that provide electricity to consumers. The link offers information about the scheduled exchange of electricity between the three areas. Figure 2 shows a model of a typical three-area power system. The power exchange deviation between two areas is calculated by:

$$\Delta P_{tie,ij}(s) = \frac{2\pi T_{ij}}{s}(\Delta f_i(s) - \Delta f_j(s)) \tag{1}$$

where $\Delta P_{tie,ij}$, Δf_i, and T_{ij} denote the tie-line power change, frequency variation, and constant coefficient between two areas i and j, respectively.

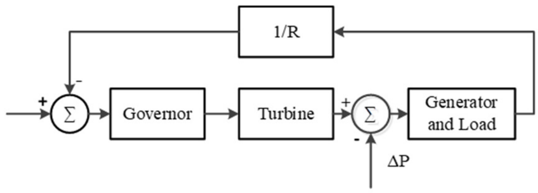

Fig. 1. The basic structure of a single-area power system.

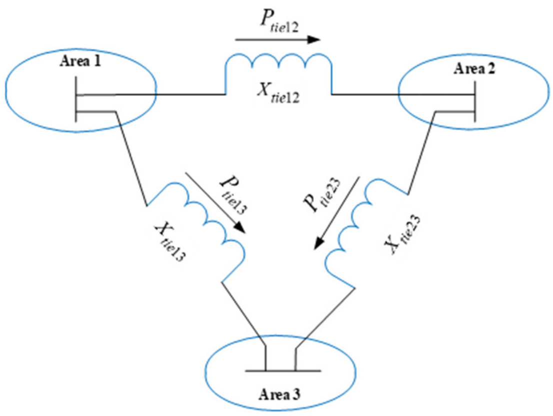

Fig. 2. The structure of three-area power systems.

A. Turbine

A turbine unit is used to convert primary energy, such as energy from steam or water, into mechanical energy (ΔP_t) that powers a generator. There are three types of turbines: Non-reheat, reheat, and hydraulic turbines. This study investigated the presence of renewable energy in all three areas and its effect on frequency stability.

1) Non-Reheat Turbine

A non-reheat turbine is a first-order unit. The time delay, expressed in T_{ch}, occurs between switching the valve and generating the turbine torque. The transfer function for a non-reheat turbine is expressed 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, as they have different stages due to high and low steam pressure. The transfer function can be expressed as:

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

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

3) Hydraulic Turbine

In a hydraulic turbine, the water pressure response is initially reversed to the gate position change and recovered after the transient response. Therefore, the transfer function of a hydraulic turbine can be described as follows:

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

Regarding stability concerns, a temporary deflection compensator is required in the governor for the hydraulic turbine. The transfer function of the temporary slump compensation is given by:

$$G(s) = \frac{T_r s+1}{T_r \cdot \frac{Rt}{R3} \cdot s+1} \quad (5)$$

where T_r, T_w, and R_t are the reset time of the hydraulic unit, water starting time, and the reset time, respectively.

B. Wind Turbine (RE sources)

A wind turbine [24] 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, and C_p are the tip speed ratio, air density factor (Kg/cu.m), wind speed (m/s), and power coefficient, respectively. The first-order transfer function model of a wind turbine is:

$$\frac{\Delta P_{wtg}(s)}{\Delta P_{wt}(s)} = \frac{1}{T_{wts}s+1} \quad (7)$$

where T_{wts} is the time constant of the wind turbine.

C. Solar Power (RE sources)

The transfer function model of solar power is [25]:

$$\frac{\Delta P_{spv}(s)}{\Delta P_{sp}(s)} = \frac{1}{T_{spv}s+1} \quad (8)$$

Figure 3 displays a block diagram of a three-area interconnected power system with RE sources and GDB along with GRC, established in the Matlab/Simulink platform. The three-area interconnected system was considered to be a typical power system model, as illustrated in Figure 2. In this system, there are nonlinear factors, such as GDB, GRC, and renewable energy sources affecting the frequency stability of the system. This is considered a complex system.

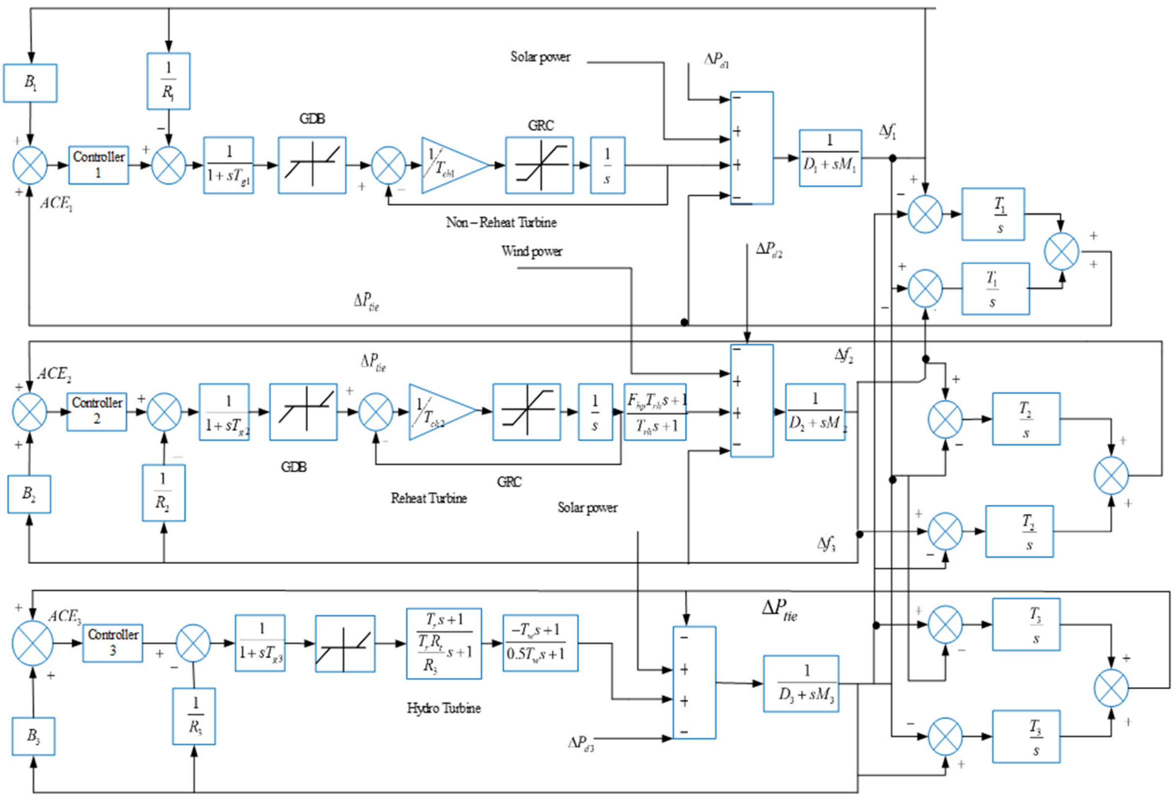

Fig. 3. A three-area interconnected power system model.

III. COMPARISON OF DIFFERENT CONTROLLERS IN VARIOUS LOAD CHANGE SCENARIOS

Figure 4 portrays the LFC structure of an interconnected power system utilizing different controllers. The main purpose of the secondary regulator is to restore the frequency offset and power flow deviation, exchanged between the systems, to zero by adjusting the Area Control Error (ACE) to zero. ACE is calculated according to:

$$ACE_i = \Delta P_{tie,i,j} + \beta_i \Delta f_i \tag{9}$$

with control inputs ACE and ΔACE. This study compared the Fuzzy-PSO-PID [26], Fuzzy-PID [27], Fuzzy-PI [28], PSO-PI, and FPID [29] controllers in five cases. Table I presents the parameters of the three-area interconnected power system. The Fuzzy-PSO-PID controller [26] was studied with the control diagram shown in Figure 5.

TABLE I. THE PARAMETERS OF THREE AREAS [27]

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)	1.0
D_1 (p.u./Hz)	1.0	D_2 (p.u./Hz)	1.0	T_R (s)	5.0
T_{ch1} (s)	0.3	T_{ch2} (s)	0.3	F_{hp}	0.3
T_{g1} (s)	0.1	T_{g2} (s)	0.2	T_{rh} (s)	7.0
R_1 (Hz/p.u.)	0.05	R_2 (Hz/p.u.)	0.05	T_{spv} (s)	1.8
B_1 (p.u./Hz)	21.0	B_2 (p.u./Hz)	21.0	T_{wts} (s)	1.5
T_1 (p.u./rad.)	22.6	T_2 (p.u./rad.)	22.6		

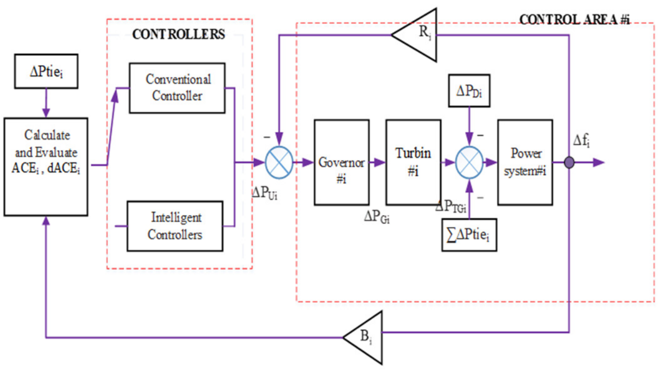

Fig. 4. The structure of the control area *i* using different controllers.

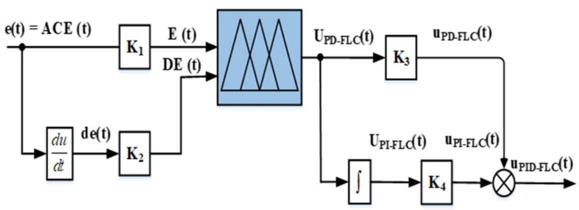

Fig. 5. The structure of the Fuzzy-PSO-PID controller.

The coefficients K_1, K_2, K_3, and K_4 were optimized using the PSO method, as depicted in Table II.

TABLE II. OPTIMAL FUZZY-PID PARAMETERS USING PSO

Coefficients	K_1	K_2	K_3	K_4
Value	800.91	154.46	624.09	709.43

J is the objective function calculated using IATE to determine the optimal parameters of the Fuzzy-PSO-PID controller. The use of IATE to determine the objective function provides the best optimal parameters. The objective function is:

$$J = IATE = \int_0^{t_{sim}} \left(\begin{array}{c} |\Delta f_1| + |\Delta f_2| + |\Delta f_3| + \\ \sum_{\substack{i,k=1 \\ (i \neq k)}}^{3} |\Delta P_{tiei,k}| \end{array} \right) tdt \tag{10}$$

where t_{sim} is the simulation time. The Fuzzy-PID controller [27] employs fuzzy inference to determine three factors of the PID regulator as a master-slave mechanism. To compare the quality of frequency controllers for three areas, simulations of a three-area power system with the participation of renewable energy sources were carried out in five cases with varying load types.

A. *Case 1*

Figure 6 illustrates the simulation results of the case where:

$\Delta P_{d1} = \Delta P_{d2} = \Delta P_{d3} = 0.03$ (Types of step), and

$\Delta P_{spv} = \Delta P_{wts} = 0.03$ (Types of pulse).

(a) (b) (c)

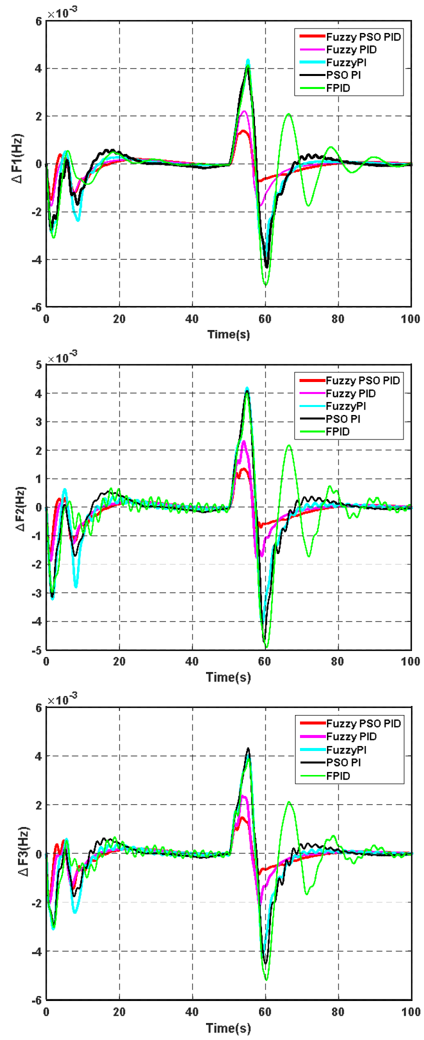

Fig. 6. Case 1: Dynamic frequency responses in three areas: (a) Δ*F1*, (b) Δ*F2*, (c) Δ*F3*.

Table III displays the results of this case, demonstrating that Fuzzy-PSO-PID outperformed the other controllers.

TABLE III. COMPARISON OF CONTROLLERS

	Error of frequency (10^{-3} Hz)			**Settling time (s)**		
	ΔF1	***ΔF2***	***ΔF3***	***ΔF1***	***ΔF2***	***ΔF3***
Fuzzy- PSO-PID	1.6	1.1	1	2	2	2
Fuzzy-PID	2.01	2	2	5	5	6
Fuzzy-PI	4	4	4	10	15	17
PSO-PI	4.01	4	4	20	20	20
FPID	4.5	4.5	4.5	50	50	55

B. Case 2

Figure 7 shows the numerical simulation outcomes of the following case:

$\Delta P_{d1} = \Delta P_{d2} = \Delta P_{d3} = 0.05$ (Types of step),

$\Delta P_{spv} = \Delta P_{wts} = 0.03$ (Types of pulse)

(a)

(b)

(c)

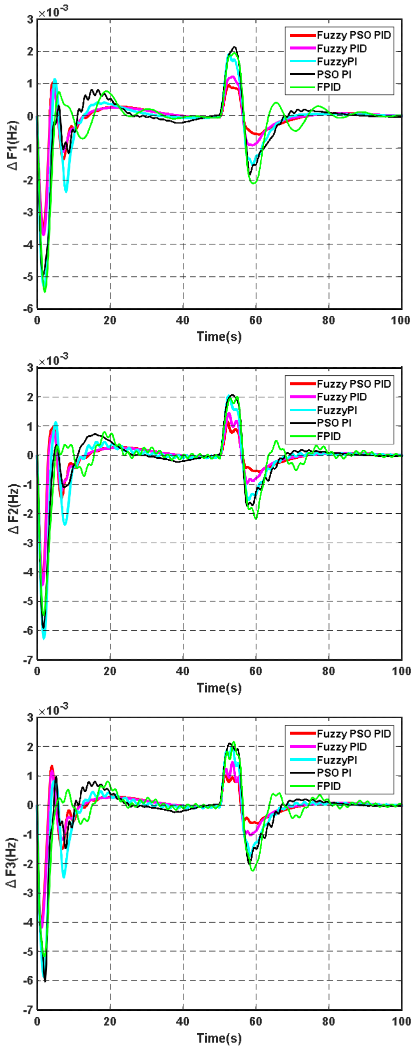

Fig. 7. Case 2: Dynamic frequency responses in three areas: (a) $\Delta F1$, (b) $\Delta F2$, (c) $\Delta F3$.

C. Case 3

Figure 8 describes the simulation results for the case of:

$\Delta P_{d1} = \Delta P_{d2} = \Delta P_{d3} = 0.05$ (Type of step), and

$\Delta P_{spv} = \Delta P_{wts} = 0.05$ (Types of pulse).

(a)

(b)

(c)

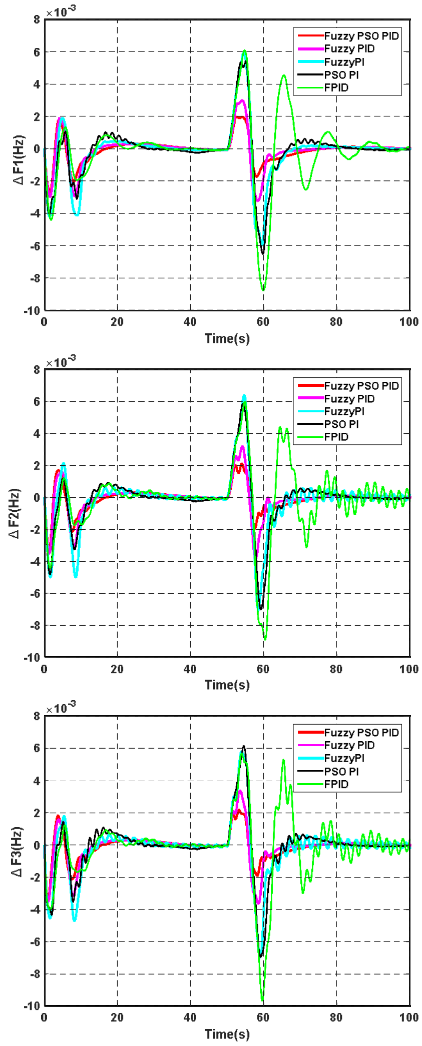

Fig. 8. Case 3: Dynamic frequency responses in three areas: (a) $\Delta F1$, (b) $\Delta F2$, (c) $\Delta F3$.

D. Case 4

Figure 9 portrays the plot curves of frequency responses in the case of:

$\Delta P_{d1} = \Delta P_{d2} = \Delta P_{d3} = 0.05$ (Type of random), and

$\Delta P_{spv} = \Delta P_{wts} = 0.05$ (Type of pulse).

E. Case 5

This case takes into account the time delay with t =2 s, which greatly affects the quality of frequency control in each area. Figure 10 presents the simulation results with the following parameters:

$\Delta P_{d1} = \Delta P_{d2} = \Delta P_{d3} = 0.05$ (Type of random), and

$\Delta P_{spv} = \Delta P_{wts} = 0.03$ (Type of pulse).

(a)

(b)

(c)

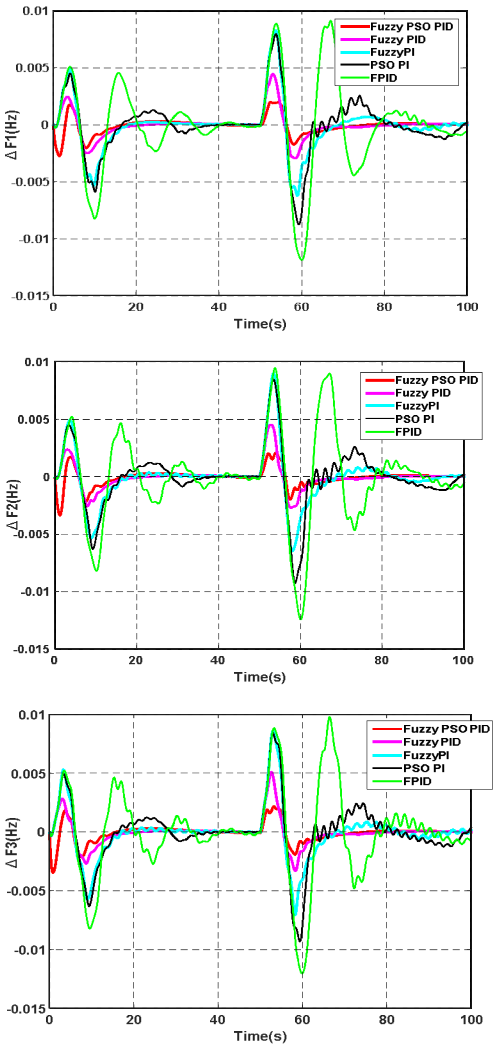

Fig. 9. Dynamic frequency responses in three areas in case 4: (a) $\Delta F1$, (b) $\Delta F2$, (c) $\Delta F3$.

The participation of renewable energy sources in an interconnected power system reduces its inertia. By observing the frequency responses of each region in each case, it is demonstrated that when using PID, PSO, and PID controllers, there is a strong system frequency deviation in each area with a large overshoot. When utilizing Fuzzy PI and Fuzzy PID controllers, the frequency error response had reduced oscillation but the overshoot was still large. The Fuzzy-PSO-PID controller did not cause overshoot and frequency deviation in stable areas. Figures 6-10 depict the frequency error responses in the three areas. When using the Fuzzy-PSO-PID controller, the frequency error and response time were the smallest. The FPID controller had the biggest bias and response time. This indicates that hybrid smart controllers give better responses than classic ones.

(a)

(b)

(c)

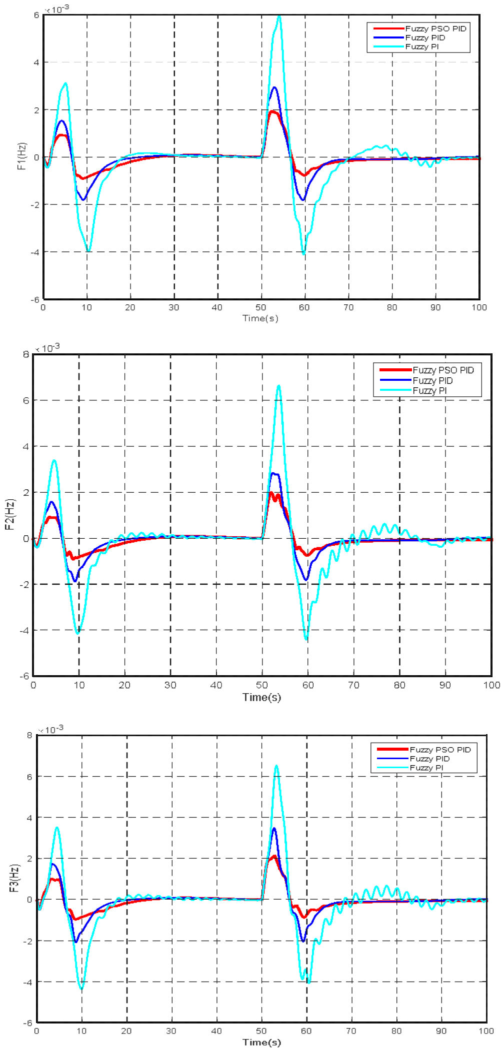

Fig. 10. Dynamic frequency responses in three areas in case 5: (a) $\Delta F1$, (b) $\Delta F2$, (c) $\Delta F3$.

An interconnected power system is a large system with many parameters that can be changed during operation. In addition, the system studied considered renewable energy to decrease its inertia. Renewable energy sources, such as solar and wind sources, are inherently variable and can experience sudden output changes. Unlike traditional power sources, like coal or gas plants, the renewable ones lack the rotational inertia provided by the spinning turbines. This inertia helps stabilize the grid against sudden fluctuations. When renewable sources dominate, the grid may experience reduced inertia, making it more susceptible to rapid frequency changes and requiring advanced control mechanisms to maintain stability. As a result, the power system faces challenges in maintaining frequency stability. As shown in Figures 6-10, simple controllers had worse performance. The results of the Fuzzy PID controller reveal that the Fuzzy logic-based controllers with fuzzy set selection generate input functions and fuzzy rules associated with the given PID controller and obtain better control quality than other controllers, such as FPID, Fuzzy PI, and PSO-PID.

However, Fuzzy PID was less efficient compared to the Fuzzy-PSO-PID controller. The reason is that due to fuzzy variable inputs, the rules are established based on the experience of the experts. With the Fuzzy-PSO-PID controller, the controller's parameters are designed according to the objective function of the optimization method, which gives more effective results.

IV. CONCLUSION AND FUTURE WORK

Load-frequency control in a power system is a serious problem in its operation and distribution. However, in a power system with nonlinear factors and renewable energy sources, it is difficult to stabilize its frequency. The comparative simulation results of different controllers in this study hilight that the hybrid intelligent controllers obtained better results than the classic ones. The future direction of this research is to study and design an efficient controller for a multi-area system with many transmitters in each area. In addition, the practical applications of the studied hybrid load-frequency controllers will be considered. In this scenario, a practical electrical power grid should be a suitable selection.

TABLE IV. ABBREVIATIONS

GDB	Governor Dead Band	FPID	Fractional PID
GRC	Generation Rate Constraint	ANFIS	Adaptive Neuro-Fuzzy Inference System
LFC	Load Frequency Control	DE-PSO	Differential Evolution and Particle Swarm Optimization
ACE	Area Control Error	BIA	Bat inspired algorithm
PSO	Particle Swarm Optimization	BBO	Biogeography-Based Optimization
GWO	Grey Wolf Optimizer	BFOA	Bacterial Foraging Optimization Algorithm
PI	Proportional Integral	PID	Proportional Integral Derivative

REFERENCES

[1] M. H. Khooban and T. Niknam, "A new intelligent online fuzzy tuning approach for multi-area load frequency control: Self Adaptive Modified Bat Algorithm," *International Journal of Electrical Power & Energy Systems*, vol. 71, pp. 254–261, Oct. 2015, https://doi.org/10.1016/j.ijepes.2015.03.017.

[2] A. Dwivedi, G. Ray, and A. K. Sharma, "Genetic Algorithm based Decentralized PI Type Controller: Load Frequency Control," *Journal of The Institution of Engineers (India): Series B*, vol. 97, no. 4, pp. 509–515, Dec. 2016, https://doi.org/10.1007/s40031-015-0191-7.

[3] S. A. Azeer, R. Ramjug-Ballgobin, and S. Z. Sayed Hassen, "Intelligent Controllers for Load Frequency Control of Two-Area Power System," *IFAC-PapersOnLine*, vol. 50, no. 2, pp. 301–306, Dec. 2017, https://doi.org/10.1016/j.ifacol.2017.12.062.

[4] S. Prakash and S. K. Sinha, "Neuro-Fuzzy Computational Technique to Control Load Frequency in Hydro-Thermal Interconnected Power System," *Journal of The Institution of Engineers (India): Series B*, vol. 96, no. 3, pp. 273–282, Sep. 2015, https://doi.org/10.1007/s40031-014-0147-3.

[5] M. R. Sathya and M. Mohamed Thameem Ansari, "Design of biogeography optimization based dual mode gain scheduling of fractional order PI load frequency controllers for multi source interconnected power systems," *International Journal of Electrical Power & Energy Systems*, vol. 83, pp. 364–381, Dec. 2016, https://doi.org/10.1016/j.ijepes.2016.04.006.

[6] M. Ma, C. Zhang, X. Liu, and H. Chen, "Distributed Model Predictive Load Frequency Control of the Multi-Area Power System After Deregulation," *IEEE Transactions on Industrial Electronics*, vol. 64, no. 6, pp. 5129–5139, Jun. 2017, https://doi.org/10.1109/TIE.2016.2613923.

[7] E. Rakhshani and J. Sadeh, "Practical viewpoints on load frequency control problem in a deregulated power system," *Energy Conversion and Management*, vol. 51, no. 6, pp. 1148–1156, Jun. 2010, https://doi.org/10.1016/j.enconman.2009.12.024.

[8] B. Sonker, D. Kumar, and P. Samuel, "Dual loop IMC structure for load frequency control issue of multi-area multi-sources power systems," *International Journal of Electrical Power & Energy Systems*, vol. 112, pp. 476–494, Nov. 2019, https://doi.org/10.1016/j.ijepes.2019.04.042.

[9] M. V. Srikanth and N. Yadaiah, "An AHP based optimized tuning of Modified Active Disturbance Rejection Control: An application to power system load frequency control problem," *ISA Transactions*, vol. 81, pp. 286–305, Oct. 2018, https://doi.org/10.1016/j.isatra.2018.07.001.

[10] A. Delassi, S. Arif, and L. Mokrani, "Load frequency control problem in interconnected power systems using robust fractional PIλD controller," *Ain Shams Engineering Journal*, vol. 9, no. 1, pp. 77–88, Mar. 2018, https://doi.org/10.1016/j.asej.2015.10.004.

[11] C. Chen, K. Zhang, K. Yuan, and X. Teng, "Tie-Line Bias Control Applicability to Load Frequency Control for Multi-Area Interconnected Power Systems of Complex Topology," *Energies*, vol. 10, no. 1, Jan. 2017, Art. no. 78, https://doi.org/10.3390/en10010078.

[12] F. U. A. Ahammad and S. Mandal, "Robust load frequency control in multi-area power system: An LMI approach," in *2016 IEEE First International Conference on Control, Measurement and Instrumentation (CMI)*, Kolkata, India, Jan. 2016, pp. 136–140, https://doi.org/10.1109/CMI.2016.7413726.

[13] S. Pande and R. Kansal, "Load Frequency Control of Multi Area System using Integral- Fuzzy Controller," *Surbhi Pande Int. Journal of Engineering Research and Applications*, vol. 5, no. 6, pp. 59–64, 2015.

[14] S. Pahadasingh, C. Jena, C. K. Panigrahi, and B. P. Ganthia, "JAYA Algorithm-Optimized Load Frequency Control of a Four-Area Interconnected Power System Tuning Using PID Controller," *Engineering, Technology & Applied Science Research*, vol. 12, no. 3, pp. 8646–8651, Jun. 2022, https://doi.org/10.48084/etasr.4891.

[15] D. V. Doan, K. Nguyen, and Q. V. Thai, "A Novel Fuzzy Logic Based Load Frequency Control for Multi-Area Interconnected Power Systems," *Engineering, Technology & Applied Science Research*, vol. 11, no. 4, pp. 7522–7529, Aug. 2021, https://doi.org/10.48084/etasr.4320.

[16] M. A. Mohamed, A. A. Z. Diab, H. Rezk, and T. Jin, "A novel adaptive model predictive controller for load frequency control of power systems integrated with DFIG wind turbines," *Neural Computing and Applications*, vol. 32, no. 11, pp. 7171–7181, Jun. 2020, https://doi.org/10.1007/s00521-019-04205-w.

[17] B. K. Sahu, S. Pati, and S. Panda, "Hybrid differential evolution particle swarm optimisation optimised fuzzy proportional–integral derivative controller for automatic generation control of interconnected power system," *IET Generation, Transmission & Distribution*, vol. 8, no. 11, pp. 1789–1800, 2014, https://doi.org/10.1049/iet-gtd.2014.0097.

[18] N. K. Bahgaat, M. I. El-Sayed, M. A. M. Hassan, and F. A. Bendary, "Load Frequency Control in Power System via Improving PID Controller Based on Particle Swarm Optimization and ANFIS Techniques," in *Research Methods: Concepts, Methodologies, Tools, and Applications*, IGI Global, 2015, pp. 462–481.

[19] T. Mahto, H. Malik, and V. Mukherjee, "Fractional Order Control and Simulation of Wind-Biomass Isolated Hybrid Power System Using Particle Swarm Optimization," in *Applications of Artificial Intelligence Techniques in Engineering*, Singapore, 2019, pp. 277–287, https://doi.org/10.1007/978-981-13-1819-1_27.

[20] A. Y. Abdelaziz and E. S. Ali, "Cuckoo Search algorithm based load frequency controller design for nonlinear interconnected power system," *International Journal of Electrical Power & Energy Systems*, vol. 73, pp. 632–643, Dec. 2015, https://doi.org/10.1016/j.ijepes.2015.05.050.

[21] S. Chaine, M. Tripathy, and D. Jain, "Non dominated Cuckoo search algorithm optimized controllers to improve the frequency regulation characteristics of wind thermal power system," *Engineering Science and Technology, an International Journal*, vol. 20, no. 3, pp. 1092–1105, Jun. 2017, https://doi.org/10.1016/j.jestch.2017.05.005.

[22] M. Gheisarnejad, "An effective hybrid harmony search and cuckoo optimization algorithm based fuzzy PID controller for load frequency control," *Applied Soft Computing*, vol. 65, pp. 121–138, Apr. 2018, https://doi.org/10.1016/j.asoc.2018.01.007.

[23] E. S. Ali and S. M. Abd-Elazim, "BFOA based design of PID controller for two area Load Frequency Control with nonlinearities," *International Journal of Electrical Power & Energy Systems*, vol. 51, pp. 224–231, Oct. 2013, https://doi.org/10.1016/j.ijepes.2013.02.030.

[24] A. Kumar and S. N. V, "Teaching-Learning Optimization Based Adaptive Fuzzy Logic Controller for Frequency Control in an Autonomous Microgrid," *International Journal of Renewable Energy Research (IJRER)*, vol. 7, no. 4, pp. 1942–1949, Dec. 2017.

[25] A. Annamraju and S. Nandiraju, "Robust Frequency Control in an Autonomous Microgrid: A Two-Stage Adaptive Fuzzy Approach," *Electric Power Components and Systems*, vol. 46, no. 1, pp. 83–94, Jan. 2018, https://doi.org/10.1080/15325008.2018.1432723.

[26] D. V. Doan, K. Nguyen, and Q. V. Thai, "Load-Frequency Control of Three-Area Interconnected Power Systems with Renewable Energy Sources Using Novel PSO~PID-Like Fuzzy Logic Controllers," *Engineering, Technology & Applied Science Research*, vol. 12, no. 3, pp. 8597–8604, Jun. 2022, https://doi.org/10.48084/etasr.4924.

[27] D. V. Doan, K. Nguyen, and Q. V. Thai, "On design of PSO-based Fuzzy-PI – like load-frequency control strategies for multi-area interconnected power systems," Ho Chi Minh City, Vietnam, Apr. 2022.

[28] A. Kandhavel, "Load frequency control." https://www.mathworks.com/matlabcentral/fileexchange/31514-load-frequency-control.

[29] S. A. Taher, M. Hajiakbari Fini, and S. Falahati Aliabadi, "Fractional order PID controller design for LFC in electric power systems using imperialist competitive algorithm," *Ain Shams Engineering Journal*, vol. 5, no. 1, pp. 121–135, Mar. 2014, https://doi.org/10.1016/j.asej.2013.07.006.