

Particle Swarm Optimization Based PI Controller for Load Frequency Control of a Single Area Power System

Gunjan Sahu¹ and Satya Prakash Makhija²

^{1,2}Department of Electrical Engineering, RSR Rungta College of Engineering and Technology, Bhilai, India.

Email: ¹gunjansahu0106@gmail.com, ²satyapmakhija@gmail.com

Abstract -

Load frequency control (LFC) is a fundamental requirement for maintaining the stability and reliability of an electric power system, particularly under continuously varying load demand. Any mismatch between generation and demand manifests as a deviation in system frequency, which must be corrected quickly and with minimum oscillation in order to keep the network within its permissible operating limits. This paper investigates the load frequency control of a single area power system, consisting of a speed governor, turbine and generator, using four different controllers: a conventional Proportional Integral (PI) controller, a Proportional Integral Derivative (PID) controller, a Fuzzy Logic Controller (FLC), and a Particle Swarm Optimization based PI (PSO-PI) controller, in which the proportional and integral gains are obtained offline by minimising an error-based objective function using the PSO algorithm. The controllers are designed and simulated in the MATLAB/SIMULINK environment for step changes in load demand, and their closed loop frequency response is compared on the basis of settling time and peak frequency deviation. A comparative analysis is carried out to identify the controller that offers the best trade-off between transient performance and steady state accuracy for a single area network.

Key Words: Load frequency control; PI controller; PID controller; Fuzzy logic controller; Particle Swarm Optimization; PSO based PI controller; Single area power system.

1. INTRODUCTION

Modern electric power systems are subjected to constant fluctuation in load demand as a result of growing population, industrialisation and the increasing penetration of variable loads. Since power cannot be stored economically in bulk, the generation of active power must be continuously adjusted to match the demand at every instant. Any imbalance between generation and load appears as a deviation of system frequency from its nominal value, and utilities are obligated to keep this deviation within a narrow band, typically of the order of ± 0.5 Hz, which is decided largely by the speed response of the turbine-governor system [1].

The task of regulating frequency by adjusting the generator output in response to load changes is known as load frequency control, and it forms one of the important functions of Automatic Generation Control (AGC). In an interconnected system with more than one control area, LFC is additionally

responsible for regulating the tie-line power exchange between areas so that each area supplies its own load changes while the scheduled interchange with neighbouring areas is maintained. In a single area system, which is the scope of the present work, there is no tie-line to be regulated and the entire task reduces to restoring the system frequency to its nominal value as quickly as possible following a load disturbance.

A wide variety of controllers have been proposed in the literature for LFC. The conventional PI controller remains the most widely adopted controller in industry on account of its simplicity and its ability to drive the steady state frequency error to zero [2]. The PID controller extends this idea with an additional derivative action that improves the transient response of the system [3]. Fuzzy logic based controllers have also received considerable attention because they can incorporate expert knowledge through linguistic rules and do not require an accurate mathematical model of the plant [4], and have been reported to perform well in both single area and multi-area interconnected systems [5], [6]. Hybrid schemes in which a fuzzy system tunes the gains of a conventional controller [7], [8], neural network based controllers [9], fuzzy model predictive control [10], [11], and optimisation based strategies for renewable-rich power systems [12], [13] have also been reported.

Alongside these approaches, metaheuristic optimisation techniques have been used extensively to tune the gains of conventional PI and PID controllers. Particle Swarm Optimization (PSO), a population based stochastic search technique inspired by the social behaviour of bird flocking and fish schooling, has been one of the most widely applied of these techniques for LFC. Gozde and Taplamacioglu [14] applied a craziness based variant of PSO to tune the AGC parameters of a thermal power system, while Qu et al. [15] used PSO to tune the controller of a multi-source power system. Mohamed et al. [16] designed a PSO based load frequency controller for an isolated microgrid, and Gautam and Goyal [17] proposed an improved PSO algorithm for a single area power system. Jagatheesan et al. [18] used a stochastic variant of PSO to design the PI controller for a thermal power system, and Gozde et al. [19] applied PSO based PI controller design to a two area reheat thermal power system. Kumarakrishnan et al. [20] used PSO to tune a PID controller for a single area power system, and Bharti et al. [21] combined PSO with multi-agent reinforcement learning for a multi-area power system. Electrosearch optimisation [22], teaching-learning based optimisation [3] and marine predator algorithm based tuning [8] indicate a broader trend towards metaheuristic tuning of LFC controllers.

The present work focuses on a single area power system, where the absence of a tie-line allows the performance of individual controllers to be examined in isolation. Four controllers — PI, PID, FLC and PSO-PI — are designed and compared for a step change in load demand. The gains of the conventional PI and PID controllers are obtained using the Cohen–Coon reaction curve method, the fuzzy controller uses a rule base derived from the frequency error and its rate of change, and the PSO-PI controller gains are obtained by minimising an integral time-weighted error criterion using PSO.

The remainder of this paper is organised as follows. Section 2 describes the single area LFC model. Section 3 presents the design of the four controllers. Section 4 outlines the Cohen–Coon and PSO based tuning techniques. Section 5 presents the simulation results and comparative analysis. Section 6 concludes the paper.

2. LOAD FREQUENCY CONTROL MODEL OF SINGLE AREA SYSTEM

The physical mechanism responsible for load frequency control is the speed governing system of the turbine–generator unit. The speed governor senses the deviation of the turbine speed from its reference value and, through a linkage mechanism, adjusts the position of the governor valve that controls the flow of high pressure steam (or water, in the case of a hydro unit) into the turbine. When the load increases, the turbine slows down and the governor increases the valve opening to deliver more power; when the load decreases, the governor reduces the valve opening. This action alone cannot restore the frequency exactly to its nominal value, so a supplementary control loop — the load frequency controller — is required to drive the steady-state frequency error to zero.

For analysis and controller design, the single area power system is represented as a cascade of three first-order transfer function blocks: the speed governor, the turbine, and the generator–load combination, together with the feedback path corresponding to the speed regulation of the governor.

$$G_g(s) = \frac{K_g}{(1+sT_g)}, G_t(s) = \frac{K_t}{1+sT_t}, G_p(s) = \frac{K_p}{1+sT_p} \quad (1)$$

where K_g and T_g are the gain and time constant of the speed governor, K_t and T_t are the gain and time constant of the turbine, and K_p and T_p are the power system gain and time constant, representing the combined inertia of the generator and the frequency sensitivity of the load. The speed regulation R ($\frac{\text{Hz}}{\text{MW}}$) forms the feedback path around the forward path, so that an increase in frequency reduces the governor reference. The load frequency controller (PI, PID, fuzzy, or PSO-Optimized PI) is placed in the forward path, acting on the frequency error $\Delta F(s)$ to generate the control signal $u(s)$ in response to a load disturbance $\Delta P_D(s)$.

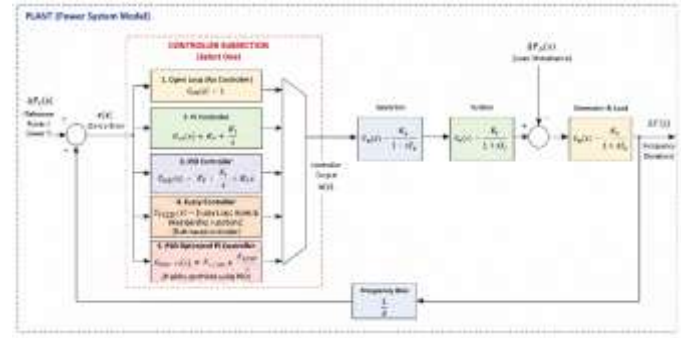


Fig -1: Proposed single-area Load Frequency Control (LFC) system with the controller subsystem.

Figure 1 illustrates the block diagram of the proposed single-area LFC system consisting of a reference input, error calculation unit, controller subsystem, governor, turbine, generator–load model, load disturbance input, droop feedback, and frequency deviation output. The controller subsystem incorporates the three four control strategies compared in this paper – PI, PID, FLC and PSO-Optimized PI controller – The reference power command $\Delta P_C(s)$ is compared with the feedback signal to generate the control error $e(s)$. This error is applied to the controller subsection, where one of five control strategies can be selected: Open Loop (No Controller), conventional PI controller, PID controller, Fuzzy logic controller and PSO-Optimized PI controller.

The controller generates the control signal $u(s)$, which is applied to the governor and turbine dynamics. The governor regulates the valve position, while the turbine converts the control action into mechanical power. The load disturbance $\Delta P_D(s)$ is introduced at the power system input, causing a frequency deviation. The generator–load model produces the output frequency deviation $\Delta F(s)$. This deviation is fed back through the frequency bias constant $\frac{1}{R}$, forming a closed-loop frequency regulation system. The main objective of the proposed PSO-optimized PI controller is to optimally tune the proportional and integral gains to achieve improved frequency response with reduced settling time, steady-state error, and performance indices. The parameters used for the single area system considered in this work, namely K_p , T_p , T_g , T_t and R , are summarised in Table I.

TABLE I. SINGLE AREA SYSTEM PARAMETERS

Parameter	Value
K_p	120
T_p	20
T_g	0.08
T_t	0.3
R	2.4

3. CONTROLLERS USED FOR LOAD FREQUENCY CONTROL

A. PI Controller

The Proportional Integral controller is the controller most commonly employed for LFC in industry because of its simple structure and its ability to eliminate steady-state frequency error. The integral action accumulates the error over time until

it is driven to zero, while the proportional term provides a fast initial correction. Its transfer function is

$$G_{PI}(s) = K_p + \frac{K_i}{s} \quad (2)$$

where K_p is the proportional gain and K_i is the integral gain. While the PI controller removes steady-state error effectively, it can produce a comparatively larger settling time and overshoot for large load disturbances.

B. PID Controller

The PID controller adds a derivative term to the PI structure so that it also reacts to the rate of change of the error:

$$G_{PID}(s) = K_p + \frac{K_i}{s} + K_d s \quad (3)$$

The derivative action anticipates the trend of the error and improves the transient response, reducing overshoot and settling time compared with a pure PI controller, though it also makes the controller more sensitive to measurement noise.

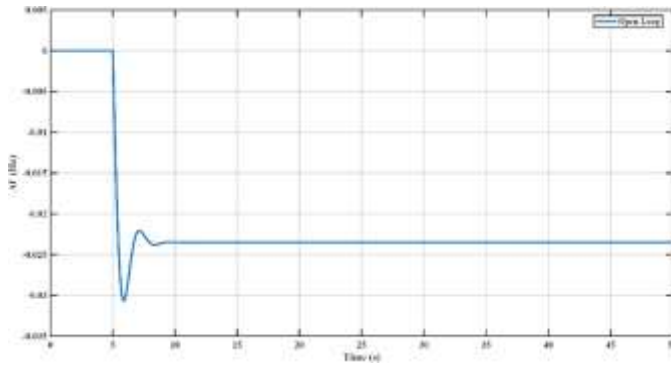


Fig -2: Open loop response of the single area system.

C. Fuzzy Logic Controller

The fuzzy logic controller (FLC) does not rely on an explicit mathematical model of the plant and instead encodes the control action as linguistic if-then rules. It has three stages: fuzzification, where the crisp inputs — frequency error e and change in error Δe — are converted to linguistic variables using membership functions; rule evaluation, where the rule base combines the fuzzified inputs; and defuzzification, which converts the fuzzy output back to a crisp control signal. Triangular membership functions are used for both inputs and the output, which is the change in the governor reference power.

D. PSO Optimized PI Controller

The PSO optimized PI (PSO-PI) controller retains the standard PI structure of Section 3.1, but its gains are not fixed by a reaction curve method or an on-line adaptive scheme; instead they are obtained offline by an evolutionary search that minimises a chosen performance index of the closed loop response. Particle Swarm Optimization is a population based stochastic technique in which a swarm of particles moves through the search space of gains (K_p , K_i), guided by its own best-known position and the best-known position found by the swarm as a whole [14], [18]. Because the search is guided directly by the actual closed-loop response rather than a linearised reaction-curve model, PSO can locate gains that reduce both settling time and peak frequency deviation more

effectively than the reaction-curve based methods used for PI and PID [16], [17].

The fitness of each candidate gain pair is evaluated by simulating the closed loop system for a step load disturbance and computing an integral time-weighted absolute error (ITAE) of the frequency deviation. PSO is run for a fixed number of iterations, and the global best particle position is taken as the final (K_p , K_i) pair. The tuning procedure is described in Section 4.B.

4. TUNING TECHNIQUES FOR CONTROLLER DESIGN

A. Cohen–Coon Technique

The gains of the conventional PI and PID controllers in this work are obtained using the Cohen–Coon reaction curve method, which determines the controller parameters from the open loop step response of the plant. The open loop gain K , the apparent time delay t_d , and the transient (process) time constant τ are first extracted from the open loop response of the governor–turbine–generator combination for a given step change in load demand. The proportional and integral gains of the PI controller are then computed as

$$K_p = \frac{\tau}{K t_d} \left[0.9 + \frac{t_d}{12\tau} \right], \quad t_i = \frac{t_d \left[30 + \frac{3t_d}{\tau} \right]}{9 + \frac{20t_d}{\tau}}, \quad K_i = \frac{1}{t_i} \quad (4)$$

The open loop response of the single area system is obtained for several magnitudes of step change in load demand, and the corresponding gain values are tabulated for use in the closed loop simulation of the conventional PI and PID controllers.

B. Particle Swarm Optimization Technique

In the PSO algorithm, each particle i in a swarm of N particles maintains a position vector $x_i = (K_{p,i}, K_{i,i})$, representing a candidate pair of PI gains, and a velocity vector v_i that determines how the position changes at each iteration. At iteration $k + 1$, the velocity and position of each particle are updated as

$$v_i^{k+1} = w \cdot v_i^k + c_1 \cdot r_1 \cdot (pBest_i - x_i^k) + c_2 \cdot r_2 \cdot (gBest - x_i^k) \quad (5)$$

$$x_i^{k+1} = x_i^k + v_i^{k+1} \quad (6)$$

where w is the inertia weight, c_1 and c_2 are the cognitive and social acceleration coefficients, r_1 and r_2 are random numbers uniformly distributed in $[0, 1]$, $pbest_i$ is the best position found so far by particle i , and $gbest$ is the best position found so far by any particle in the swarm [19], [20]. At each iteration, the fitness (ITAE of the frequency deviation) of every particle is evaluated by simulating the closed loop system with the corresponding gain pair, and the personal best and global best positions are updated accordingly. The algorithm is terminated after a fixed number of iterations or when the improvement in the global best fitness falls below a preset tolerance, and the final $gbest$ position is adopted as the tuned (K_p , K_i) pair for the PSO-PI controller. The swarm size, inertia weight, and acceleration coefficients used in this work are listed in Table II.

TABLE II . PSO PARAMETERS USED FOR TUNING THE PSO-PI CONTROLLER.

PSO Parameter	Value
Swarm size (N)	20
Inertia weight (w)	Adaptive, 0.9–0.4
Cognitive coefficient (c1)	1.49
Social coefficient (c2)	1.49
Maximum iterations	30
Objective function	ITAE of ΔF

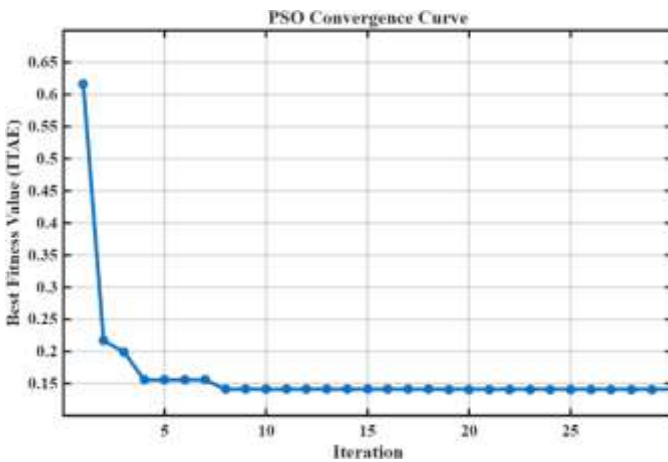


Fig -3: Convergence curve of the Particle Swarm Optimization (PSO) algorithm showing the variation of ITAE with iterations

Fig. 3 shows The PSO convergence curve demonstrates a rapid reduction in the best fitness value during the initial iterations, indicating effective exploration of the search space. The fitness value gradually stabilizes at approximately 0.14 after the 8th iteration, showing that the algorithm has reached a near-optimal solution. The stable convergence behavior confirms the effectiveness and reliability of the PSO algorithm in optimizing the controller parameters

5. SIMULATION RESULTS AND COMPARATIVE ANALYSIS

The closed loop performance of the single area system is evaluated in the MATLAB/SIMULINK environment for a step change in load demand, using each of the four controllers described in Section 3 in turn. For every case, the frequency deviation ΔF is recorded as a function of time, and the resulting transient response is used to extract the settling time, peak frequency deviation, steady-state error (SSE), Integral Absolute Error (IAE), and Integral Time Absolute Error (ITAE) for that controller.

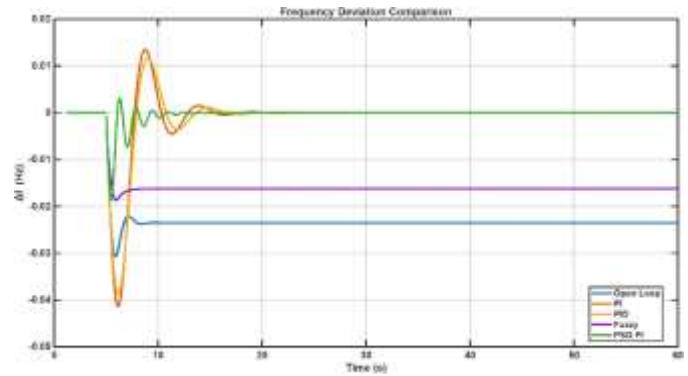


Fig -4: Frequency deviation (ΔF) with change in load demand for the four controllers.

Fig. 2 shows the open-loop frequency response of the single-area power system under a change in load demand, resulting in a noticeable frequency deviation. Fig. 4 compares the frequency responses obtained using the four controllers, namely PI, PID, Fuzzy, and PSO-PI. The controlled responses significantly reduce the frequency deviation compared with the open-loop response.

The membership functions used for the fuzzy logic controller are shown in Fig. 5. The Fuzzy logic controller employs two input variables, namely Error (e) and Change of Error (Δe), and one output variable namely controller output. Each variable is represented using five linguistic membership functions: Negative Big (NB), Negative Small (NS), Zero (ZE), Positive Small (PS), and Positive Big (PB). The membership functions are defined according to the operating ranges specified in the MATLAB Fuzzy Inference System (FIS) design. The corresponding fuzzy rule base is summarised in Table II.

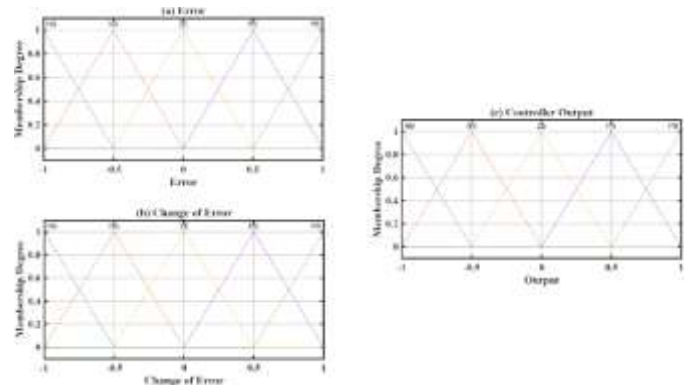


Fig -5: Membership functions of the input and output variables used in the fuzzy Logic controller: (a) Error, (b) Change of Error, (c) Controller Output

Settling time, peak frequency deviation, steady-state error, Integral Absolute Error, and Integral Time Absolute Error obtained for each of the four controllers are summarised in Table III.

TABLE III. COMPARISON OF PI, PID, FUZZY AND PSO-OPTIMIZED PI CONTROLLER

Controller	Peak	Settling	SSE	IAE	ITAE
Open Loop	0.0307	7.6219	0.023506	1.0574	29.0893
PI	0.0413	14.7238	0.000024	0.1020	0.7830
PID	0.0386	15.4428	0.000024	0.0990	0.7645
Fuzzy	0.0187	7.2260	0.016181	0.7274	20.0226

Controller	Peak	Settling	SSE	IAE	ITAE
PSO-PI	0.0186	11.8923	0.000024	0.0214	0.1411

From the results, it can be seen that the conventional PI controller, while simple, tends to give a comparatively longer settling time. The PID controller improves the transient response through its derivative action but can be more sensitive to noise. The fuzzy logic controller adapts to the instantaneous operating condition of the system and is generally found to reduce the settling time in comparison with the fixed-gain controllers [1]. The PSO-PI controller, whose gains are tuned offline to directly minimise the ITAE of the frequency deviation, is generally found to achieve a further reduction in settling time and peak frequency deviation compared with the Cohen–Coon tuned PI and PID controllers, since the optimisation is carried out on the actual nonlinear closed loop response rather than on a linearised reaction-curve approximation of the plant. These trends for the single area system are broadly consistent with the improvements reported for PSO based controllers in earlier single area and multi-area studies [17], [20].

Table III compares the performance of different controllers using peak response, settling time, SSE, IAE, and ITAE. The Open-Loop system has a peak of 0.0307, settling time of 7.6219 s, and relatively high SSE (0.023506), IAE (1.0574), and ITAE (29.0893), indicating poor steady-state regulation.

The PI controller significantly reduces the SSE to 0.000024, with IAE and ITAE of 0.1020 and 0.7830, respectively. The PID controller further improves the error performance, achieving an IAE of 0.0990 and the lowest ITAE among the conventional controllers (0.7645).

The Fuzzy controller provides the best transient response, with the lowest peak (0.0187) and shortest settling time (7.2260 s). However, its SSE (0.016181) remains higher than that of PI, PID, and PSO-PI controllers.

The PSO-PI controller achieves a low SSE of 0.000024, a settling time of 11.8923 s, the lowest overall ITAE of 0.1411. and its peak response (0.0186) is comparatively lower, it provides a good balance between transient and steady-state performance. Hence, the PSO-PI controller demonstrates improved overall error performance and effective steady-state regulation, making it a suitable choice for the proposed system.

6. CONCLUSION

This paper has presented the design and comparative evaluation of PI, PID, fuzzy logic, and PSO optimized PI controllers for the load frequency control of a single area power system. The gains of the conventional PI and PID controllers were obtained using the Cohen–Coon reaction curve tuning method, the fuzzy logic controller was designed using a two-input, one-output fuzzy inference system based on the frequency error and its rate of change, and the PSO-PI controller gains were obtained by minimising the ITAE of the frequency deviation using the Particle Swarm Optimization algorithm. Simulation results for a step change in load demand show that, while the conventional PI controller is effective at removing steady-state frequency error, both the fuzzy controller and, in particular, the PSO optimized PI controller offer a noticeably faster and smoother transient response for the single area system. Future work may

extend this single area study to a two-area or multi-area interconnected system, and may also compare PSO with other metaheuristic optimisation techniques for tuning the controller gains.

REFERENCES

- [1] K. Thenmalar. (2021). Fuzzy logic based load frequency control of power system. *Materials Today: Proceedings*, 45, 8170–8175.
- [2] A. R. Buragohain, & D. N. K. Das. (2024). Load frequency control of a single area system using fuzzy logic controller and comparison with integral and PID controller. Available at SSRN 4958990.
- [3] A. Singh, S. Yadav, N. Tiwari, D. K. Nishad, & S. Khalid. (2025). Optimized PID controller and model order reduction of reheated turbine for load frequency control using teaching learning-based optimization. *Scientific Reports*, 15(1), 3759.
- [4] A. Abazari, H. Monsef, & B. Wu. (2019). Load frequency control by de-loaded wind farm using the optimal fuzzy-based PID droop controller. *IET Renewable Power Generation*, 13(1), 180–190.
- [5] M. Kheshti, L. Ding, H. Askarian-Abyaneh, A. R. Singh, S. Zare, & V. Terzija. (2021). Improving frequency regulation of wind-integrated multi-area systems using LFA-fuzzy PID control. *International Transactions on Electrical Energy Systems*, 31(3), e12802.
- [6] A. Dokht Shakibjoo, M. Moradzadeh, S. Z. Moussavi, & L. Vandevelde. (2020). A novel technique for load frequency control of multi-area power systems. *Energies*, 13(9), 2125.
- [7] M. U. Jan, A. Xin, M. A. Abdelbaky, H. U. Rehman, & S. Iqbal. (2020). Adaptive and fuzzy PI controllers design for frequency regulation of isolated microgrid integrated with electric vehicles. *IEEE Access*, 8, 87621–87632.
- [8] A. H. Yakout, H. Kotb, H. M. Hasanien, & K. M. Aboras. (2021). Optimal fuzzy PIDF load frequency controller for hybrid microgrid system using marine predator algorithm. *IEEE Access*, 9, 54220–54232.
- [9] S. D. Al-Majidi, M. Kh. AL-Nussairi, A. J. Mohammed, A. M. Dakhil, M. F. Abbod, & H. S. Al-Raweshidy. (2022). Design of a load frequency controller based on an optimal neural network. *Energies*, 15(17), 6223.
- [10] M. Negahban, M. V. Ardalani, M. Mollajafari, E. Akbari, M. Talebi, & E. Pouresmaeil. (2022). A novel control strategy based on an adaptive fuzzy model predictive control for frequency regulation of a microgrid with uncertain and time-varying parameters. *IEEE Access*, 10, 57514–57524.
- [11] S. Kayalvizhi, & D. V. Kumar. (2017). Load frequency control of an isolated micro grid using fuzzy adaptive model predictive control. *IEEE Access*, 5, 16241–16251.
- [12] S. Gumedde, K. Behara, & G. Sharma. (2025). Analytical and optimisation-based strategies for load frequency control in renewable-rich power systems. *Energies*, 18(23), 6295.
- [13] H. A. Yousef, A. K. Khalfan, M. H. Albadi, & N. Hosseinzadeh. (2014). Load frequency control of a multi-area power system: an adaptive fuzzy logic approach. *IEEE Transactions on Power Systems*, 29(4), 1822–1830.
- [14] H. Gozde, & M. C. Taplamacioglu. (2011). Automatic generation control application with craziness based particle swarm optimization in a thermal power system. *International Journal of Electrical Power & Energy Systems*, 33(1), 8–16.
- [15] Z. Qu, W. Younis, Y. Wang, & P. M. Georgievitch. (2024). A multi-source power system's load frequency control utilizing particle swarm optimization. *Energies*, 17(2), 517.
- [16] T. Mohamed, H. Abubakr, M. M. Hussein, & G. Shabib. (2019). Load frequency controller based on particle swarm optimization for isolated microgrid system. *International Journal of Applied Energy Systems*, 1(2), 69–75.
- [17] S. K. Gautam, & N. Goyal. (2010, December). Improved particle swarm optimization based load frequency control in a single area

- power system. In 2010 Annual IEEE India Conference (INDICON) (pp. 1–4). IEEE.
- [18] K. Jagatheesan, B. Anand, N. Dey, T. Gaber, A. E. Hassanien, & T. H. Kim. (2015, September). A design of PI controller using stochastic particle swarm optimization in load frequency control of thermal power systems. In 2015 Fourth International Conference on Information Science and Industrial Applications (ISI) (pp. 25–32). IEEE.
- [19] H. Gözde, M. C. Taplamacıoğlu, I. Kocaarslan, & M. A. Şenol. (2010). Particle swarm optimization based PI-controller design to load-frequency control of a two area reheat thermal power system. *Journal of Thermal Science and Technology*, 30(1), 13–21.
- [20] V. Kumarakrishnan, G. Vijayakumar, D. Boopathi, K. Jagatheesan, S. Saravanan, & B. Anand. (2020). Optimized PSO technique based PID controller for load frequency control of single area power system. *Solid State Technology*, 63, 7979–7990.
- [21] K. K. Bharti, V. P. Singh, & S. Singh. (2020). PSO-based: MARL approach for frequency regulation of multi-area power system. *Journal of Electrical Engineering & Technology*.
- [22] Y. A. Dahab, H. Abubakr, & T. H. Mohamed. (2020). Adaptive load frequency control of power systems using electro-search optimization supported by the balloon effect. *IEEE Access*, 8, 7408–7422.