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Original Article

Frequency Stabilization in Hybrid Microgrid Systems Implementing PSO and Firefly Algorithm Tuned PID Controllers

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Abstract - *Alternative energy sources are gaining interest due to their affordability and sustainability. Energy derived from renewable sources is increasingly essential to electrical grids. Different sources of energy, for example, systems that store energy in batteries, electric cars, electrolyzers, fuel cells, and Photovoltaic (PV) panels, are integrated into multi-area electrical systems through frequency regulation of the load. Microgrids have significant frequency and power stability limitations due to their reliance on sustainable power sources. The fluctuating demand patterns and the inherent uncertainty of renewable energy sources intensify this challenge. Employing Proportional Integral Derivative (PID) controllers, which are calibrated using various techniques, mitigates power and frequency fluctuations. A comparison is made between linear controllers fine-tuned using Particle Swarm Optimisation (PSO) and FFA by varying the size of the population for a fixed number of iterations. Controllers optimized with PSO demonstrate superior performance compared to those optimized with Firefly, exhibiting reduced peak deviations and abbreviated settling times.*

Keywords - *Hybrid Microgrid System, Fire Fly Algorithm tuned PID Controller (FFAPID), Load Frequency Control, Particle Swarm Optimization tuned PID Controller (PSOPID).*

1. Introduction

Adding green energy sources to modern power grids makes it harder to keep the load frequency stable, especially in two-area hybrid systems that are fully merged. Power and frequency variations are common in sustainable energy systems because of the unpredictability of renewable sources of energy. In these kinds of situations, microgrids can help with the energy management in the electrical power industry, featuring DC, AC, and AC/DC hybrid configurations. AC microgrids operate as independent grids in regions with inadequate electrical power provision. Heat pumps, freezer pumps and Electric vehicles are all examples of distributed energy utilities. The regulation of load frequency is essential for keeping the electricity grid reliable and regulating grid frequency so that it adapts to load variations. It is considered a fundamental function of power systems since it regulates frequency and prevents fluctuations in tie-lines [1]. Linking generated energy to demand, or LFC, is a paramount control problem. The performance of the electrical network deteriorates when load disturbances impact the exchange. The system's usual operating point is therefore modified by load disruptions [2]. Blackouts and cascade failures can happen in the electrical system if it is not managed carefully due to its complexity. The stability of the system is ensured by load frequency control, which regulates generator output and power and frequency balance. Microgrid frequency control systems, with an emphasis on hierarchical and decentralized approaches, are the subject of this article. It delves into cutting-edge control techniques, including adaptive control and AI/ML technologies, while tackling issues like communication latency, power fluctuations, and system inertia [3]. Controller design has garnered the attention of academics from several angles and is essential to the Hierarchical bi-level LFC system [4]. This article talks about how hybrid power systems are starting to rely more and more on Automatic Generation Control (AGC) methods, how to optimize these methods, the problems they face, the potential for study in this area, and why real-time control schemes are necessary [5]. WOA has the potential to improve the regulation of load frequency in renewable energy power plants, which would result in increased stability and responsiveness, as demonstrated by the work [6]. The Intelligent Energy Control System (IECS) for microgrids provides further assurance of efficient, sustainable, and dependable operation by means of sophisticated coordination and load control [7]. Frequency stability is an essential component in terms of running a microgrid, particularly when intermittent sustainable power sources like solar photovoltaics are included in the system. Based on the findings of research, it has been determined that frequency fluctuations may be reduced by including energy storage technologies. Moreover, consistent power generation and frequency stability can be facilitated by fuel cells, aqua electrolyzers, biogas generators, and biodiesel generators.

The Mayfly Optimization Algorithm-Based PID Controller, which offers better performance, less overshoot, and enhanced dynamic response, is used in [8] to introduce a novel approach to preserving frequency stability in networked microgrid systems. A Combined PID Regulator with 2-DoF, sometimes referred to as a 2-DoF Controller, is presented in this work to automate generation control in wind-integrated linked power systems. This controller was developed to achieve the aforementioned objectives, which include enhancing the efficiency and robustness of the system, as well as making it a trustworthy choice for future smart grids [9]. Current and fractional-order PID controllers are the focus of this research because of their potential applications in keeping power systems' load frequencies constant. This work focuses specifically on the improved performance of these controllers when compared to typical PID controllers [10]. This research proposes a new control strategy for wind-powered AC/DC power systems.

The Fuzzy-PID controller is changed using the Arithmetic Optimisation Algorithm [11]. Regulating the frequency of loads in power networks that rely on renewable energy sources, the paper [12] presents a hybrid fuzzy logic controller that improves performance by lowering frequency deviations, settling periods, and damping. The PSO-GSA hybrid is one method for improving automated load frequency management in the dynamically connected power systems, a method detailed here. It exhibits better damping properties and superior dynamic performance [13]. Electric cars, wind turbines, and diesel generators are all part of a hybrid microgrid system. Microgrid frequency stability may be enhanced by integrating electric automobiles, wind turbines, and controllers adjusted using the Smell Agent Optimization Algorithm [14]. The research [15] examines the effects of solar photovoltaic integration on system performance utilizing conventional controllers within a microgrid framework described in [14], with an emphasis on frequency management.

A PID controller optimized using the Firefly Algorithm is proposed for load frequency management, demonstrating superior performance and robustness across various demand conditions in [16]. The research gap indicates that, although numerous metaheuristic algorithms (such as PSO, FA, GA, WOA, AOA, etc.) have been investigated for microgrid frequency regulation, there exists a paucity of comparative analysis between PSO- and FA-tuned PID controllers within a hybrid microgrid that uses multiple renewable sources in two areas (including PV, wind, EVs, fuel cells, etc.). A grid-connected microgrid with PV, wind, and biodiesel generators-supported by adjustable loads like heat pumps and PHEVs-is shown in this work with frequency stabilization. Metaheuristic algorithm-tuned PI/PID controllers are used in a Virtual Power Plant (VPP) coordinated control scheme [17]. Concentrates on a hybrid optimization technique (FF-PSO) for PID tuning in microgrids. The system includes wind turbines, fuel cells, diesel engines, flywheels, and batteries for energy storage [18]. A mixed microgrid is used to directly evaluate two PID controllers that have been enhanced with the Firefly Algorithm (FA) and Particle Swarm Optimisation (PSO). A comprehensive analysis of renewable integration challenges in multi-area hybrid microgrids, focusing exclusively on the comparison between PSO and FA-tuned PID controllers. The present research compares the Firefly-tuned PID controller with the particle swarm optimization-tuned PID controller in regulating frequency and power fluctuations inside a proposed microgrid system that integrates many energy sources, including a first-order solar PV system.

2. An Interconnected Micro Grid System's Generalized Block Diagram

The use of multi-layered control structures in Load Frequency Control (LFC) [13] methods has been the subject of much research. Nevertheless, suboptimal controllers frequently fail to achieve zero steady-state error. In order to get around this restriction, scientists have created finite-time optimal control techniques that provide zero steady-state error. System functioning is guaranteed even in the event of control level failures, thanks to the hierarchical architecture of control levels. Additionally, global controllers have shown encouraging results when using the advantages of connectivity. In order to reduce control effort in multi-area power systems, a unique perturbation strategy has been utilized. Incorporating the controllers of the fast and slow subsystems results in the overall control strategy, each of which has its own controller. The microgrid system with two areas interconnected is depicted in Figure 1, which is a typical block schematic.

3. Proposed Hybrid Microgrid System

A frequent auxiliary power source in marine microgrids is Ship Diesel Generators (SDGs) [17, 18]. These generators are known for their efficiency, low maintenance requirements, and ability to reduce unstable oscillations. A three-pronged approach describes the current status of electric vehicles: operational, charging, and regulated. The high output and energy capacity of controllable EVs limit their ability to charge and discharge [19-21]. Microgrid systems that are energy efficient are the focus of this research. Examples of such systems include fuel cells, aqua-electrolyzers [22, 23], and small-scale diesel generators [17]. Advantages of these systems include better energy efficiency, higher reliability, and quick startup.

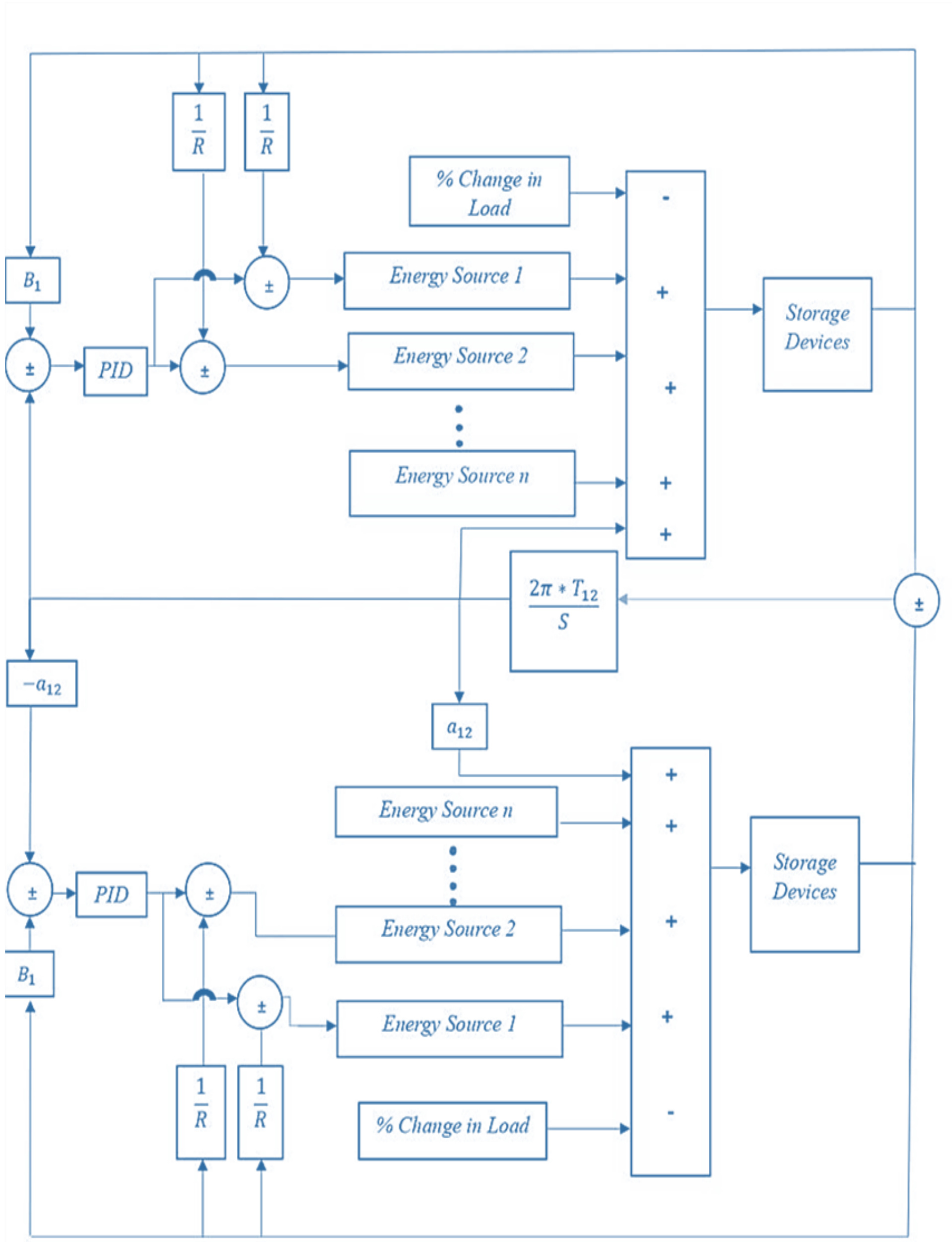

Fig. 1 Schematic for an interconnected microgrid system spanning two areas

Generators fuelled by biodiesel [24], wind turbines and biogas plants are an eco-friendly and renewable energy source to smooth out power spikes and dips; they employ energy storage [22] devices like batteries and photovoltaic systems [25]. Figure 1 presents a schematic block design for the proposed interconnected microgrid system. In order to stabilize disruptions in a microgrid system that spans two areas utilizing traditional control techniques, this study employs a PID controller. Variations in frequency and tie-line power exchange are taken into account when analyzing the system's performance using the Area Control Error (ACE) [14] statistic. The PID controller offers the fastest response time, reduces oscillations, and enhances stability through the use of derivative control action. Efficiently minimizing the associated squares of frequency fluctuations and twinning Power to lessen the performance index Jmin and raise the system's overall efficiency [16].

$$J_{\min} = \int_0^{Time} \{\Delta f_1^2 + \Delta f_2^2 + \Delta P_{tie}^2\}\, dt \qquad (1)$$

Where

Δf_1 and Δf_2 are used to describe the differences in power along the connection lines between the two linked regions and the frequency changes between regions 1 and 2.

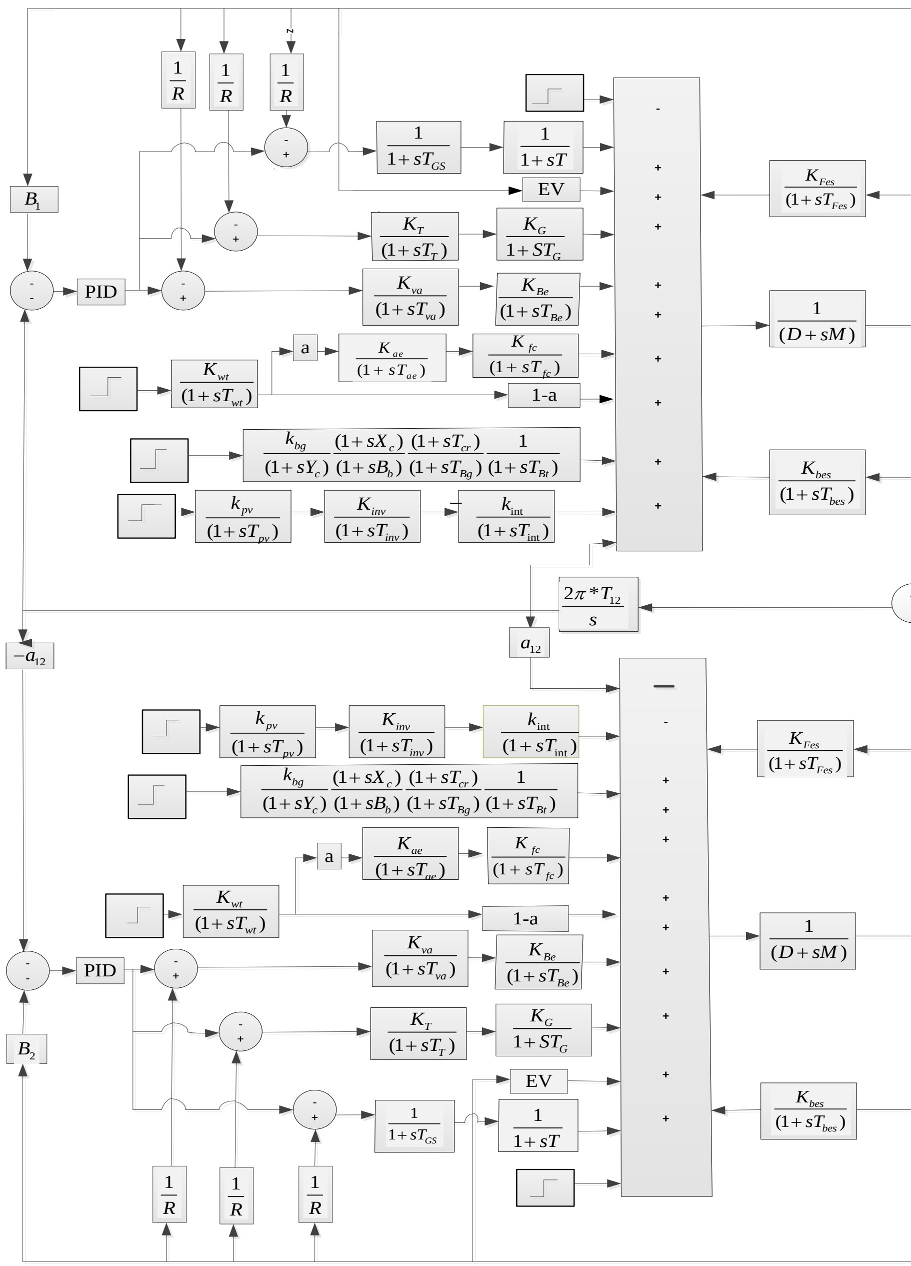

Fig. 2 Proposed two-area interconnected micro grid system

4. Particle Swarm Optimization for Hybrid Microgrid Controllers

Particle Swarm Optimisation (PSO) is a type of optimization technique [26] that uses a search space simulation to uncover solutions inspired by bird flocks and fish schools. The optimal answer is determined by utilizing a swarm of particles. This algorithm operates on three principles: personal best memory, global best influence, and velocity and positioning update. PSO is used in control system tuning, machine learning, image processing, and engineering optimization. Position (x_i) and velocity (v_i) vectors are the search space's starting points. The current position and speed are determined by Equations 1 and 2, with C_1, C_2 representing acceleration coefficients and R_1, R_2 representing user-defined parameters.

$$v_i^{(t+1)} = x_i^{(t)} + C_1R_1\left(p_{Besti} - x_i^{(t)}\right) + C_2R_2\left(g_{Besti} - x_i^{(t)}\right) \quad (2)$$

$$x_i^{(t+1)} = x_i^{(t)} + v_i^{(t+1)} \quad (3)$$

The process flow diagram for solving the PSO algorithm is as follows.

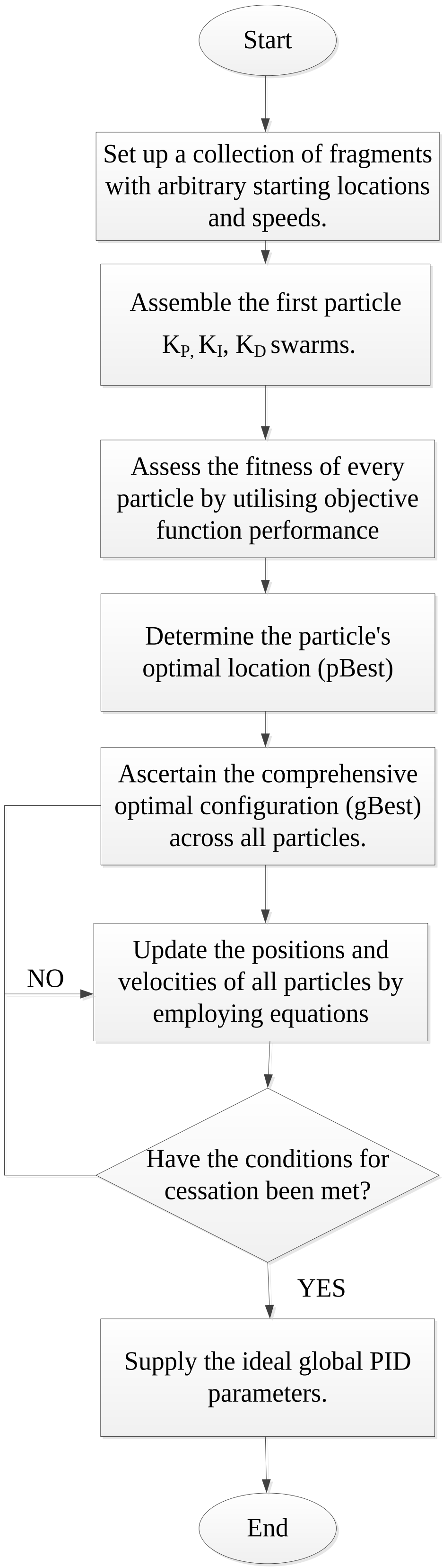

Fig. 3 PSO algorithm flowchart for tuning controllers in a hybrid microgrid system

The Firefly Algorithm (FFA) is one naturalistic optimization method that tackles complex issues by utilizing the social behaviour of fireflies [16]. Attraction, luminosity intensity, and random movement are its three primary governing principles. Many fields make use of the FA, such as optimization, benchmarking, networking, and image processing, among others. First, the algorithm generates a simple firefly population. Then, it uses PID parameters to evaluate fitness. Finally, it changes the light intensity of the fireflies. In order to discover the global optimum that applies to all generations, iterations are reached. To determine how far apart fireflies are, scientists utilize the Cartesian distance measure, which accounts for the fact that the insects' attractiveness diminishes with increasing distance. Using collective activities to handle complicated situations, the FFA is similar to other swarm intelligence approaches.

```
1. Initialize FA parameters:
     - Population size n (number of fireflies)
     - Maximum iterations MaxIter
     - Light absorption coefficient γ
     - Randomization parameter α
     - Attractiveness β0
     - Search space bounds for Kp, Ki, Kd

2. Generate initial population of fireflies:
     For each firefly i = 1 to n:
         Randomly initialize (Kp_i, Ki_i, Kd_i)
         Evaluate fitness J_i using system model

3. While (iteration < MaxIter):
     For each firefly i:
         For each firefly j:
             If (J_j < J_i):   // firefly j is brighter
                 Move firefly i towards firefly j:
                     (Kp_i, Ki_i, Kd_i) = (Kp_i, Ki_i, Kd_i)
                                          + β * (Kp_j - Kp_i, Ki_j - Ki_i, Kd_j - Kd_i)
                                          + α * random_step
                 Ensure bounds are respected
                 Recalculate fitness J_i

     Update best solution found so far

4. Return PID parameters (Kp_best, Ki_best, Kd_best)
```

Fig. 4 Pseudo code for firefly algorithm tuned PID controllers

```
Input: Objective function J (e.g., Integral of Squared Error of system response)
Output: Optimal PID parameters (Kp, Ki, Kd)

1. Initialize PSO parameters:
     - Swarm size n (number of particles)
     - Maximum iterations MaxIter
     - Inertia weight w
     - Cognitive coefficient c1
     - Social coefficient c2
     - Search space bounds for Kp, Ki, Kd

2. Generate initial swarm:
     For each particle i = 1 to n:
         Randomly initialize (Kp_i, Ki_i, Kd_i)
         Initialize velocity Vi
         Evaluate fitness J_i
         Set personal best pBest_i = (Kp_i, Ki_i, Kd_i)
     Identify global best gBest among all particles
```

(a)

```
3. While (iteration < MaxIter):
       For each particle i:
           Update velocity:
               Vi = w * Vi
                    + c1 * rand() * (pBest_i - Xi)
                    + c2 * rand() * (gBest - Xi)
           Update position:
               Xi = Xi + Vi
           Ensure bounds are respected
           Evaluate new fitness J_i
           If (J_i < fitness(pBest_i)):
               Update pBest_i = Xi
           If (J_i < fitness(gBest)):
               Update gBest = Xi

4. Return PID parameters (Kp_best, Ki_best, Kd_best = gBest)
```

(b)

Fig. 5(a), and (b) Pseudo code for PSO algorithm tuned PID controllers.

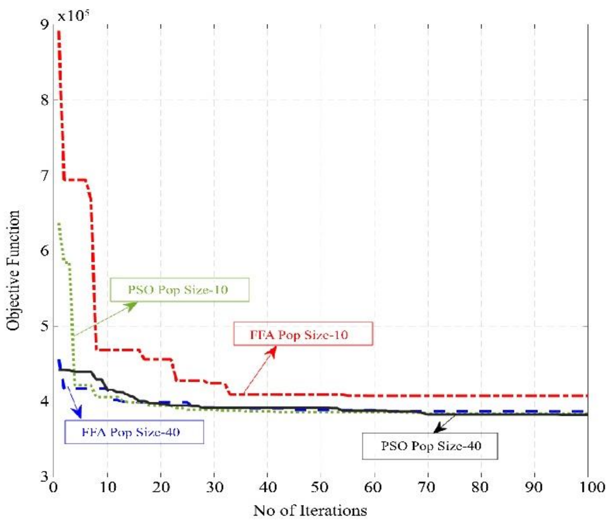

Fig. 6 Convergence of FFAPID and PSOPID controllers for different population sizes, 10 and 40

5. Analysis of Results for Proposed Hybrid Microgrid System

This case study examines a 2% step change in natural disruption for both locations. The conventional PID controller was optimized with the Firefly Algorithm (FFA) and Particle Swarm Optimisation (PSO) method, utilizing population sizes of 10 and 40 over 100 iterations. Pictured in Figure 6 are the objective function optimization curves for FFAPID and PSOPID, two PID controllers that use Particle Swarm Optimisation, with populations of 10 and 40, respectively. The parameters for the Firefly algorithm, tuned and PSO-tuned PID controllers for 100 iterations with population sizes 10 and 40 are included correspondingly in Tables 1 and 2. The frequency deviations for Area 1 with a PID controller optimized using PSO are displayed in Figures 7 and 8, whereas the frequency deviations for Area 2 with a population size of 10 and 2% Step Natured Disturbance are displayed in Figure 9. Additionally, the inter-tie line power deviation is displayed.

Table 1. Shows the optimal PID control unit designs for FFA

Controller/Parameters	FAPID	PSOPID
K_{P1}	28.299	17.9576
K_{I1}	0.8919	0.9200
K_{D1}	5.0028	5.0236
K_{P2}	17.3850	22.1823
K_{I2}	0.7730	0.5434
K_{D2}	4.3652	4.6301

Table 2. The configurations of the FFA and PSO optimized PID control units for a population size of 40

Controller/Parameters	FFAPID	PSOPID
KP1	21.2840	18.4671
KI1	0.9747	1.0000
KD1	4.7340	4.9886
KP2	22.1121	22.8515
KI2	0.6021	0.8562
KD2	4.9651	4.7119

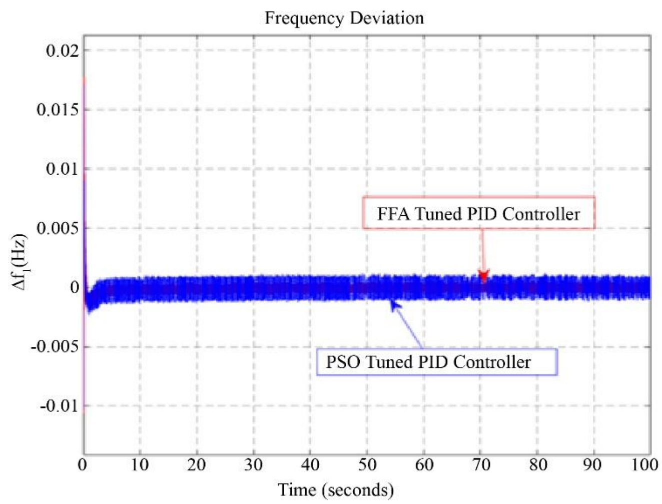

Fig. 7 Examination of frequency fluctuations in Region-1 employing FFAPID and PSOPID controllers having a population size of 10

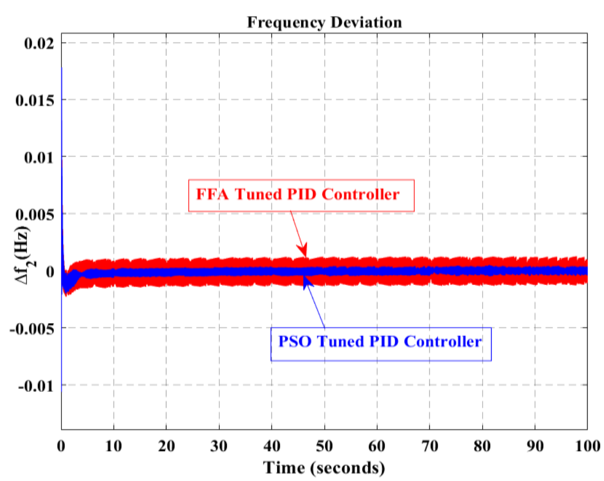

Fig. 8 Examination of frequency fluctuation in Region-2 employing FFAPID and PSOPID controllers having a population size of 10

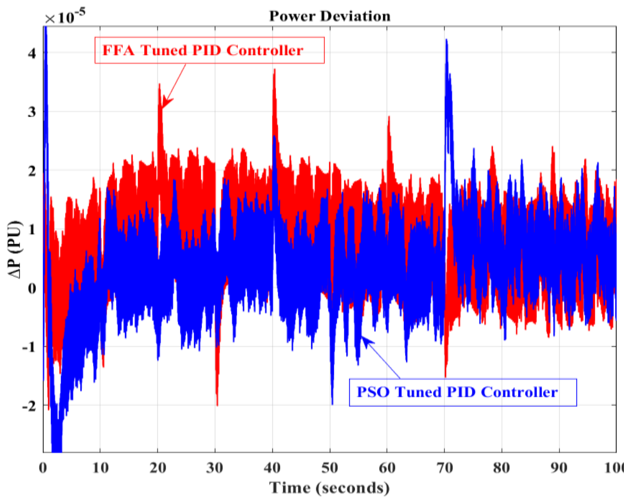

Fig. 9 Analyzing the variation of power deviation in the tie line with FFAPID & PSOPID for population size 10

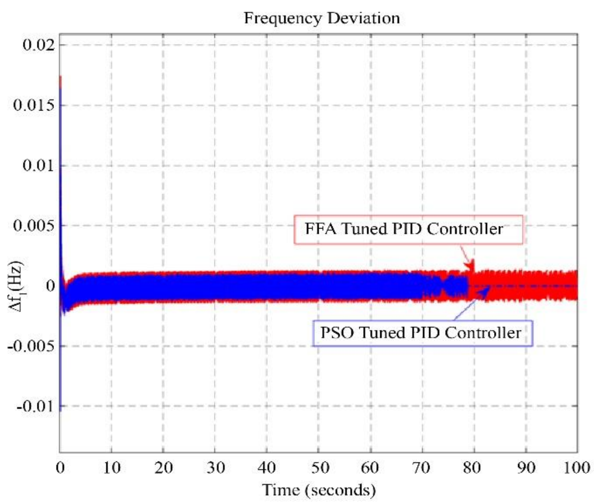

Fig. 10 Analysis of variations in Area-1 relating to frequency deviation employing FFAPID and PSOPID controllers having a population size of 40

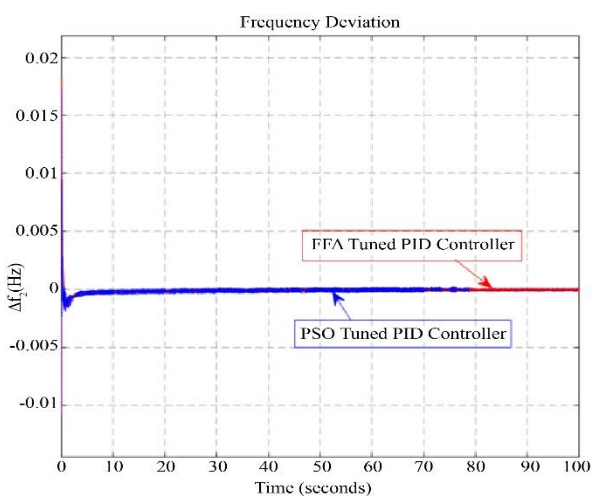

Fig. 11 Analysis of Area-2 frequency deviation fluctuations with FFAPID and PSOPID controllers and a 40-Swarm population

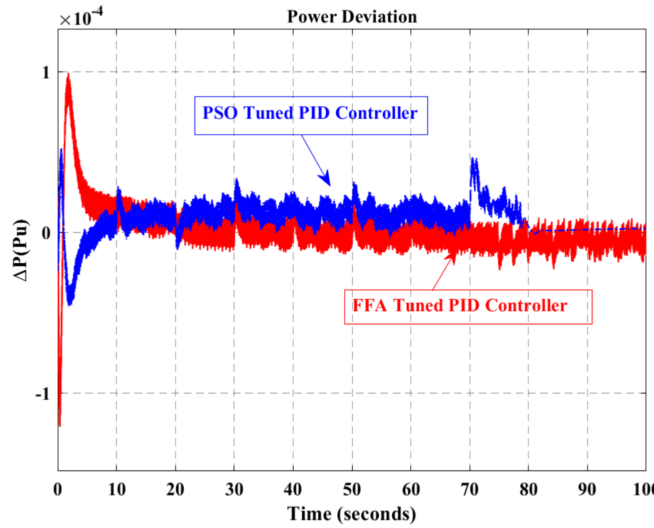

Fig. 12 Change in power deviation in the tie line compared to FFAPID and PSOPID for a representation size of 40

Two regions' frequency variations are shown in Figures 10 and 11 when adjusted using Firefly and PSO methods for the PID controller utilized in the suggested system of linked micro grids in two areas. Change in Power in the tie line is seen in Figure 12. Figures show that the PSO optimized controller outperforms the Firefly PID controller for both population sizes, 10 and 40. With a population size of forty, the tuning controller shows less variation in both regions' frequency and tie line power changes.

Table 3. Evaluation of performance metrics with FFA and PSO optimized PID control units

Performance Metric	FA-Tuned PID	PSO-Tuned PID
Frequency Overshoot (Hz)	0.008	0.004
Frequency Settling Time (Sec)	70	40
Inter Tie-ine Power (PU)	3*10-5	1*10-5

6. Conclusion

The recommended approach is in a two-area connected microgrid that incorporates several sources of renewable energy, with electric cars, wind turbines, solar photovoltaic systems, and fuel cells. Research addresses issues with electricity stability and frequency. PID controllers were modified utilizing the Firefly Algorithm (FFA) and Particle Swarm Optimisation (PSO) to govern the system's reaction to step load disturbances.

According to simulation results, PSO-optimized controllers outperformed their FFA-tuned counterparts. In particular, PSO facilitated shorter settling times, decreased Power variations in tie-line variations, and decreased peak frequency variations. The system demonstrated better dynamic behavior and improved frequency regulation with a population of 40. This suggests that in swarm-based optimization, higher population numbers lead to improved controller tuning.

All things considered, PSO is a more reliable and successful method for maximizing PID parameters in intricate microgrid systems. Only simulation-based evaluations of PID controllers that have been tuned for FA and PSO are included in this study; real-time or hardware validation is not. Future studies on hybrid microgrids will concentrate on empirical testing and sophisticated optimization techniques. The results lend credence to the incorporation of intelligent optimization strategies for the stable and dependable operation of microgrids with a high proportion of renewable energy. Altering microgrid configurations to employ second-order solar PV systems rather than first-order ones and supplanting traditional controllers with higher-order ones are potential areas for future research.

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Appendix

Table 4. System parametric values and nomenclature [16]

Representations	Details	Mathematical Values
T_{Gs}, T, and R_s	The ship's diesel generators' regulator settings and time-related variables	0.5, 0.25, 3 [14]
K_G, K_T, T_T, T_G, and R [14]	The diesel generator's gains, time limits, and governor metrics	1, 1, 0.1 s, 8 s, 2.5
K_{va}, K_{Be}, T_{va}, T_{Be}, and R	Benefits, time restrictions, and controller parameters of biodiesel power plant	1, 1, 0.05 s, 0.5 s, 2.4 [14]
[K_{bg}, X_c, Yc, T_{cr}, T_{Bg}, and T_{Bt}	Gain, reactance, admittance, and time constraints metrics of bio-gas turbine [14]	0.5, 0.6, 1, 0.05, 0.01 s, 0.23 s, 0.2 s
K_{ae} and T_{ae}	Aqua-electrolyzer's time and gain constraints	1/500, 0.5 s
K_{fc} and T_{fc}	Fuel cell's time and gain constraints	1/100, 4 s
Kbes and Tbes	Gain and time constraint of battery energy storage [14]	−1/300, 0.1 s
KFes and TFes	Gain and time constraint of the flywheel energy storage system [14]	−1/100, 0.1 s
T_{12}	Synchronizing power coefficient	0.0867s
Δ	Change	-------
K_{pv} and T_{pv}	Gain and time constant of PV system [14]	1.8s,1
K_{inv} and T_{inv}	Gain and time constant of the inverter [14]	0.04,1
K_{inc} and T_{inc}	Gain and time constant of the interconnected system [14]	0.004,1