Designing a Novel Hybrid Fuzzy~GWO~PID Load-Frequency Controller for a complicated Large-Scale Four-Area interconnected Power Grid with RES and SMES

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ABSTRACT

Stable grid frequency control in modern interconnected power systems is increasingly challenging, especially with the increasing integration of Renewable Energy Sources (RES). This study solves the Load Frequency Control (LFC) problem in a complex four-area reheat turbine power system incorporating photovoltaic generation together with nonlinear characteristics, i.e., Governor Dead Band (GDB) and Generation Rate Constraints (GRC), and a Superconducting Magnetic Energy Storage (SMES) device. A novel hybrid controller, Fuzzy~GWO~PID, is proposed that combines the adaptability of fuzzy logic, the global search efficiency of the Grey Wolf Optimizer (GWO), and the precise regulation of a conventional Proportional-Integral-Derivative (PID) controller. The controller performance is benchmarked against a fractional-order PI$^\lambda$D and a GWO-optimized PID controller, aiming to minimize frequency deviations and improve dynamic stability under stochastic load variations and intermittent renewable energy fluctuations. Simulation results over various cases of load changes demonstrate that the proposed hybrid Fuzzy~GWO~PID controller outperforms the PI$^\lambda$D and GWO~PID controllers. This type of novel LFC controller achieves much better control performances such as faster settling times, reduced overshoot, and improved dynamic response. This work obviously intends to highlight the effectiveness of integrating fuzzy logic with metaheuristic optimization for robust LFC in modern power grids with high renewable penetration.

Keywords-Fuzzy~GWO~PID; PI$^\lambda$D; GWO; LFC; interconnected power system; RES; SMES

I. INTRODUCTION

It is a fact that the increasing penetration of Renewable Energy Sources (RES) in interconnected power systems has significantly disrupted Load Frequency Control (LFC) paradigms, leading to major challenges in frequency stability and power balance due to the inherent stochasticity and intermittency of RES generation [1]. LFC remains a critical function in multi-area power systems, tasked with maintaining generation-demand balance while minimizing frequency deviations and tie-line power flow fluctuations [2]. Traditional LFC implementations, particularly Proportional-Integral-Derivative (PID) controllers, have been widely used due to their straightforward design and efficacy in linear systems [3]. However, the increasing complexity of today's power systems is characterized by nonlinear phenomena such as Generation Rate Constraints (GRC) and Governor Dead Band (GDB). GDB refers to the frequency deviation range within which the governor system of a generating unit does not respond or take action to participate in primary frequency control. GDB occurs due to mechanical friction, linkage backlash, and overlapping clearances in hydraulic valves within the governor mechanism. According to IEEE standards, the typical GDB for thermal turbines is approximately 0.06% (0.036 Hz), whereas for hydraulic turbines, it is approximately 0.02%. In addition, the GRC represents the physical limit on the rate of power output change imposed by the mechanical constraints of the turbine (e.g., thermal stress in steam turbines or water hammer effects in hydro turbines). The GRC introduces nonlinearity into the power system and significantly affects dynamic performance due to its restrictive nature on rapid power adjustments. Both GDB and GRC contribute to the nonlinear dynamics of power system frequency regulation, affecting stability, control response, and overall grid reliability. In addition, the incorporation of advanced energy storage technologies, including Superconducting Magnetic Energy Storage (SMES), necessitates the development and deployment of sophisticated control methodologies [4].

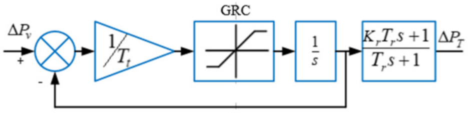
Fuzzy Logic Controllers (FLCs) have emerged as a robust approach for addressing the nonlinearities and uncertainties inherent in power systems due to their ability to approximate human-like reasoning [5]. The incorporation of metaheuristic optimization algorithms, including Particle Swarm Optimization (PSO) and Grey Wolf Optimizer (GWO), has further enhanced controller performance by facilitating the optimal parameterization of control systems under dynamic operational regimes [6, 7]. Hybrid control methodologies, which combine the adaptive capabilities of FLCs with the optimization capabilities of metaheuristic algorithms, have demonstrated significant potential for enhancing LFC performance, particularly in power grids with substantial RES integration [8]. Specifically, GWO-optimized PID controllers have exhibited improved convergence rates and precision compared to conventional PSO-tuned implementations [9].

The integration of stochastic RES into multi-area power systems complicates the LFC strategy by requiring precise balancing of generation and demand across interconnected regions [10]. Four-area systems with reheat turbines, prevalent in thermal power plants, further exacerbate the LFC challenges due to their inherent nonlinearities, including GRC and GDB, and sluggish dynamic response [11]. These factors compromise frequency regulation, necessitating sophisticated control strategies capable of accommodating both slow thermal dynamics and rapid RES fluctuations [12]. Incorporating SMES, a fast-acting energy storage technology, improves frequency stability through rapid power injections during transients [13]. Literature demonstrates that optimized PID controllers significantly improve frequency regulation [14], and modified Sliding Mode Control (SMC) strategies effectively mitigate frequency deviations despite GRC and GDB nonlinearities [15]. Hybrid controllers, such as Fuzzy~PSO~PID, have been proposed to stabilize the frequency in multi-area systems considering nonlinearities and RES integration [16]. In addition, SMES has been shown to be effective in mitigating frequency fluctuations caused by RES intermittency [17]. A type of fuzzy~PID controllers has also been applied to address frequency deviations in high-RES systems, achieving improved dynamic performance [18]. Hybrid control strategies integrating GRC and SMES enhance stability [19], whereas robust control frameworks account for the GRB effects [20]. The synergistic integration of SMES with RES has been shown to improve grid stability and frequency regulation [21].

This study proposes a novel hybrid Fuzzy~GWO~PID controller for the LFC in a four-area interconnected power system incorporating reheat turbines, GRC, GDB, SMES, high-RES penetration and High Voltage Direct Current (HVDC). HVDC transmission uses direct current to move large amounts of electricity efficiently over long distances. This method reduces power losses compared to traditional AC systems, making it well suited for connecting distant RES, interconnecting AC grids that operate at different frequencies, and building undersea power cables. The process involves converting AC power to DC at the source, transmitting the DC power, and then converting it back to AC at the destination, which provides enhanced control and stability for the power network.

For the purpose of simulation investigation, the transfer functions of the network components in MATLAB are presented in Table I**.** The simulation model illustrating the integration of solar energy is shown in Figure 1, the SMES model is depicted in Figure 2, and LFC model of the considered four-area interconnected power system is illustrated in Figure 3. The proposed controller leverages the rule-based adaptability of fuzzy logic to manage real-time uncertainties, whereas GWO optimizes PID gains to ensure robust performance under varying operating scenarios. The contributions of this work are twofold: (1) a comparative analysis of standalone PI$^{\lambda}$D, GWO-PID controllers, highlighting the limitations of existing approaches; and (2) empirical validation of the superiority of the hybrid Fuzzy~GWO~PID controller in damping frequency oscillations, reducing settling time, and enhancing resilience to RES variability. Furthermore, this study contributes to the ongoing global transition toward sustainable energy systems by offering practical insights for grid operators responsible for managing power networks with high penetration of RES.

TABLE I. TRANSFER FUNCTIONS OF MAJOR UNITS IN CONTROL AREAS BUILT IN MATLAB/SIMULINK

Unit	Transfer function in MATLAB/Simulink
Governor	$\frac{1}{T_g s+1}$ T_g is the steam governor time constant
Reheat turbine	$\frac{K_r T_r s+1}{(T_t s+1)(T_r s+1)}$ K_r is the reheat constant T_r is the reheat time constant T_t is the steam turbine time constant
Reheat turbine with GRC	
Generator and load	$\frac{K_p}{(T_p s+1)}$ K_p is the power system gain T_p is the power system time constant

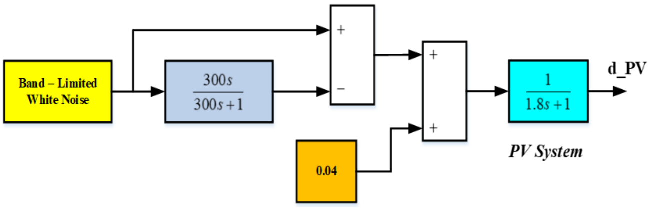


Fig. 1. PV system modeling in MATLAB/ Simulink [22].

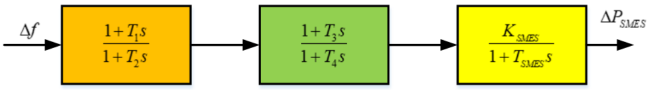


Fig. 2. SMES device modeling in MATLAB/ Simulink [22].

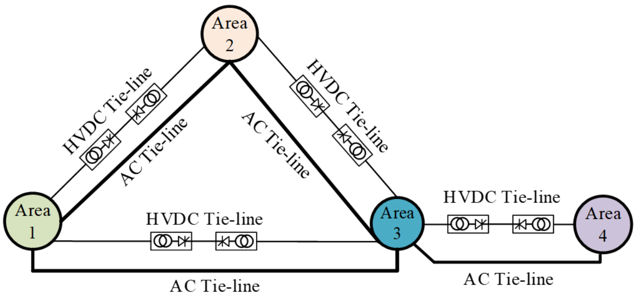


Fig. 3. LFC model of a four-area interconnected power system.

II. PROPOSING A NOVEL HYBRID FUZZY~GWO~PID CONTROLLER

Figure 4 illustrates the proposed Fuzzy-GWO-PID control methodology. This approach integrates fuzzy logic with the GWO algorithm to dynamically tune the parameters of a conventional PID controller. The process starts with the system error and the rate of change of the error being fed as inputs to the fuzzy logic controller. Using predefined membership functions and rule-based systems, the fuzzy controller generates optimized PID gains (K_P, K_I, K_D). These gains are then refined by the GWO algorithm, shown in Figure 5, which searches for the optimal set of parameters to minimize a predefined cost function, such as frequency deviations and tie-line power fluctuations. The enhanced PID parameters are then applied to the system, ensuring robust frequency regulation and improved overall system stability. This hybrid methodology effectively addresses the complexities and uncertainties inherent in interconnected power systems with high penetration of renewable energy. The fuzzy system has two inputs and three outputs with membership functions and a fuzzy logic rule base as presented in the Tables II, III, and IV. This integrated control structure is applied to a complicated four-interconnected power system as presented in the previous section, with the aim of achieving an improved control system performance.

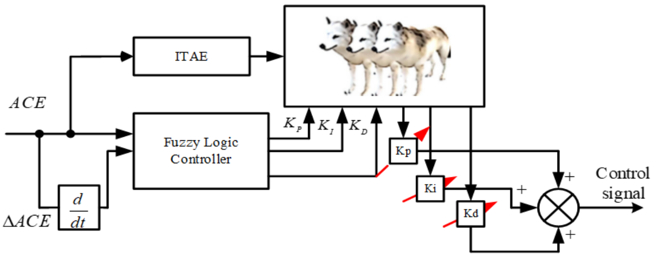


Fig. 4. The structural diagram of the proposed Fuzzy~GWO~PID controller.

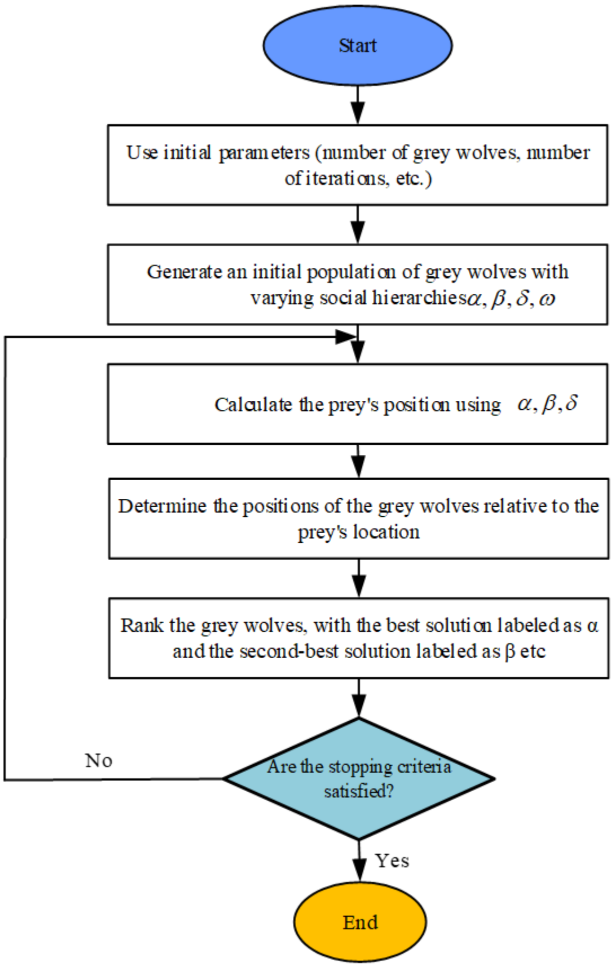


Fig. 5. A typical flow chart of the GWO algorithm.

TABLE II. FUZZY LOGIC RULES FOR K_P

	ACE							
ΔACE		NL	NM	NS	ZE	PS	PM	PL
	NL	PL	PL	PL	PM	PS	ZE	ZE
	NM	PL	PL	PM	PS	ZE	ZE	NS
	NS	PL	PL	PM	PS	ZE	NS	NM
	ZE	PM	PM	ZE	NS	NS	NM	NM
	PS	PM	PM	PS	ZE	NS	NM	NL
	PM	PS	PS	ZE	NS	NM	NM	NL
	PL	ZE	ZE	PS	NS	NM	NL	NL

TABLE III. FUZZY LOGIC RULES FOR K_I

	ACE							
ΔACE		NL	NM	NS	ZE	PS	PM	PL
	NL	NL	NL	NM	NM	NS	ZE	ZE
	NM	NL	NM	NM	NS	ZE	ZE	ZE
	NS	NM	NM	NS	ZE	ZE	PS	PM
	ZE	NM	NS	ZE	ZE	PS	PM	PM
	PS	NS	NS	ZE	PS	PS	PM	PL
	PM	ZE	ZE	PS	PS	PM	PM	PL
	PL	ZE	ZE	PS	PM	PM	PL	PL

TABLE IV. FUZZY LOGIC RULES FOR K_D

		ACE						
		NL	NM	NS	ZE	PS	PM	PL
ΔACE	NL	PS	PS	ZE	ZE	ZE	ZE	ZE
	NM	NS	NS	NS	ZE	PS	PS	PS
	NS	NM	NS	ZE	ZE	PS	PS	PM
	ZE	NL	NM	NS	ZE	PS	PM	PL
	PS	NM	NS	NS	ZE	ZE	PS	PS
	PM	NM	NM	NS	ZE	PS	PS	PM
	PL	PS	ZE	ZE	ZE	PM	PL	PL

The optimization of the proportional (K_P), integral (K_I), and derivative (K_D) control parameters for the GWO-based controller is achieved through the minimization of a defined objective function. This objective function, formulated as shown in (1), incorporates the frequency deviations (Δf_i, where $i = 1, 2, 3, 4$) of each area and the tie-line power flow variations (ΔP_{tie}) between the areas. The simulation time (t_sim), as detailed in Section III, serves as the integration limit for this objective function. Notably, this criterion is equivalent to the Integral Absolute Time Error (IATE), a widely accepted performance index used to evaluate the dynamic response of control systems.

$$J = \text{IATE} = \int_0^{t\_sim} \begin{pmatrix} |\Delta f_1| + |\Delta f_2| + |\Delta f_3| + |\Delta f_4| \\ + \sum_{i,k=1}^{4} |\Delta P_{tie\ i,k}| \end{pmatrix} t\, dt \qquad (1)$$

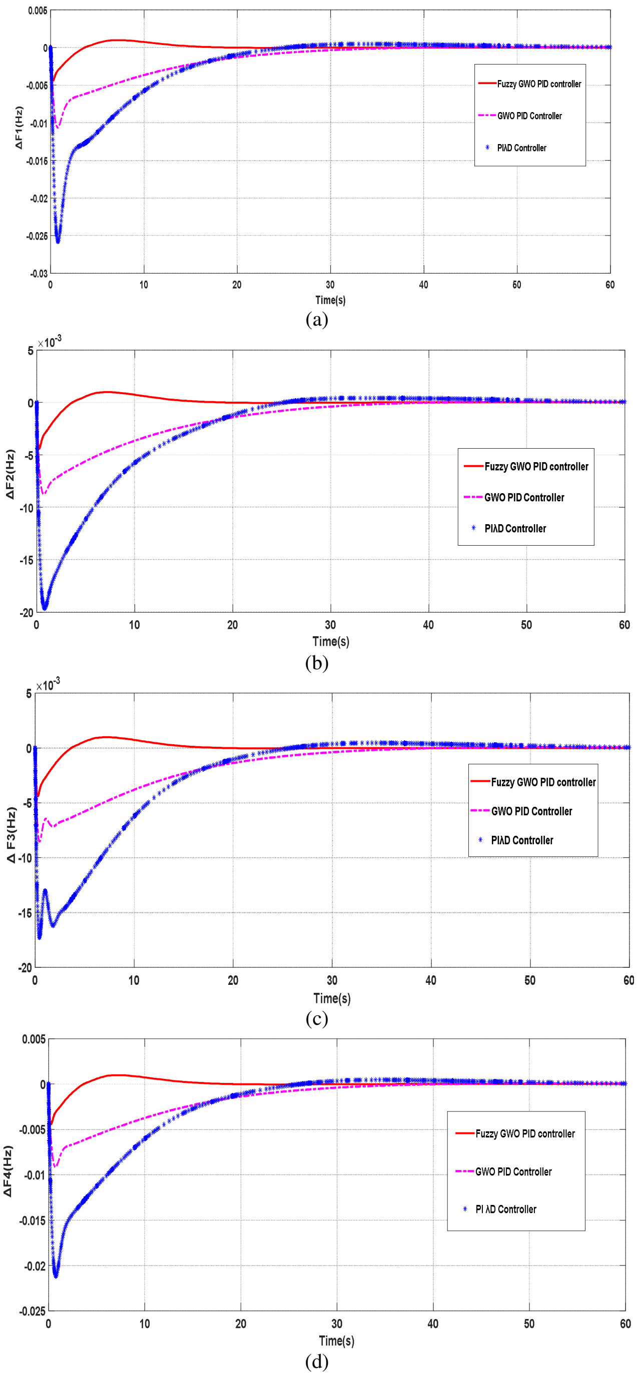
III. NUMERICAL SIMULATIONS AND DISCUSSION

Performing numerical simulations is considered a practical tool for analyzing the sensitivity of control system performance to input parameters, and for evaluating the stability and accuracy of the model under diverse operational conditions. In this study, a series of simulation scenarios are performed using the established mathematical model of the four-area power system and the developed hybrid controller. These scenarios include variations in the controller configurations and the introduction of stochastic load disturbances, allowing a comprehensive assessment of the effectiveness of the proposed control solution. Two practical simulation cases are considered as follows:

- Case 1: Load variations are represented as discrete step changes, each with an amplitude of four percent, to simulate abrupt load changes. The simulation results obtained using MATLAB/Simulink are presented in Figures 6, 7 and 8.
- Case 2: Random load variations are introduced and simulated at the initial time and at 35 s. The simulation results obtained using MATLAB/Simulink are presented in Figures 9, 10, and 11.

The comparative performance evaluation of the $PI^{\lambda}D$, GWO~PID, and Fuzzy~GWO~PID controllers, based on the ITAE criterion as given in (1) and shown in Figures 7, 10, and the Integral Absolute Error (IAE) metric as given in (2) and shown in Figures 8, 11, quantitatively assesses their effectiveness in frequency control.

$$J = \text{IAE} = \int_0^{t\_sim} \begin{pmatrix} |\Delta f_1| + |\Delta f_2| + |\Delta f_3| + |\Delta f_4| \\ + \sum_{i,k=1}^{4} |\Delta P_{tie\ i,k}| \end{pmatrix} dt \qquad (2)$$



(a)

(b)

(c)

(d)

Fig. 6. Dynamic frequency responses in four areas (for case 1): (a) ΔF1, (b) ΔF2, (c) ΔF3, (d) ΔF4.

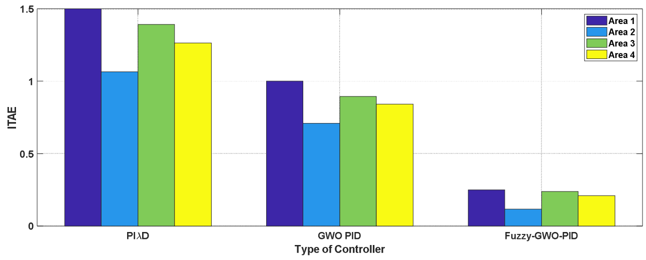


Fig. 7. Comparative results applying the ITAE criterion in case 1.

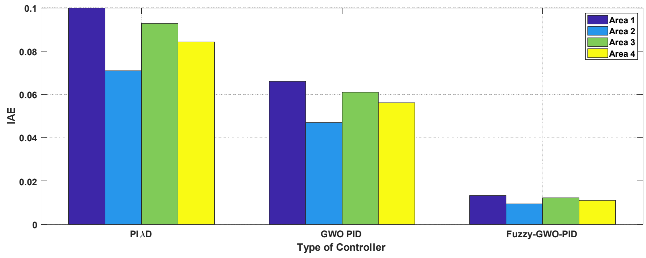
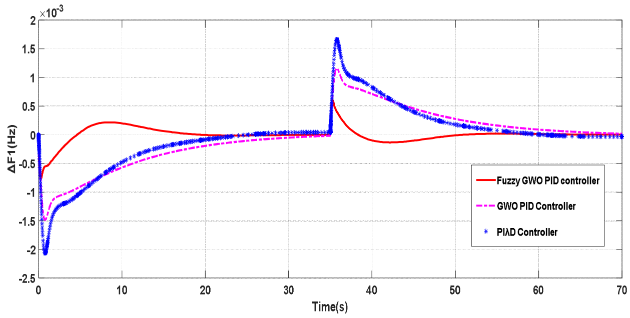
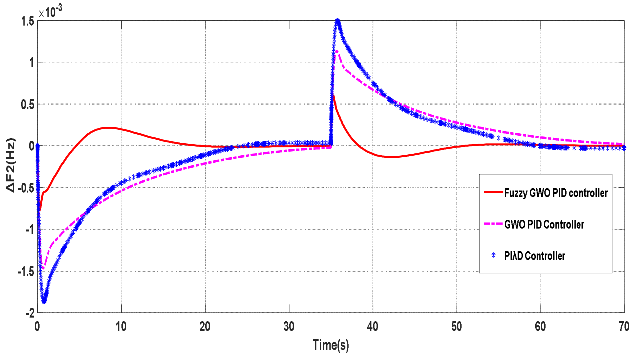


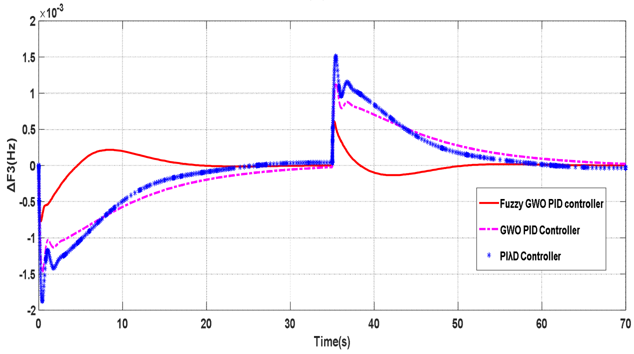
Fig. 8. Comparative results applying the IAE criterion in case 1.



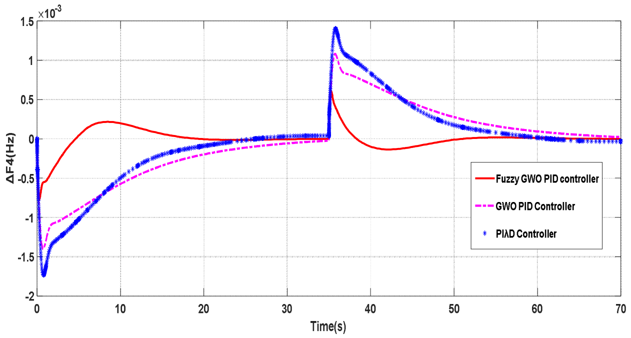
(a)



(b)



(c)



(d)

Fig. 9. Dynamic frequency responses in four areas (for case 2): (a) ΔF1, (b) ΔF2, (c) ΔF3, (d) ΔF4.

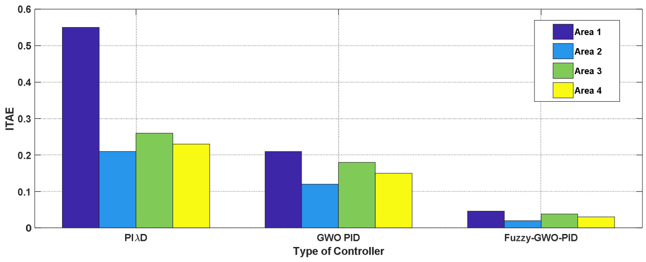


Fig. 10. Comparative results applying the ITAE criterion in case 1.

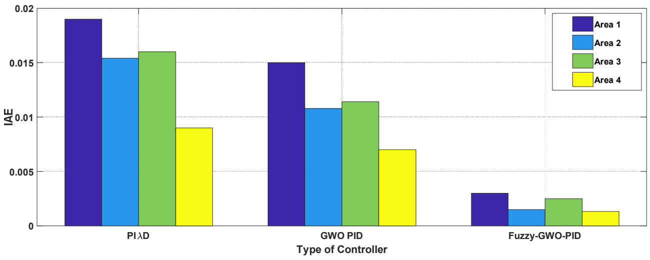


Fig. 11. Comparative results applying the IAE criterion in case 2.

The difference between the ITAE and IAE metrics is that the IAE metric excludes the time factor and represents the ability to evaluate the overshoot better than the ITAE metric, which focuses more on the steady-state errors. Not only these two effective control criteria, but also the figures represent meaningful comparative evaluations to select an appropriate LFC controller for a particular interconnected power grid. The following are some comments on these evaluations:

1. The PI$^{\lambda}$D controller that applies the fractional-order calculus exhibits an improved dynamic response compared to conventional PID controllers, achieving lower ITAE and IAE values. This enhancement is attributed to its ability to mitigate system nonlinearities arising from GRC and GDB.
2. However, the GWO~PID controller, optimized via the GWO algorithm, outperforms the PI$^{\lambda}$D controller in minimizing frequency deviations, as indicated by significantly reduced ITAE and IAE values. This superiority is due to the ability of the GWO algorithm to fine-tune the PID parameters for enhanced robustness under fluctuating renewable energy conditions.

3. Among the controllers evaluated, the Fuzzy~GWO~PID exhibits the best performance, achieving the lowest ITAE and IAE values. This improvement is due to the integration of fuzzy logic with GWO-optimized PID control, which enhances the adaptability in handling uncertainties and nonlinearities induced by GRC, GDB, and renewable energy intermittency. Additionally, the incorporation of SMES further enhances the performance of all controllers by enabling rapid energy exchange, thereby mitigating frequency deviations during transient disturbances.
4. The Fuzzy~GWO~PID controller achieves the shortest settling time and minimal overshoot, making it the most effective solution for frequency stability in power systems with high renewable energy penetration. The ITAE metric, which penalizes prolonged deviations, highlights the long-term stability of the Fuzzy~GWO~PID controller, whereas the IAE metric confirms its precision in minimizing frequency fluctuations. In conclusion, the Fuzzy~GWO~PID controller emerges as the most robust and efficient control strategy for frequency regulation in power systems integrating GRC, GDB, SMES, and renewable energy generation.
5. The performance of the $PI^{\lambda}D$, GWO-PID, and Fuzzy~GWO~PID controllers was evaluated in a four-area interconnected power system incorporating reheat turbines, RES, GRC, GDB, and the SMES. Each controller demonstrated distinct characteristics in terms of frequency stabilization, settling time, and resilience to disturbances.
6. The $PI^{\lambda}D$ controller provided improved dynamic response compared to traditional PID controllers due to its ability to handle nonlinearities and system uncertainties more effectively. However, its performance was limited in scenarios with high-RES penetration and significant nonlinearities, such as GRC and GDB, where it exhibited longer settling times and larger frequency deviations.
7. The GWO~PID controller using the GWO shows superior performance over the $PI^{\lambda}D$ controller. The GWO algorithm effectively tuned the PID parameters, resulting in faster convergence and reduced frequency oscillations. This controller demonstrated better adaptability to RES variability and improved damping of inter-area oscillations. Nevertheless, its reliance on fixed PID gains limited its ability to fully compensate for the complex nonlinear dynamics introduced by GRC and GDB.
8. The proposed Fuzzy~GWO~PID controller emerged as the most effective solution, combining the adaptability of fuzzy logic with the optimization capabilities of GWO. The fuzzy logic component enabled real-time adjustment of control parameters, which improved the system's ability to handle uncertainties and nonlinearities. Meanwhile, the GWO-optimized PID gains ensured robust performance under varying operating conditions. This hybrid approach significantly reduced settling time, minimized frequency deviations, and improved overall system stability, even under high-RES penetration and in the presence of the nonlinear GRC and GDB units along with the SMES component.

IV. CONCLUSION AND FUTURE WORK

In summary, the comparative performance analysis of the proposed Fuzzy~GWO~PID controller against the $PI^{\lambda}D$ and GWO-PID controllers in the context of frequency control in a complex four-area reheat thermal turbine system incorporating Renewable Energy Sources (RES), Governor Dead Band (GDB), Generation Rate Constraints (GRC), and Superconducting Magnetic Energy Storage (SMES) reveals significant performance improvements. The Fuzzy~GWO~PID controller demonstrates superior effectiveness in mitigating frequency deviations and minimizing tie-line power fluctuations compared to the $PI^{\lambda}D$ and GWO~PID controllers. These enhancements are due to the synergistic integration of fuzzy logic with the Grey Wolf Optimizer (GWO) algorithm, which enhances adaptability and robustness, enabling the control system to efficiently manage the stochastic variability of RES and the complex dynamics of the interconnected grid. While the GWO~PID controller offers significant improvements over the conventional Proportional-Integral-Derivative (PID) controller through optimized parameter tuning, the Fuzzy~GWO~PID controller provides the most effective frequency control through real-time, intelligent adjustment of PID parameters based on dynamic system conditions. These findings highlight the strong potential of hybrid intelligent control strategies in ensuring grid stability and operational reliability amidst increasing penetration of RES, thus supporting the transition towards more sustainable and resilient power systems. It is evident that these contributions can be applied in real in real-world modern power systems.

ACKNOWLEDGMENT

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APPENDIX

The four-area power system parameters used for the simulation are:

- $Pr1 = 2000$ MW; $Pr2 = 4000$ MW; $Pr3 = 8000$ MW; $Pr4 = 10000$ MW.
- $R1 = R2 = R3 = R4 = 2.4$ HZ/p.u.MW.
- $B1 = B2 = B3 = B4 = 0.425$ HZ/p.u.MW.
- $T_gs1 = T_gs2 = T_gs3 = T_gs4 = 0.08$ s.
- $T_t1 = T_t2 = T_t3 = T_t4 = 0.3$ s.
- $T_ps1 = T_ps2 = T_ps3 = T_ps4 = 20$ s.
- $K_ps1 = K_ps2 = K_ps3 = K_ps4 = 120$ HZ/p.u.MW.
- $a\text{ij} = -Pr\text{i}/Pr\text{j}$.
- $T_r1 = T_r2 = T_r3 = T_r4 = 10$ s.
- $K_r1 = K_r2 = K_r3 = K_r4 = 0.5$.

The tie-line synchronizing coefficients are:

- $T_{21} = T_{12} = T_{32} = T_{23} = T_{13} = T_{31} = T_{34} = T_{43} = 0.086$ s.

The SMES model parameters are:

- $K_{SMES} = 0.2035$, $T_{SMES} = 0.03$ s, $T_1 = 0.2333$ s, $T_2 = 0.016$ s, $T_3 = 0.7087$ s, $T_4 = 0.2481$s.

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