Published in AJSE, Vol:23, Issue: 1
Received on 24th October 2023
Revised on 18th January 2024
Published on 25th April 2024

AIUB JOURNAL OF SCIENCE AND ENGINEERING
ISSN: 1608 – 3679 (print) 2520 – 4890 (Online)
DOI; 10.53799/ajse.v23i1.967

Performance Analysis of Automatic Generation Control for a Multi-Area Interconnected System Using Genetic Algorithm and Particle Swarm Optimization Technique

Nafisa Tabassum, Effat Jahan, Niloy Goswami and Md. Saniat Rahman Zishan

***Abstract*— The primary focus of this paper is to assess an interconnected power system using different optimization techniques. The main purpose is to employ different optimization techniques, including genetic algorithms (GA) and particle swarm optimization (PSO), to systematically enhance the performance of a multi-area or two-area automatic generation control (AGC) system, aiming to optimize the three PID controllers gain values and improve system performance under diverse loading conditions. The modeling of the two areas includes components such as governors, turbines, and loads, with the tie line representing the interconnection between the two areas. Two case studies are conducted exploring different loading conditions in the megawatt (MW) range, including increasing load demand and decreasing load demand. The analysis involves four scenarios, covering without any kind of controller, another with solely a proportional integral derivative (PID) controller, a PID controller enhanced through a genetic algorithm (GA), and lastly, a PID controller improved through particle swarm optimization (PSO). The optimization process utilizes the integral time absolute error (ITAE) as the objective function to evaluate the system's performance. The simulation outcomes for ITAE, settling time, overshoot, and undershoot for frequency deviation of area one, area two, and power deviation in the tie-line are compared with previous similar studies to assess the novelty of this work. The article highlights the importance of the multi-area AGC system and the significance of different optimization techniques in enhancing its performance.**

***Index Terms*— Optimization, Power Deviation, PSO, Load Demand**

I. INTRODUCTION

OVER the last few years, the quick increase in load demand within the power systems has led to significant and inflexible load fluctuations. As the demand on the system grows, the system's frequency experiences a decline, which causes under-frequency circumstances; consequently, the generator speed also decreases. Similarly, sudden decrease in load will increase the frequency, which leads to an over frequency condition [1–3]. The importance of load frequency control (LFC) is critical in ensuring the stable operation of a power system by modifying the frequency and power flow of the electricity generated and transmitted over the transmission lines [4–6]. LFC constantly observes the system's frequency as well as transmission capacity. It determines the net deviation of the parameters from their specified values, which is additionally called the area control error (ACE). To lower the ACE, LFC modifies the generators' valve settings. Automatic generation control (AGC) seeks to reduce the ACE to zero, resulting in the automatic adjustment of frequency and tie-line power to zero [7, 8]. To assure the reliability of the LFC system, it is necessary to implement an appropriate controller. A PID (proportional-integral-derivative) controller is efficient at eradicating faults within the system and increasing output flexibility. The use of a PID controller can be an effective means of preserving stability within the LFC system [9]. Area generation control (AGC) is crucial for the stable and reliable operation of power systems. AGC helps maintain a balance between the total electric load in a specific area and the total generation capacity available. This load-frequency balance is essential to prevent frequency fluctuations that can lead to power outages or equipment damage. Rapid changes in electricity demand or a sudden loss of generation can create imbalances in the power system. The importance of AGC is crucial in coordinating and balancing power flows between interconnected areas to avoid overloads and maintain voltage stability.

The majority of past work centered the governor's secondary controller design and the design of the 'R', which is the speed regulation parameter. Various diverse methods, including classical optimization and genetic algorithm are used to calculate generator parameters [10]. Numerous studies have been carried out to enhance and optimize the stability of systems of single and multiple-area control for area generation. For optimization purposes, numerous algorithms have been studied, such as genetic algorithm (GA) [11], particle swarm optimization (PSO) [12], firefly algorithm (FA) [13], grey wolf optimization (GWO) [14], sine cosine algorithm (SCA) [15, 16], fuzzy logic-based approaches [17],

Nafisa Tabassum is a master's student at the Department of Electrical and Electronic Engineering, American International University-Bangladesh (AIUB), Dhaka, Bangladesh. Email: nafisatabassumnisha@gmail.com

Effat Jahan is an Assistant Professor of the Department of EEE at American International University-Bangladesh. E-mail: effat@aiub.edu

Niloy Goswami is a Sessional Faculty Member at the Department of EEE, American International University-Bangladesh (AIUB), Dhaka, Bangladesh. Email: niloygoswami98@gmail.com or ngoswami@aiub.edu

Md. Saniat Rahman Zishan is an Associate Professor, Dept. of EEE American International University-Bangladesh (AIUB), Dhaka, Bangladesh. Email: saniat@aiub.edu

cuckoo search algorithm [18], hybrid fuzzy neural network [19], and others that have been modified by Researchers to improve performance. Guha et al. studied the use of Grey Wolf optimization in the two-area interconnected system LFC issue; this study demonstrates controller gain optimization using an Integral Time Absolute Error (ITAE)-based objective function, and analyzes the effectiveness of the proposed GWO algorithm with that of the Ensemble of Mutation and Crossover Strategies and Parameters in Differential Evolution (EPSDE), Comprehensive Learning of Particle Swarm Optimization (CLPSO), and other associated techniques [20]. In reference [21, 22], researchers propose various approaches for power systems and also describe different AVR and LFC systems using optimization strategies such as ANN, GA, PSO, and Adaptive Neuro Fuzzy Inference System (ANFIS) with the objective function of keeping the system frequency at the scheduled values throughout typical operations as well as within minor interruptions. Sahu et al. reported in a paper on AGC utilizing a novel Modified Sine Cosine Algorithm (M-SCA); and an aided PID controller, that controlled the error signal along with the nominal value of the tie line power and able to decline settling time, peak overshoot, and undershoot of the generated dynamic outcomes, as well as provide a better ITAE value than other implemented controllers [23]. In reference [24], PID controllers with genetic algorithm (GA) designed for the enhanced control of AGC thermal two area power system and compared the conventional integral with their studied performance of the fractional order PID (FOPID)-based AGC system. Gupta et al. [25] introduced the grey wolf optimization technique to improve the AGC system with the ITAE function as a preferable choice for optimizing the parameters in comparison with other techniques. Panda et al. discussed the AGC of a networked system using the multi objective optimization approach provided by the Non-Dominated Shorting Genetic Algorithm-II (NSGA-II). In order to develop a Pareto optimum set of solutions, the NSGA-II method is used to balance competing goals such as ITAE, settling times in frequency and tie-line power deviations [26]. Jagatheesan et al. studied about AGC of a multi-area interconnected equal reheat thermal power system and optimized the system using a PID controller; both the GA and the PSO techniques are compared to the effectiveness of the studied FA algorithm. However, this method required an adjustment as the total amount of iterations gets higher, which reduces peak overshoot and undershoot but also increases the settling time [27].

The main motivation behind the work is to address the complexities and challenges of managing massive, interconnected power systems. Through the integration of GA and PSO, the research seeks to achieve efficient optimization, adaptability to changing conditions, and scalability for real-world power grid applications. The proposed approaches hold the potential to optimize power generation control across multiple interconnected areas, ensuring grid stability, load management, cost-effectiveness, thereby enhancing fundamental dependability and sustainability of the power system. This study significantly improves a two-area AGC system by tuning PID controllers with GA and PSO. The study demonstrates improved performance metrics, demonstrating the usefulness of the optimized controllers in managing load variations and enhancing system balance relative to conventional AGC systems.

The fundamental purpose of this article is to represent multiple optimization techniques for AGC system to keep the system's frequency steady as well as line flows according to predetermined values along with disturbances. Utilizing PSO, and a GA technique to figure out the optimum load frequency control output. The GA and PSO optimization techniques are to find the best possible system performance level. The structure of the full article is as follows: In Section II, the multi area system modeling of this study is discussed which is simulated in MATLAB/SIMULINK commercial software, whereas in Section III, proposed optimization techniques are described with the simulation results alongside case-by-case comparisons and a comprehensive analysis of previous similar studies. Finally, Section IV concludes with a few concluding observations and some future scopes for this study.

II. SYSTEM MODELING

In an AGC of a single-area system, the basic system considers one generating station and one set of loads. The two single area or generation stations are interconnected via a transmission line, that is called “Tie Line”. The power system model being discussed is commonly employed in the study to explore the dynamic responses of the interconnected system under various conditions, including both increasing and decreasing load demand scenarios.

The model of two-area interconnected system via tie-line is shown in Fig. 1, which is used for simulation of the overall AGC system in this paper. Every area comprises a speed governor, turbine, inertia, and load. Notably, Area Control Error signals (ACE-1 and ACE-2) are emphasized, representing the deviation between scheduled and actual frequencies in each area. PID Controllers 1 and 2 are visibly connected to these ACE signals, showcasing their pivotal role in the control strategy. The PID controller 3 on the tie line in a two-area AGC system is used to balance power, regulate frequency, and ensure desired load sharing between the two areas. It adjusts power flow based on frequency changes and maintains stability in the system. These controllers analyze the errors and implement corrective actions to regulate turbine outputs, ensuring that system frequencies align with desired setpoints. The visual representation encapsulates the dynamic interactions within the AGC system, emphasizing the feedback control mechanisms crucial for sustaining stable and efficient power generation across the two areas. In this Fig. 1, governor time constant is T_g, turbine time constant is T_t, frequency bias factor B_1 is 20.6 and B_2 is 16.9. Both areas speed regulation parameters are R_1 and R_2. Load disturbance of area 1 and area 2 is $\Delta P_{L1}\ and\ \Delta P_{L2}$ [28]. Deviation of frequency in both areas Δf_1 and Δf_2.

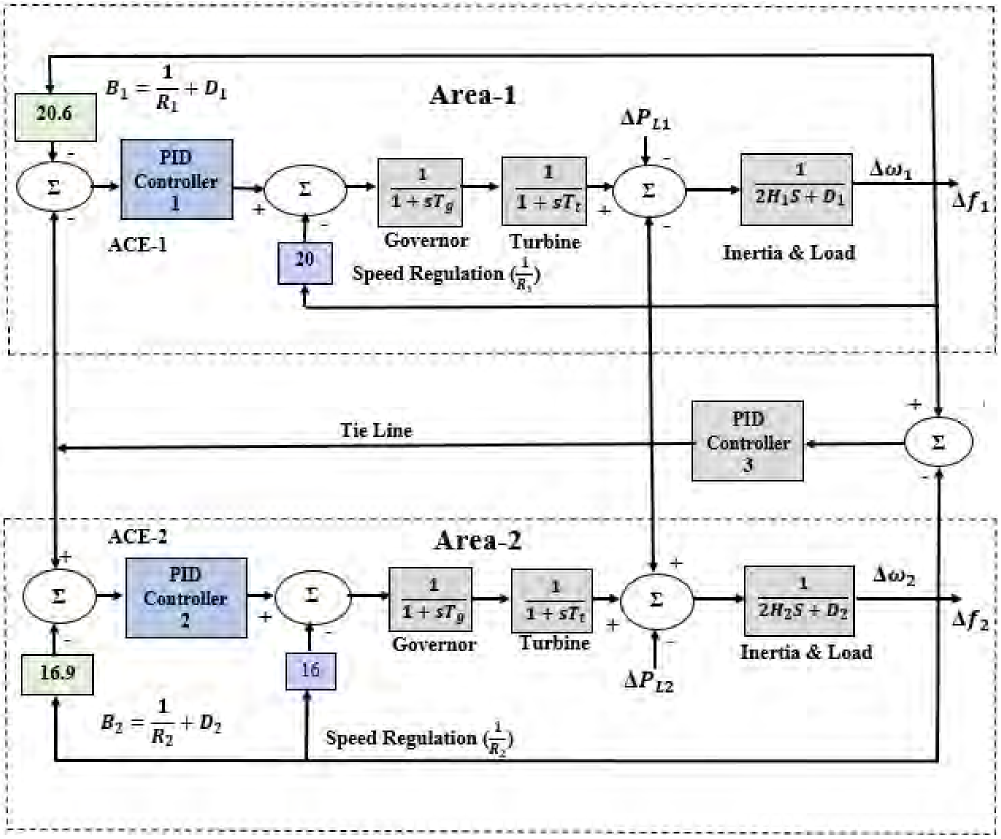

Fig. 1. Two area AGC system Block diagram.

Angle difference of voltages = δ_1- δ_2. If $\delta_1 > \delta_2$, power can transfer from area-1 to area-2 as, power transfer depends on angle δ_1 and δ_2. So, small changing in tie line power flow, as considering an additional load is in the area-2:

$$\Delta P_{12} = P_s[\delta_1 - \delta_2] \tag{1}$$

Differentiate and take the Laplace Transform.

$$s\Delta P_{12}(s) = P_s[\Delta\omega_1(s) - \Delta\omega_2(s)] \tag{2}$$

This Equation 2 can be represented as the following diagram in Fig. 2. This model is a depiction of the tie line flow. Adding this tie line block diagram between two single-area systems builds a two-area system.

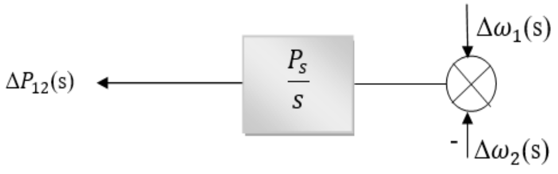

Fig. 2. Tie-line block diagram.

The block diagram that follows in Fig. 3 depicts the modifications occurring in the two single-area systems as a result of their interconnection and the load demand of the second area drowns power from the first area.

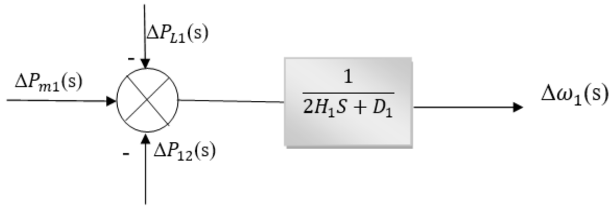

Fig. 3. Generator load model in area 1.

Fig. 4 demonstrates the tie line power flowing into the second area in a two-area AGC system. The tie line represents the interconnection between the two areas, and the power exchange between them is monitored and controlled to maintain system stability and balance generation and demand.

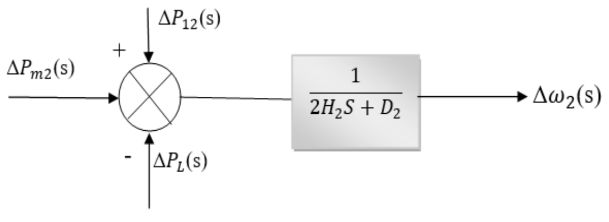

Fig. 4. Generator load model in area 2.

Conventional LFC utilizes the tie line bias control method, where each area aims to minimize its area control error (ACE) towards zero. Each area control error is shown below:

$$ACE_i = \sum_{J=1}^{n} \Delta P_{ij} + K_i + \Delta\omega \tag{3}$$

During a disturbance, the interaction in neighbouring areas is dictated by the area bias K_i and steady state frequency deviation $\Delta\omega$.

A. Genetic Optimization (GA)

To achieve significant improvements, the GA approach is employed for determining the best values of the PID controller. Measuring the Integral Time Multiplied Absolute Error, abbreviated as ITAE is a usual aspect of control system design performance evaluation. The objective function of the load frequency control model in this particular design is based on the time dependent ITAE. The time values are initially set to a minimum, but as time passes, the error signal increases accordingly.

Fig. 5 portrays a detailed flowchart for the GA applied to optimize PID controllers in a two-area AGC system. The process begins by defining the number of variables, followed by a series of generations. Within each generation, the flow diverges into two paths: one involves the placement of PID controllers 1 and 2 after the ACE summation block, while the other integrates PID controller 3 in the tie line of the two-area AGC. The system undergoes fitness scaling, utilizing a tournament selection function, an adaptive feasible crossover function, and arithmetic mutation. This intricate genetic algorithm iteratively refines the PID controller gains, aiming to enhance the overall system's performance. The process continues through multiple generations until the maximum generation is reached. The optimized values for PID controller gains are ultimately obtained, leading to the conclusion of the algorithmic process. Fig. 5 encapsulates the systematic optimization approach employed for tuning PID controllers in the context of a two-area AGC system. By iteratively refining PID controller gains, the algorithm seeks to achieve optimal system performance, ensuring stability and robustness in the face of dynamic changes.

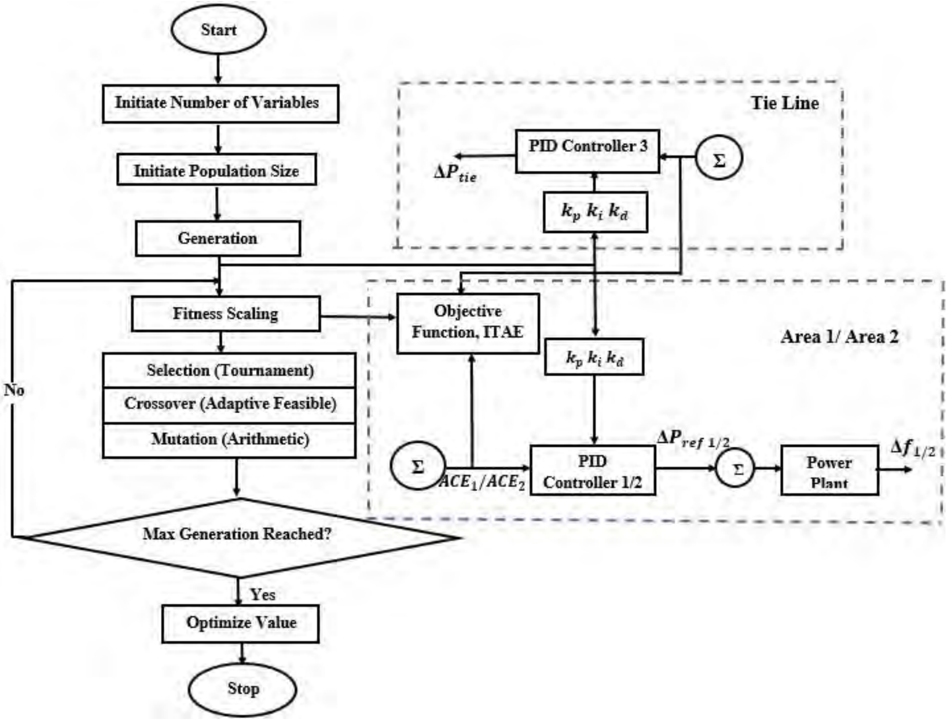

Fig. 5. Flowchart for GA in this system.

The system's performance can be significantly improved by utilizing the ITAE-based objective function [7, 8]. Hence, it is employed as the global function for optimum design of the claimed PID controller [29]. The frequency deviation ($\Delta f_1$and Δf_2) and tie-line power deviation (ΔP_{tie}) are used as cost functions to lower the ITAE. Equation 4 describes the way to mathematically define the cost function or the objective function or ITAE [30].

$$ITAE = \int_{t=0}^{t_{final}} t(|\Delta f_1| + |\Delta f_2| + |\Delta P_{tie}|)\, dt \tag{4}$$

The controller parameters define the limits of the optimization problem that can be considered LFC. The following is a formulation of the design problem to reduce ITAE, while considering for PID controller:

$$K_{p,min} \le K_p \le K_{p,max} \tag{5}$$

$$K_{i,min} \le K_i \le K_{i,max} \tag{6}$$

$$K_{d,min} \le K_d \le K_{d,max} \tag{7}$$

Here, $K_{PID,min}$ is the minimal and $K_{PID,max}$ is the maximal gain of PID controller parameters.

B. Particle Swarm Optimization (PSO)

The PSO algorithm, which belongs to the class of bioinspired optimization algorithms, is known for its simplicity in searching for the most effective solution to a given problem. In the context of optimizing P, I and D gain values; the PSO algorithm aims to maximize their values according to the ITAE objective function. Once the optimization process is complete, the controller is updated with the optimized values. It is crucial to strike a balance between understanding and practical implementation for the PSO algorithm to perform at its best [31]. The following is the fundamental formula for PSO:

$$V_{ij} = \omega^* V_{ij} + c_1 r_1 \left(P_{ij} + X_{ij}\right) + c_2 r_2 \left(P_{gj} + X_{ij}\right) \qquad (8)$$

Here, ω= inertia co-efficient; $c_1 c_2$= acceleration constant; $r_1 r_2$= random number.; V_{ij}= velocity; P_{gj}= global best position; X_{ij}= particles position; P_{ij}= personal best position.

Fig. 6 depicts a comprehensive flowchart outlining the PSO process for tuning PID controllers in a two-area AGC system. The flowchart features the positions of the three PID controllers, highlighting the block dedicated to optimizing the overall system. Within the flowchart, the updates of global best position and personal best position are performed based on previous responses, leading to optimized values for the PID controller gain. The process initiates by selecting variables for PSO, and from this variable selection, it diverges into two paths: one involving PID controllers 1 and 2 placed after the ACE summation block, and the other integrating PID controller 3 connected to the tie line of the two-area AGC. The objective function, derived from the feedback of the ACE summation block for PID controllers 1 and 2, as well as the tie line summation block for PID controller 3, guides the optimization process. The PSO algorithm progresses through a series of steps, including particle initialization, updating particle positions and velocities, evaluating fitness, and updating personal and global bests. This iterative process continues until a specified maximum iteration is reached, ultimately yielding optimized values for the PID controllers' parameters.

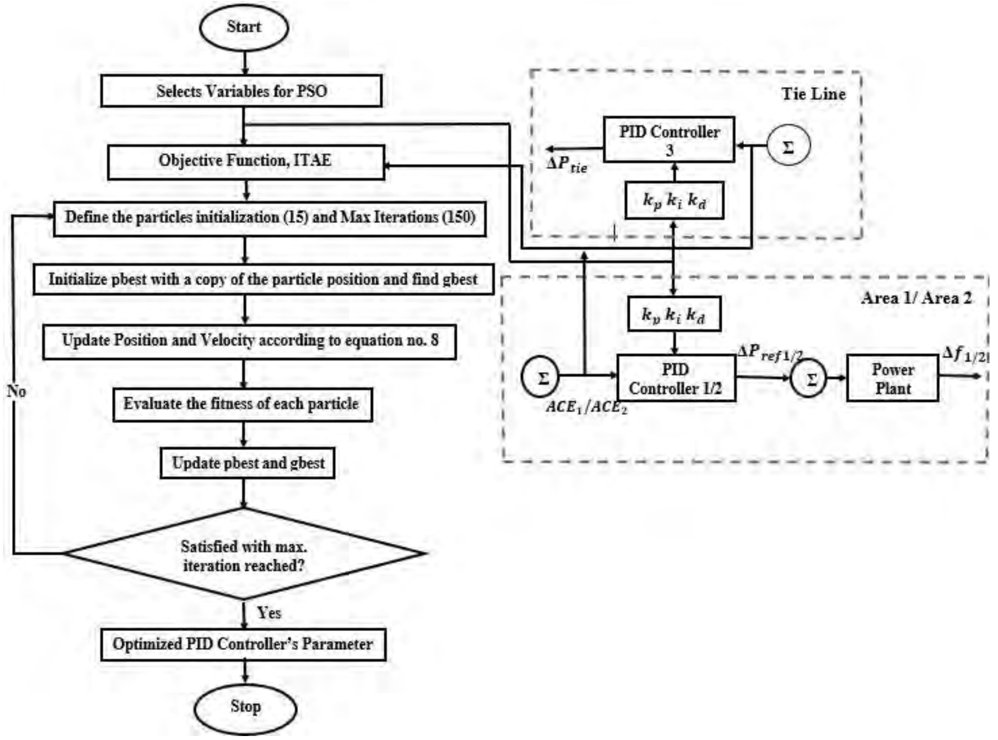

Fig. 6. Flowchart for PSO in this system.

The PSO algorithm, as illustrated in Fig. 6, encapsulates a methodical process for fine-tuning PID controllers to enhance the performance of a two-area AGC system. The inclusion of distinct paths for PID controllers 1 and 2, as well as PID controller 3, showcases the adaptability of the optimization process to different components of the AGC architecture. The iterative nature of PSO involves initializing particles, updating their positions and velocities based on a mathematical equation, and evaluating fitness at each iteration. The optimized values for PID controller parameters obtained through this process contribute to the overall efficiency and stability of the AGC system. This flowchart serves as a visual representation of the PSO methodology, providing valuable insights into the systematic tuning of PID controllers for dynamic and complex power system control.

III. RESULT ANALYSIS

I. Case Study 1: Increasing Load

Fig. 7 depicts the iteration trend of the PSO technique for managing the increasing load condition in the AGC system. The training is conducted for 150 iterations to achieve the optimal outcome across the system. Notably, the graph exhibits a linear trend, particularly after 100 iterations, indicating that the PSO technique has successfully identified its best optimum solution for AGC. This observation aligns with the findings reported in [23], which also demonstrate a similar trend.

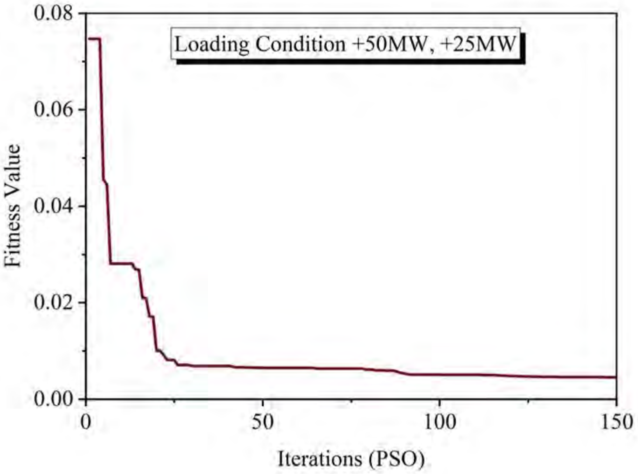

Fig. 7. PSO trained curve based on iterations for increasing load demand.

In Fig. 8, two different plots are shown based on training data using GA optimization for the increasing load condition in a two-area AGC system. As there are several stages in GA, the data is trained for 20 generations with 100% of the criteria met, where the best fitness value is around 0.0079588 and the mean fitness value is 0.01099, as shown in Fig. 8 (a). The optimized values for nine consecutive gain values under this loading condition are depicted in Fig. 8 (b).

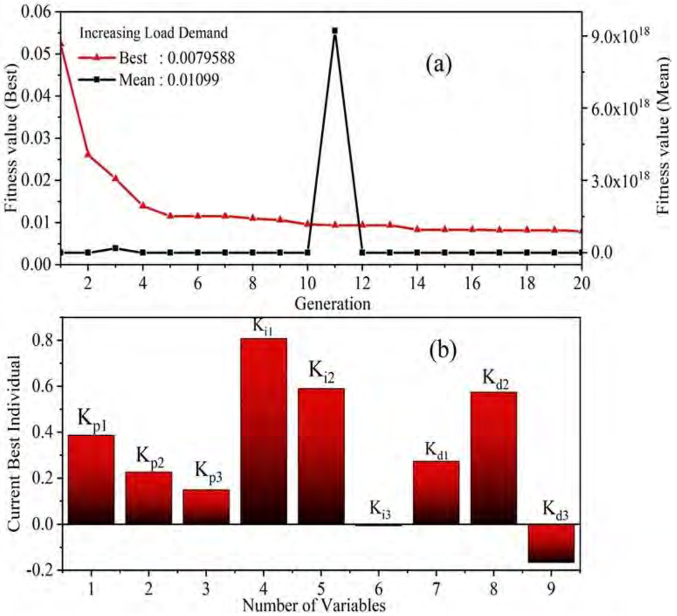

Fig. 8. Data tuning plots using GA for increasing load demand.

With the growing demand for electricity, there arises a greater requirement for power within the system leading to a consequent decrease in the overall frequency [32]. Fig. 9 illustrates the area one frequency deviation generation control under four different scenarios. In each scenario, there is an increase in demand of 50MW or 0.05 pu in area one and 25MW or 0.025 pu in area two. The standard frequency for this system is considered as 50 Hz. The plot reveals that the PSO method demonstrates greater stability compared to the other plots in this particular condition.

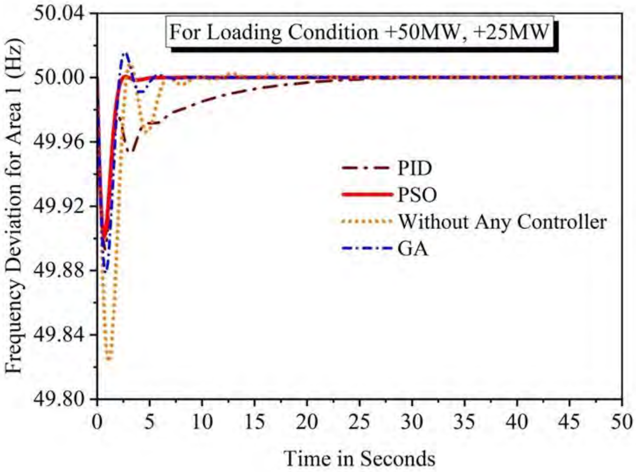

Fig. 9. For increasing load conditions change in frequency in Area 1.

In Fig. 10, the area two frequency deviation in AGC is presented. The simulation is conducted over a duration of 50 seconds. From the graph, it is evident that the PSO plot achieves faster stabilization of the system compared to the other three plots. Following the PSO, the GA plot demonstrates a higher level of stability compared to scenarios where only the PID controller or no controller is employed in the two-area generation control system.

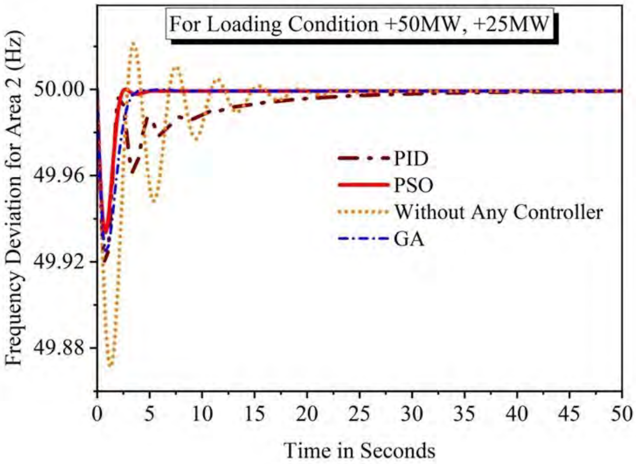

Fig. 10. For increasing load conditions change in frequency in Area 2.

Fig. 11 depicts the tie-line power representation in response to an increasing load demand of 0.05 pu in area one and 0.025 pu in area two. Without any controller in the system, the power deviation is significant, indicating the instability. Although the PID controller helps mitigate the deviation to some extent, it falls short of achieving the desired level of stability. However, the technique of PSO and GA optimization demonstrates their crucial roles, as depicted in Fig. 11. The GA optimization technique exhibits improved stability after the PSO technique, effectively reducing the power deviation and improving the overall performance of the system. These findings emphasize the significance of PSO and GA in achieving better stability and control of tie-line power in the increasing load demand condition for the two-area generation control system.

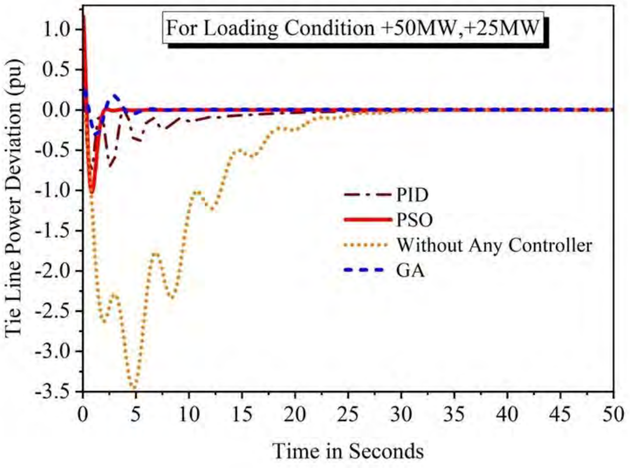

Fig. 11. Tie-line power change for increasing load demand.

II. Case Study 2: Decreasing Load

Fig. 12 shows a considerably varying inclination in PSO training, which contrasted with case study 1. In both cases, the total number of iterations stays at 150. However, in the case of a decreasing load scenario, the graph shows a linear trend appearing after 110 iterations, showing that the PSO approach has identified the most optimized solution. The finding shows the PSO algorithm's sensitivity to shifting load circumstances, as seen by the varied patterns detected during the training phase. These findings provide a spotlight on the flexibility and usefulness of the PSO approach for optimizing AGC system performance under different load demand conditions.

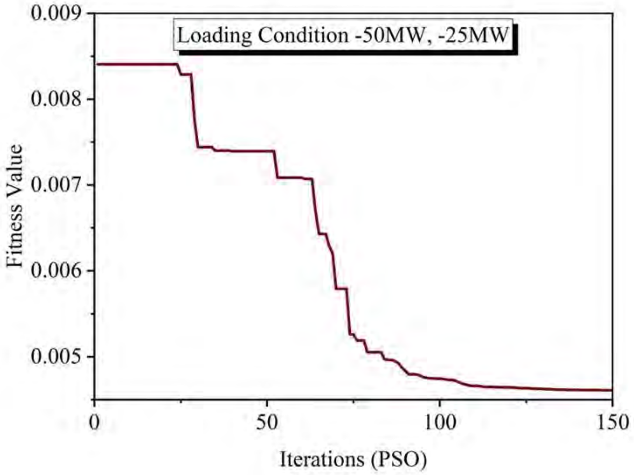

Fig. 12. PSO trained curve based on iterations for decreasing load demand.

Fig. 13 showcases two distinct plots obtained using the GA approach, with each plot representing the training and, in Fig. 13 (b), the optimization of nine potential best gain values for the PID controller. The training process successfully met the 100% criteria for the specified number of generations. The best fitness value achieved is around 0.00999, indicating optimal performance, while the mean fitness value averages around 0.01559, as shown in Fig. 13 (a).

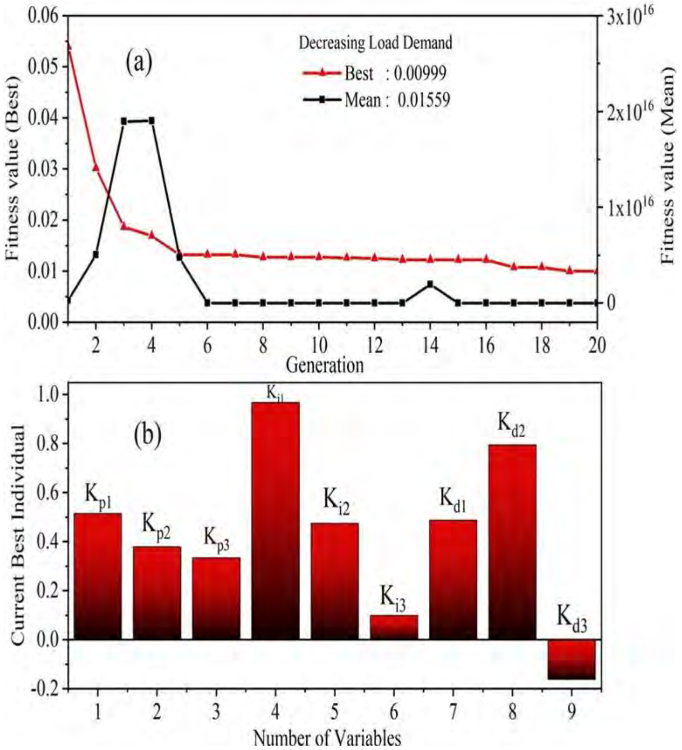

Fig. 13. Data tuning plots using GA for decreasing load demand.

If load demand is decreased, the grid frequency will be increased, and vice versa [33]. Fig. 14 demonstrates the frequency deviation of area one generation control in four distinct scenarios. In each scenario, there is a decrease in demand, denoted by negative values, of 50 MW or 0.05 pu for area one and 25 MW or 0.025 pu for area two. The graph reveals that the PSO technique achieves stable attainment of the standard frequency of 50 Hz, followed by the GA approach. In contrast, the response without any controller and the PID controller exhibit poor performance, requiring a longer time to stabilize.

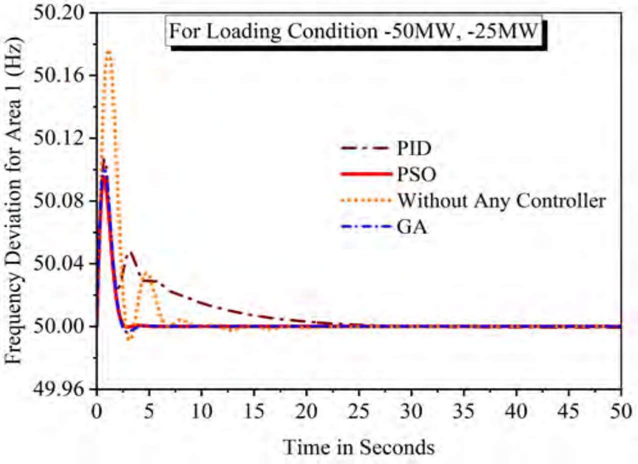

Fig. 14. For decreasing load conditions change in frequency in Area 1.

Fig. 15 represents the AGC performance in area 2 under conditions of decreasing load demand. The plot reveals that without any controller, the system exhibits higher fluctuations, indicating instability. Similarly, the PID controller does not provide an optimal response in this scenario. Notably, both the PSO and GA techniques exhibit a time difference in achieving stability at the desired 50 Hz frequency under this decreased load demand condition.

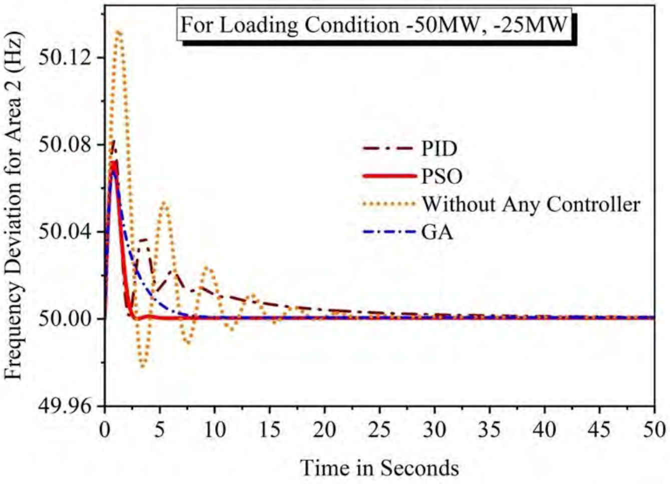

Fig. 15. For decreasing load conditions change in frequency in Area 2.

The deviation in tie-line power is a critical concern in interconnected power systems, since it has the potential to produce transients and instability in the power system. This issue comes as a consequence of power flow imbalances between interconnected areas, which can have a negative impact on system performance and overall stability [34].

Fig. 16 demonstrates the deviation of tie line power in the absence of any controller, which exhibits significant instability and undesirable fluctuations. The substantial deviation underscores the importance of implementing effective control mechanisms to mitigate such instability. In this regard, both the PSO and GA techniques showcased superior performance compared to the absence of a controller or the use of only a PID controller. The PSO and GA techniques effectively minimized the deviation and enhanced system stability under the decreasing load demand condition.

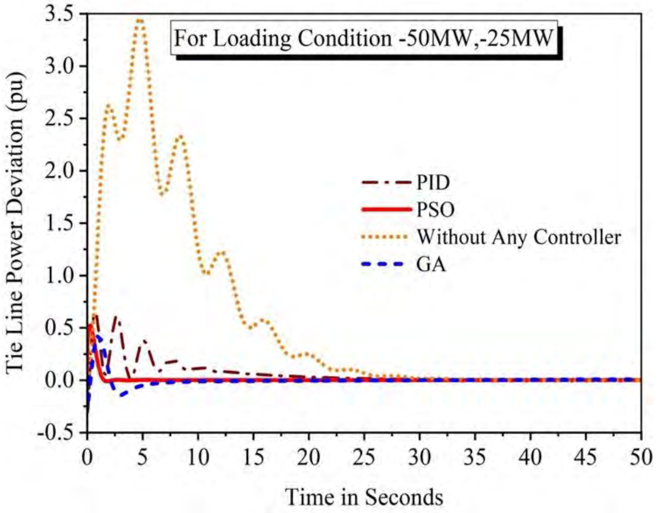

Fig. 16. Tie-line power change for decreasing load demand.

Table I shows the nine optimized gain vales for different loading conditions with GA and PSO. The gain values are mainly optimized for tune the PID controller to perform better in increasing or decreasing load demand in two area AGC system. The improved performance of the system indicates greater reliability as the value of the Integral Time Absolute Error (ITAE) decreases. A lower ITAE value indicates that the system achieves better accuracy and minimizes errors over time, leading to improved overall performance and increased reliability. Thus, minimizing the ITAE value is a key objective in system design and control optimization [35, 36]. Table I presents the ITAE values for each condition, indicating the reliability of the results obtained. Notably, the best ITAE value for this system is observed under the increasing load demand condition, with a value of 0.004549 for the PSO technique and 0.01289 for the GA technique. These values are considerably lower compared to the ITAE values recorded in other conditions, indicating superior performance and improved control effectiveness.

Table II provides the settling time, overshoot, and undershoot values pertaining to the two-area AGC system across various scenarios. The measurements are recorded for frequency deviation of area one (Δf_1), frequency deviation of area two (Δf_2), and power deviation of tie-line (ΔP_{Tie}). Additionally, the PSO technique yields the minimum values for settling time, overshoot, and undershoot across the two different case scenarios, indicating its superior performance in achieving faster response, reduced oscillations, and better control stability.

A system that exhibits shorter settling time, reduced overshoot, and decreased undershoot is considered more suitable and performs better. These parameters indicate the system's ability to quickly reach a stable state, minimize deviations from the desired response, and maintain control within acceptable bounds [37, 38]. Table III presents a comparison of previous research studies that employed different optimization techniques for the AGC system in two-areas. The focus is on the best outcomes achieved in terms of settling time and ITAE values. In this work, the PSO technique demonstrates superior performance in several aspects. Firstly, the PSO technique yields a lower area one frequency deviation, but the Hybrid Firefly Algorithm and Pattern Search (hFA-PS) [7] and Grey Wolf Optimization (GWO) [20] exhibit closer performance compared to this result. Secondly, the PSO technique achieves the lowest area two frequency deviation among the previous works. Thirdly, the tie-line power deviation is significantly reduced with the optimized PSO technique in this study, surpassing the performance of other techniques used in prior research. Lastly, the PSO technique also demonstrates the lowest ITAE value in this study, with the Fractional Order Integral-Tilt Derivative (PSO-FOI-TD) technique having a closer performance reported in [40] but having differences in the values. These findings emphasize the effectiveness of the PSO technique in optimizing the two-area AGC system in this work, highlighting its superiority in achieving better control and system stability.

TABLE I
OPTIMIZE VALUES FOR THE DIFFERENT LOADING CONDITION

Loading Condition (MW)		Controller Gains									ITAE Value
		K_{p1}	K_{p2}	K_{p3}	K_{i1}	K_{i2}	K_{i3}	K_{d1}	K_{d2}	K_{d3}	
Area 1, Area 2 [GA]	+50, +25	0.388073	0.22732	0.150678	0.807556	0.590698	-0.00655	0.27469	0.574604	-0.16695	0.01289
Area 1, Area 2 [GA]	-50, -25	0.514905	0.379501	0.334823	0.967244	0.474725	0.1	0.487646	0.795371	-0.1619	0.02445
Area 1, Area 2 [PSO]	+50, +25	0.639495	0.661502	0.943543	1	0.876468	5.24×10^{-06}	0.49416	0.697032	-0.59332	0.004549
Area 1, Area 2 [PSO]	-50, -25	0.639124	0.516672	0.778007	0.999969	0.797948	-3.78×10^{-06}	0.533377	0.63171	0.197283	0.004609

TABLE II
COMPARISON BETWEEN FOUR POSSIBLE APPROACHES

Loading Condition (MW)			Settling Time (sec)			Overshoot (%)			Undershoot (%)		
			Δf_1	Δf_2	ΔP_{Tie}	Δf_1	Δf_2	ΔP_{Tie}	Δf_1	Δf_2	ΔP_{Tie}
Without Any Controller	Area 1, Area 2	+50,+25	33.674	22.567	34.1	4.737	17.059	0.78	19.608	40.096	40.086
		-50, -25	26	31.8	29.8	19.61	40.088	39.8	4.737	17.059	1.07
With PID	Area 1, Area 2	+50, +25	30.775	13.8	30.8	1.453	1.436	0.853	0.505	0.510	1.855
		-50, -25	35.5	30.5	29	0.505	0.510	0.892	0.895	1.436	0.978
GA	Area 1, Area 2	+50, +25	5.335	3.887	8.42	1.315	0.505	-38.751	0.568	1.951	113.09
		-50, -25	4.1	9.2	8.1	0.521	1.979	0.436	1.775	0.505	33.528
PSO	Area 1, Area 2	+50, +25	2.48	2.46	2.048	0.505	1.531	47.426	1.720	2.022	-0.945
		-50, -25	2.75	2.727	1.54	0.505	0.505	0.510	0.863	0.937	1.215

TABLE III
COMPARISON OF DIFFERENT OPTIMIZATION TECHNIQUES WITH THE ITAE VALUES

Parameter		hFA–PS	FA	BFOA	PSO-FOI-TD	GA	PSO	GWO	Fuzzy PIDF-PSO	Fuzzy PIDF-BA	GA*	PSO*
Settling Time (sec)	Δf_1	2.8	3.1	4.7	13.30	14.54	14.54	2.64	5.4468	5.9858	4.1	2.75
	Δf_2	4.5	4.9	6.4	12.8	15.22	15.22	2.86	10.269	9.3781	9.2	2.727
	ΔP_{Tie}	4	4.3	5.1	16.9	19.86	19.86	3.14	10.421	10.453	8.1	1.54
ITAE Value		0.2782	0.3240	0.4788	0.0098	NR	NR	0.1308	0.02535	0.03094	0.02445	0.004609
References (Year)		[7] (2015)	[7] (2015)	[39] (2013)	[40] (2021)	[12] (2021)	[12] (2021)	[20] (2016)	[41] (2021)	[41] (2021)	This Work	This Work

* NR = Not Reported

TABLE IV
COMPARISON OF THE PARAMETERS WITH PREVIOUS SIMILAR APPROACHES

Parameter		GA	TLBO-PS: TID	Fuzzy PIDF-BA	Fuzzy PIDF-PSO	FPDN-FPTID	GA*	PSO*
Overshoot (%)	Δf_1	14.78	4.5	1.31	1.15	0.1238	0.521	0.505
	Δf_2	10.36	3.36	0	0	0.0796	1.979	0.505
	ΔP_{Tie}	5	5	0	0	0.0168	0.436	0.510
Undershoot (%)	Δf_1	49.49	25.3	11.40	14.65	3.494	1.775	0.863
	Δf_2	20.89	23.12	2.03	1.75	3.107	0.505	0.937
	ΔP_{Tie}	1.5	0.64	0.26	0.24	0.018	33.528	1.215
Reference (Year)		[11] (2016)	[42] (2020)	[41] (2021)	[41] (2021)	[43] (2023)	This Work	This Work

Table IV displays a comparison between the current research and previous studies in terms of overshoot and undershoot. The best outcomes achieved in each previous work are compared to the best outcomes of this study. For area one frequency deviation, both GA and PSO techniques in this study exhibit lower overshoot compared to other previous works; however, the Fuzzy-PIDF-BA and Fuzzy-PIDF-PSO techniques achieve zero overshoot, as reported in [41]. Regarding undershoot, both GA and PSO techniques in this study demonstrate superior performance for both area one and area two frequency deviations compared to previous works. These findings demonstrate the accuracy of GA and PSO approaches in reducing undershoot and thereby improving system performance and control precision. The overall performance of the different techniques in the AGC system is calculated by the given equation,

$$The\ Overall\ Performance = Area\ 1\ Settling\ Time\ (ST) + Area\ 2\ ST + Tie\ Line\ ST + ITAE \tag{9}$$

Fig. 17 indicates the comparison of the overall performance of the AGC two-area system with previous research. In this AGC two-area system, a low value of the overall performance indicates that the system is settling quickly and has a minimal cumulative error over time, which are highly favorable characteristics.

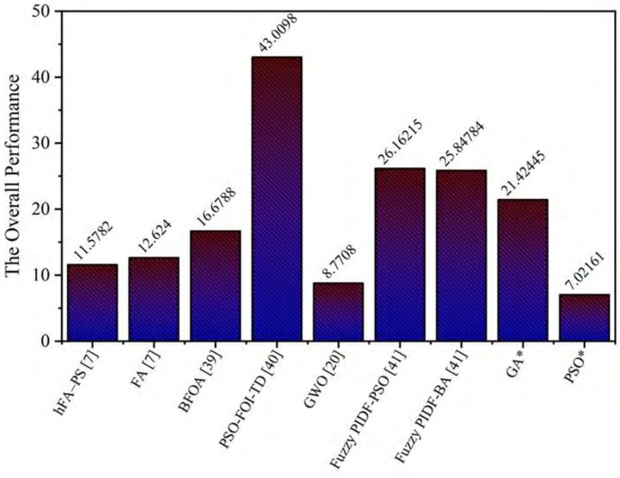

Fig. 17. Comparison of the overall performance.

V. CONCLUSION

This article introduces two distinct optimization approaches for comparing the case scenarios. The system's performance is determined according to load demands. The simulation results showed a great impact on the overall power system where GA and PSO techniques are utilized to tune the PID controller, which led to significantly improved stability, reduced settling time, and minimized frequency deviations in both areas. Additionally, the comparison with previous research highlighted the novelty of this work and the advantages of the proposed optimization techniques, since earlier works have been performed with almost the same kind of load variations. However, from the analysis of the case studies, in almost all the cases, the PSO optimization technique performed better in terms of frequency and tie-line power deviation than other techniques. Moreover, this article provides valuable insights into the more comprehensive analysis and optimization of multi-area AGC systems. In the future, further research can be studied based on this with the impact of demand response, where the analysis can be demand-side management to optimize load patterns in a two-area AGC system. Again, the integration of energy markets between two-area AGC systems, exploring the impact of market mechanisms on system operation and stability, and developing price forecasting models for optimizing economic dispatch and enhancing market efficiency can be another future scope of this paper.

APPENDIX

A Multi-area or two area system connected via a Tie-line model use the following parameter for this study: Base Power for both area one and two = 1000 MVA; Speed Regulation, R_1= 0.05, R_2=0.0625;Frequency sensitivity load co-efficient, D_1= 0.6, D_2= 0.9; Inertia Constant, H_1=5, H_2=4; Governor Time Constant, T_{g1}=0.2 sec, T_{g2}=0.3 sec; Turbine Time Constant, T_{t1}=0.5 sec ,T_{g2}=0.6 sec

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Nafisa Tabassum earned her BSc. Engg. Degree in Electrical & Electronic Engineering (EEE) from the American International University-Bangladesh (AIUB) in 2022. Currently, she is pursuing her MSc. in EEE at the same institution. Her research interest focused on power system optimization and the integration of the Internet of Things (IoT) to advance the field of electrical engineering, exploring innovative intersections between these domains.

Effat Jahan graduated from American International University-Bangladesh (AIUB) in 2013 and 2014 with a B.Sc. Engg. and an M.Sc. Engg. in Electrical and Electronic Engineering, respectively. She also achieved the Magna Cum Laude (academic honor) award for her outstanding performance in her Bachelor's degree program. Her Ph.D. degree was at the Kitami Institute of Technology (KIT) in Japan. Her Ph.D. research focuses on power system frequency stabilization, including large-scale offshore wind farms, VSC-HVDC transmission system design and analysis, and power system dynamics analysis. She is currently working as an Assistant Professor in the Electrical and Electronic Engineering Department.

Niloy Goswami received his BSc. degree in Electrical & Electronic Engineering (EEE) in 2021 from American International University-Bangladesh (AIUB) and received his MSc. degree in EEE from AIUB in January 2024. He has worked as a graduate teaching assistant in the department of EEE, faculty of engineering at AIUB. After completing his MSc., he joined as a Sessional Faculty Member at the Department of EEE at AIUB on January 2024. The areas of his research focus include power system control and optimization, the application of patch antennas in biomedical engineering, and the role of patch antennas in the evolution of next-generation wireless communication.

Md. Saniat Rahman Zishan received B.Sc. in Electrical and Electronic Engineering and Master of Engineering in Telecommunications degree from American International University-Bangladesh (AIUB). He completed PhD from Universiti Sultan Zainal Abidin in the field of e-Health. On September 2009, he started his teaching career as a lecturer in AIUB. At present he is serving as an Associate Professor and Director of the Faculty of Engineering in the same university. He also worked as the Special Assistant of Office of Student Affairs (OSA) from December 2012 to till September 2018. Mr. Zishan has published more than 50 articles in different journals and international and national level conferences. His research interest includes e-Health, wireless Communication, Signal Processing, Telemedicine and Robotics. Mr. Zishan is a member of the Institute of Electrical and Electronics Engineers (IEEE) and Institution of Engineers, Bangladesh (IEB).