Frequency Regulation of Interlinked Microgrid System Using Mayfly Algorithm-Based PID Controller

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Abstract: The primary goal of this article is to design and implement a secondary controller with which to control the system frequency in a networked microgrid system. The proposed power system comprises of Renewable energy sources (RESs), energy-storing units (ESUs), and synchronous generator. RESs include photovoltaic (PV) and wind turbine generator (WTG) units. The ESU is composed of a flywheel and a battery. Because renewable energy sources are not constant in nature, their values fluctuate from time to time, causing an effect on system frequency and power flow variation in the tie line. The nonlinear output from the RESs is balanced with the support of ESUs. In order to address this situation, a proportional integral derivative (PID) controller based on the Mayfly algorithm (MA) is proposed and built. Comparing the responses of controllers based on the genetic algorithm (GA), differential evolution (DE), and particle swarm optimization (PSO) technique-optimized to demonstrate the superiority of the MA-tuned controller. The results of the validation comparisons reveal that the implemented MA-PID controller delivers and is capable of regulating system frequency under various load demand changes and renewable energy sources. A robustness analysis test was also performed in order to determine the effectiveness of the suggested optimization technique (1%, 2%, 5%, and 10%) step load perturbation (SLP) with ±25% and ±50% variation from the nominal governor and reheater time constant).

Keywords: frequency deviation; load frequency control; Mayfly algorithm; PID controller; secondary control

1. Introduction

The installation of renewable energy sources addresses the problems caused by conventional energy sources in the environment during electric power generation and the matching of sudden load-demand situations. Pollution (air, water, and noise) and global warming are major issues for the environment, and one source of pollution is electric power generation. The traditional techniques of generating electricity cause environmental degradation. In order to reduce pollution, RESs (solar and wind power plants) are being introduced into the power generation sector. One of the key causes for the penetration of RESs is the shortage of fossil fuels. The inclusion of RESs is a difficult undertaking because RESs are typically nonlinear power-generation sources. When incorporating RESs into the electricity grid, numerous quality challenges arise—notably, the oscillation of system frequency. In order to overcome this crisis, the load frequency control (LFC) method is used to maintain frequency standards in the power system, and a secondary controller must be implemented into the scheme in order to preserve frequency stability [1–3]. In particular, the secondary controller maintains the frequency stands and important parameters within
the predetermined standard values (settling time and stability). The settling time is the time required to bring the frequency oscillation to a predefined value. Stability is maintaining the retained standard values in the system frequency at sudden loading conditions.

Many authors have researched these problems, and the results of their research are mentioned in the literature review. The frequency stability of an isolated microgrid (MG) system was investigated in [1] using a coefficient diagram approach—a PID accelerator controller, and its performance, was compared with published PID and 2DoF-PID controllers. The author in [2] discussed and designed a fuzzy PID controller as a secondary controller for a multimicrogrid, and the result of a conventional PID controller was used for comparison, in order to validate the supremacy of the proposed controller. In the work of [4], the fuzzy tilt integral derivative controller was used for frequency stabilization in a hybrid MG, and the improvement of the proposed controller was proven from the result comparison between the classical PID and fuzzy PID controllers. The author of [5] invented the Slap Swarm Optimization (SSO) technique-adjusted cascade (PI-PD) controller in order to regulate the system frequency of an MG with an electric car, and a robustness test was conducted. The author of [3] used a self-tuned FPID in order to study solar- and wind-integrated microgrids. In the work of [6], a renewable energy-based microgrid combined with a pumped energy storage unit was subjected to LFC via an artificial sheep algorithm-calibrated PI controller, and a robustness test was conducted for feasibility. In the work presented in [7], a PI controller examined a distributed generation (DG) system with a wind turbine generator, and the Ziegler–Nichols method response was compared with that of the proposed controller for supremacy. The author of [8] investigated an interconnected microgrid using a multiverse optimization-based FPID controller, and fuzzy PID and PID controller responses were compared with the proposed controller. The author of [9] proposed a novel chaotic crow search algorithm for a hybrid microgrid, and the conventional integral controller was utilized for the result comparison. The performance of a PSO-PID controller, built by the author for a microgrid [10], was compared with a conventional PID controller to demonstrate the supremacy of the PSO-PID controller. In the work discussed in [11], a modified black hole optimization approach based on a multi-objective fractional-order fuzzy PID was devised, and the real-time data were compared with the proposed controller’s performance.

In the work of [12], the author investigated a single-area multisource power system for LFC using PSO-PID controller, and the response was compared with the conventional, GA and DE algorithms to show the supremacy of the proposed controller. The performance of the grey wolf optimization (GWO) approach-adjusted PID controller was implemented in a microgrid integrated with a thermal power plant in [13], and the genetic algorithm, PSO, and ACO technique-tuned PID controller results were compared with those of the proposed controller. In the work of [14], multivariable generalized predictive control theory was used in order to implement LFC in MG (wind + EV). This study also included the performance of PID and fuzzy controllers for the supremacy of the proposed controller. The author of [15] presented a moth–flame optimization method-based FPID controller for a microgrid, for which the fusibility of MFO-FPID controller results were compared with those of classical controllers. In the work of [16], an imperialist competitive algorithm (ICA)-tuned cascade controller (c-PIDF) was implemented as a supplementary controller in a microgrid. In order to justify the efficacy of the ICA-cPIDF controller, its performance was compared with genetic algorithm- and cuckoo search algorithm-based controllers. A PSO-PID controller was used in order to study RESs integrated with a multisource power grid in [17]. In order to justify the improvement of the PSO-PID controller, the results were compared with those of the conventional PID controller. A cascade PI-TID controller was deployed as a supplementary controller in an isolated microgrid consisting of wind, biogas, and biodiesel power sources, which is optimized by the Harris hawks optimization technique [18], and the performance results were compared with those of TID and PID controllers. In the work of [19], an arithmetic optimization algorithm-tuned fuzzy PID controller was utilized for the LFC of a wind-integrated power grid. In the work presented
in [20], the performance of a hybrid microgrid was investigated by ACO-PID controller, and its performance was compared with that of the conventional method PID controller. In the work of [21], a wind power-based hybrid power system with a moth swarm algorithm-based PID controller was examined for LFC, and this study was extended to with/without SMES performance analysis. In the work of [22], the MA-PID controller was implemented in a standalone power network as a tributary controller. The superiority of the Mayfly algorithm was justified by the result comparison of the GA and PSO techniques. The Mayfly algorithm was used in a variety of applications, including proton exchange membrane fuel cell modelling [23,24]. In the work of [25], MPC was used to forecast the microgrid. The author in [26] used the WHO approach to maintain voltage stability in the power supply. In [27], ANN was used to improve the stability of a wind-farm-integrated power grid. In [28] author used hPSO and GWO to analyse the performance of a PV panel.

The response of a multimicrogrid was evaluated by the atom search optimization (ASO)-adjusted PID controller, and the results were compared with GA and PSO-PID controllers by the author in [29]. In the work presented in [30], the Ziegler–Nichols approach-tuned PID controller was used as a subordinate controller for a stand-alone microgrid system including with wind farm and an MPPT-based solar plant. The SSO-FPID controller developed in [31] was used for the LFC of a microgrid made up of solar PV, wind turbine, biogas, and biodiesel units, to regulate system frequency. Its performance was superior to that of a traditional PID controller. In the work of [32], the author constructed a PID controller tuned by the Honey Badger Algorithm (HBA) for a microgrid that included PV, wind turbine, biogas, and biodiesel units. A law-based sliding mode controller was constructed for the LFC of a microgrid (wind/hydrogen/battery DC microgrid), and a comparison study demonstrated the dominance of the proposed controller [33].

In the renewable energy sources are installed in many places, for example, in Nepal, 3 kW [34] and 3000 MW [35] solar power plants are being installed [36]. A comparative literature survey is presented in Table 1, in an attempt to analyse the research gap in the LFC of microgrids.

### Table 1. Comparative literature survey.

<table>
<thead>
<tr>
<th>Ref. No</th>
<th>Optimizer</th>
<th>Controller</th>
<th>Control Area</th>
<th>Source</th>
<th>Comparative Study</th>
</tr>
</thead>
<tbody>
<tr>
<td>[9]</td>
<td>Chaotic crow search algorithm</td>
<td>PID</td>
<td>two areas MG</td>
<td>Thermal, solar, wind, EV, ESS</td>
<td>Conventional PID</td>
</tr>
<tr>
<td>[10]</td>
<td>Particle swarm optimization</td>
<td>PID</td>
<td>Isolated MG</td>
<td>PV, wind, FC, BESS</td>
<td>Conventional PID</td>
</tr>
<tr>
<td>[16]</td>
<td>Imperialist Competitive Algorithm</td>
<td>PID</td>
<td>multi-MG</td>
<td>Thermal, DEG, FESS, BESS</td>
<td>GA and CSA-PID</td>
</tr>
<tr>
<td>[17]</td>
<td>Particle swarm optimization</td>
<td>PID</td>
<td>Single area</td>
<td>Thermal, solar, wind</td>
<td>Conventional PID</td>
</tr>
<tr>
<td>[18]</td>
<td>Harris hawks optimization</td>
<td>PI</td>
<td>Isolated MG</td>
<td>PV, wind, biogas, biodiesel</td>
<td>GOA, CSA and GA-PID</td>
</tr>
<tr>
<td>[20]</td>
<td>Ant colony optimization</td>
<td>PID</td>
<td>hybrid MG</td>
<td>Thermal, FC, HAE, ESS</td>
<td>Conventional-PID</td>
</tr>
<tr>
<td>[22]</td>
<td>Mayfly Algorithm</td>
<td>PID</td>
<td>Single area</td>
<td>Thermal, hydro, gas</td>
<td>GA, PSO-PID</td>
</tr>
<tr>
<td>[29]</td>
<td>Ziegler Nichols</td>
<td>PID</td>
<td>Multi-MG</td>
<td>PV, wind, diesel</td>
<td>GA, PSO-PID</td>
</tr>
<tr>
<td>[30]</td>
<td>Slap swarm optimization</td>
<td>FPID</td>
<td>Isolated MG</td>
<td>PV, wind, biogas</td>
<td>SSO-PID</td>
</tr>
<tr>
<td>[32]</td>
<td>Honey Badger Algorithm</td>
<td>PID</td>
<td>Isolated MG</td>
<td>PV, wind, biogas, biodiesel</td>
<td>Conventional-PID</td>
</tr>
<tr>
<td>[33]</td>
<td>Quick reaching law</td>
<td>PID</td>
<td>Isolated MG</td>
<td>Wind, battery</td>
<td>Conventional-PID</td>
</tr>
</tbody>
</table>
The process of identifying gaps in the existing research effort is known as a literature review. The review in this study reveals that the penetration of RESs in the power-generating sector has recently increased. The implementation of RESs is fraught with difficulties. Wind, PV, energy storage devices, and other components comprise the MG power system/hybrid power system. Maintaining system stability is critical when integrating RESs into the existing power grid. In this regard, numerous academics have created a variety of secondary controllers, and computational/optimization procedures have been suggested for the optimization of the controllers’ parameters. Finally, in this study, an MA-adjusted PID controller was proposed and implemented.

1.1. Research Gap and Motivation

Conventional power systems and renewable energy sources are applied to generate the required electric power for all consumers with good quality. However, recently, air pollution and shortages of raw material power generation have moved the focus from conventional sources to renewable energy sources for generating electric power for consumers. Additionally, renewable-based generating power is integrated with conventional power through the design of a microgrid system to balance load demand. The possible solutions are discussed and presented in the above literature review section, as well as in Table 1. Whenever rapid load demand arises in the microgrid, fluctuations in system frequency and produced voltage impact the quality of generated electricity. In order to overcome these issues, several secondary controllers and energy storage techniques have been designed and effectively implemented. The designers of the secondary controller utilized several optimization techniques to obtain controller gain values with a suitable cost function. In order to overcome the drawbacks of conventional power systems and the requirement of a secondary controller in this proposed article, a microgrid system was designed (conventional + renewable energy source + energy storage system) with a secondary (PID) controller for frequency stabilization during emergency load situations.

The foremost objective of the studies presented in the literature review section was to reduce time domain specification parameters (settling time, steady state error, peak over, and undershoot) in power generating systems during unexpected load changing situations. Based on that, any algorithm-based controller does not provide a better-controlled response. Therefore, the design of a suitable controller with superior optimization is required for better LFC performance in power systems during sudden load demand conditions. The MA is a recently developed optimization technique, and is an easily implemented method for solving both continuous and discrete problems. Similarly, this algorithm rarely becomes stuck in local optimum points [34]. The major advantages of the proposed MA is, it has fast convergence rate, nuptial dance and random flight, which improve the balance between exploration and exploitation. Based on this potential, the MA technique is utilized for the design of a PID controller in the proposed microgrid/multigrid for performance improvement.

1.2. Innovation of the Article

The Mayfly algorithm is a well-known and efficient optimization tool for solving complex real-time optimization problems. In this work, the Mayfly algorithm is utilized to tune the controller parameters in a microgrid/multimicrogrid power system in order to provide quality power to consumers during sudden load demand situations.

1.3. The Main Contribution of the Article

• Developing a microgrid and a multimicrogrid incorporated with RESs (PV and wind) and an energy storage system;
• Developing a suitable secondary controller (PID) for the proposed power system;
• Utilizing the projected Mayfly algorithm for controller gain parameter tuning in order to regulate the system’s operation during sudden load demand situations;
• Explaining the enhanced response of the MA-optimized controller (over the GA, PSO, and DE method-designed controllers);
• Conducting robust and sensitivity analyses in order to demonstrate the supremacy of the proposed algorithm for tuning the gain values of the controller in certain situations.

1.4. Implication of the Article

• Investigating the RES-based microgrid;
• Utilizing the Mayfly algorithm in order to optimize the proposed auxiliary controller;
• Providing both SLP and random load pattern (RLP) load interruption to the system, and the response comparison against the GA, PSO, and DE techniques. Also, robustness test conducted to prove the reliability of the MA-PID controller.

2. Proposed System Modelling

In this section, the designs of the proposed isolated microgrid and an interconnected microgrid are discussed.

2.1. Microgrid (MG)

A microgrid is created by combining thermal, PV, wind, and energy storage systems (BESS, FESS). The governor and turbine are part of the thermal power plant. Figure 1 depicts the general construction of an alternating current (AC) microgrid. The Appendix A contains the nominal parameters of the proposed system model [37]. The mathematical function of the proposed system model is provided in Equations (1)–(7), and the transfer function model of the investigated system is presented in Figure 2 [37]. In Figure 2, B denotes the biasing constant, R represents the regulator constant, del P is the small load disturbance, f represents the system frequency, and Δf denotes the change in frequency.

![Diagram of AC microgrid components]

Figure 1. The general structure of an AC microgrid.
2.2. Thermal Power Plant

Mechanical power is generated in a thermal power plant using steam power, a reheater unit, and a turbine. The generator uses this spinning power to generate electricity. The governor of a steam turbine is one of the primary components that controls and regulates the turbine’s speed depending on feedback response. The governor output signal regulates the flow of steam to the turbine by controlling the position of the nozzles in the turbine [13]. The Laplace function of the units in a thermal power plant is provided in Equations (1) and (2). $T_g$ and $T_t$ are denoted as the governor and turbine time constants, respectively [10].

\[
\text{Governor (Thermal power system)} = \frac{1}{1 + sT_g} \quad (1)
\]

\[
\text{Turbine (Thermal power system)} = \frac{1}{1 + sT_t} \quad (2)
\]

A wind farm refers to a group of windmills. Wind energy is a zero-emission energy source for generating electricity. Wind turbines transform wind energy into electricity by using the force of the rotor blades, which act similarly to the rotor blades of an aircraft. The air pressure difference between the sides of the blade causes lift and drag. The rotor is either directly connected to the generator, or connected via a series of gears, which aid in increasing the generator’s speed [21]. The transfer function model of the wind turbine is shown in Equation (3). In Equation (3), $T_{WTG}$ represents the wind turbine generator time constant [38].

\[
\text{Wind energy turbine} = \frac{1}{1 + sT_{WTG}} \quad (3)
\]

2.3. PV System

The transfer function model of the PV system is depicted in Equation (4). Solar power is one of the key power sources used to balance load requests in the MG power system, and it is also a readily available supply. The solar cell in the PV system converts sunlight into usable electrical power. PV does not require any fuel to generate power and produces no noise, air, or water pollution [17]. The time constant of the PV system is denoted as $T_{PV}$ in Equation (4).

\[
\text{PV system} = \frac{1}{1 + sT_{PV}} \quad (4)
\]
2.4. Energy Storage Units

The energy storage system aids in the improvement of microgrid stability under high-load scenarios. It mitigates the negative impact of wind, solar, and other intermittent energy sources, while improving grid capacity [27]. In this proposed work, battery energy and flywheel energy storage systems are implemented in order to store the energy during nominal/minimal load demand conditions. The transfer functions are provided in Equations (5) and (6).

\[
\text{Battery energy storage system} = \frac{1}{1+sT_{\text{BESS}}} \tag{5}
\]

\[
\text{Flywheel energy storage system} = \frac{1}{1+sT_{\text{FESS}}} \tag{6}
\]

In the above equation, \(T_{\text{BESS}}\) is the time constant of the battery energy storage system, and \(T_{\text{FESS}}\) represents the time constant of the flywheel energy system.

2.5. Multi-MG

In order to increase the system’s power capacity, MGs are linked using a tie line. By consuming electricity from the isolated MGs, the tie line, also known as the grid line, balances the load demand in the grid line. A multi-MG (MMG) is conceived and created in this work by linking two isolated MGs. Figure 3 [37] depicts the mathematical function of the multi-MG.

![Figure 3. Transfer function model of the multi-MG.](image)

3. Controller Design and Methodology

3.1. PID Controller

The secondary controller is critical for implementing the LFC scheme in the power system. Because power systems include a primary controller, known as a speed regulator, they are not always reliable in loading circumstances. When unexpected loading occurs in the power system, it takes a long time to stabilize the system. In order to address this...
issue, a secondary controller is designed and installed in the power system. The PID controller is utilized as a supplementary controller. The PID controller comprises three distinct controllers, each with its own control action. The steady-state error is reduced by the proportional controller, eliminated by the integral controller, and maintained by the derivative controller. The PID controller transfer function is presented in Equation (7) [13].

\[ G_{PDS}(s) = K_p + \frac{K_i}{s} + K_ds \]  

(7)

where \( K_p, K_i, \) and \( K_d \) are the proportional, integral, and derivative controller gain parameters, respectively.

3.2. Mayfly Algorithm

Mayflies are insects of the Ephemeroptera order, which is the oldest group of insects. They are mainly visible in the UK throughout May, which is where their name comes from. This algorithm was motivated mostly by the behaviour of adult mayflies (which includes crossover, mutation, swarming, nuptial dance, and random walk). Two sets of mayflies are initially generated at random to represent the male and female populations. In the second phase, the velocity of each male fly is updated, and then flies are ranked depending on their velocity. In the end, the highest-ranking flies mate with female flies. Likewise, the gain values are tweaked using this algorithm. Figure 4 depicts the MA’s functional flow [23].

![Figure 4. Functional flow of the MA.](image)

3.2.1. Male Mayfly Movement

Each of the male mayflies adjusts its position with respect to its own and its neighbour’s positions. \( x_i^t \) is the present position of the \( i \)th mayfly in the search space at time \( t \). The position change, calculated by adding velocity \( v_i^{t+1} \), is expressed in Equations (8) and (9) [39].

\[ x_i^{t+1} = x_i^t + v_i^{t+1} \]  

(8)
Speed of the male mayfly

\[ v_{ij}^{t+1} = v_{ij}^{t} + a_{1}e^{-\beta r_{2}^{2}}(P_{best_{ij}} - x_{ij}^{t}) + a_{1}e^{-\beta r_{2}^{2}}(g_{best_{ij}} - x_{ij}^{t}) \]  

(9)

where

\( v_{ij}^{t} \) = Velocity of Mayfly (ith at time t).

\( ij \) = Dimension in search space.

\( x_{ij}^{t} \) = Fly position at time t.

\( a_{1}, a_{2} \) = Coefficients of social effects.

\( P_{best_{ij}} \) = Local best value.

\( g_{best_{ij}} \) = Best location of Mayfly.

The best mayflies in the group change their speed continually in order to improve their global best. Updated velocity is presented in Equation (10). The dance coefficients, represented as \( d \) and \( r \), are random numbers between \(-1\) and \(1\) [40].

\[ v_{ij}^{t+1} = v_{ij}^{t} + d + r \]  

(10)

3.2.2. Female Mayfly Movement

The female fly updates its position by increasing its speed, and \( y_{i}^{t+1} \) is the ith mayfly position at time t.

\[ y_{i}^{t+1} = y_{i}^{t} + v_{i}^{t+1} \]  

(11)

The process of attraction happens randomly, with the first-ranked female attracted by the best males. The remaining flies are attracted accordingly, based on their fitness. For the minimization problem, the velocity is expressed as follows. \( r_{mf} \) is the distance between male and female flies [40].

\[ v_{ij}^{t+1} = \begin{cases} v_{ij}^{t} + a_{2}e^{-\beta r_{2}^{2}}(x_{ij}^{t} - y_{ij}^{t}) & \text{if } f(y_{i}) > f(x_{i}) \\ v_{ij}^{t} + r_{1} \times r & \text{if } f(y_{i}) > f(x_{i}) \end{cases} \]  

(12)

Most of the popular optimization methods require zero derivative points. In order to solve nonlinear problems, more variables are used for the dimension in the search space, and the search space is increased. The numerical solving methods may be stuck at the point of local optimum. Therefore, there is no guarantee of finding the best global optimum solution. In order to overcome the shortfalls of the numerical methods, more metaheuristic algorithms are used to solve complex optimization problems. The Mayfly algorithm can be easily implemented for both continuous and discrete problems. Additionally, this method rarely becomes stuck in local optimum points [40].

The major advantages of the MA [40]:

- MA has a fast convergence and a fast convergence rate;
- The nuptial dance and random flying contribute to the equilibrium between exploitation and exploration.

The MA is suggested in the research to optimize the secondary controller parameters, such as \( K_{p}, K_{i}, \) and \( K_{d} \). Table 2 displays the optimized controller parameters. The upper and lower value limits of controller gains (\( K_{p}, K_{i}, \) and \( K_{d} \)) are chosen as \(0\) and \(1\), respectively, during the optimization process for the minimization of the cost function (Performance Indices J).
Table 2. MA-optimized controller gain parameters.

<table>
<thead>
<tr>
<th>System Modelling/Optimized Gain Parameter</th>
<th>Controller 1</th>
<th>Controller 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(K_p)</td>
<td>(K_i)</td>
</tr>
<tr>
<td>Microgrid (SLP)</td>
<td>0.9750</td>
<td>0.9999</td>
</tr>
<tr>
<td>Microgrid (RLP)</td>
<td>0.9999</td>
<td>0.9999</td>
</tr>
<tr>
<td>Multi-MG (SLP)</td>
<td>0.9805</td>
<td>0.9998</td>
</tr>
<tr>
<td>Multi-MG (RLP)</td>
<td>0.9999</td>
<td>0.9999</td>
</tr>
</tbody>
</table>

4. Performance Analysis of MG with SLP and RLP

This section illustrates the performance of the suggested optimized controller for a single-area MG power system. Its performance was evaluated using the MATLAB simulation tool. In Case 1, the system’s response was investigated using an SLP, and in Case 2, the system’s reaction was examined using an RLP.

4.1. Case 1: MG with SLP

The projected controller (MA-PID) is suggested as a subordinate controller to test the behaviour in the LFC crisis. In order to test the suggested technique-tuned controller’s ability, a one percent step load disturbance was applied. The responses of the system GA, PSO, and DE-PID controllers were compared in order to demonstrate the superiority of the projected MA-based PID controller. Figure 5 depicts the outcome comparison of the system frequency.

Figure 5. del F comparison of MG for SLP.

Figure 5 shows that the controller designed with the projected MA technique is superior to alternative methods for resolving frequency oscillations during unexpected load demand. It quickly settles the oscillation (8 s) compared to the GA and PSO method-based controllers (8 s = MA < 10 s = DE < PSO = 10.5 s < GA = 11 s) and reduces the peak values under emergency load demand situations. Table 3 shows the numerical parameter values (time domain description) for Figure 5.
Table 3. Controlled parameters of del F.

<table>
<thead>
<tr>
<th>Controlled Parameters/Optimization Technique</th>
<th>Ts</th>
<th>POS</th>
<th>PUS</th>
</tr>
</thead>
<tbody>
<tr>
<td>GA-PID</td>
<td>12</td>
<td>0.057</td>
<td>$2 \times 10^{-3}$</td>
</tr>
<tr>
<td>PSO-PID</td>
<td>11</td>
<td>0.057</td>
<td>$0.6 \times 10^{-3}$</td>
</tr>
<tr>
<td>DE-PID</td>
<td>10</td>
<td>0.060</td>
<td>0</td>
</tr>
<tr>
<td>MA-PID</td>
<td>08</td>
<td>0.062</td>
<td>$2.5 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

4.2. Case 2: MG with RLP

The suggested system was tested in this part using a random load pattern in order to evaluate the performance of the projected MA method-based PID controller. A random load was applied to the proposed system with $\pm 0.01$ as its maximum and minimum. The frequency deviation comparison with RLP is clearly illustrated in Figure 6.

![Figure 6. del F comparison in the MG with RLP.](image)

When RLP was applied to the proposed system, the first system frequency had a maximum peak value of 0.06 Hz, as shown in Figure 6. After a while, the peak values lowered to $1 \times 10^{-3}$ Hz, and the error was reduced to zero. When the load changed, the frequency deviated somewhat from its nominal values, which were controlled by the proposed auxiliary controller.

5. Performance Analysis of MMG with SLP and RLP

The developed multi-MG (MMG) system presented in Section 2 was investigated by applying 1% SLP and an RLP to the system in order to study the behaviour of the projected MA-PID controller. The performance was examined by considering the following two scenarios (Case 1 with SLP and Case 2 with RLP).

5.1. Case 1: MMG with SLP

Section 5.1 investigates the performance analysis of the suggested controller tuning approach (MA-PID) in the MMG with 1% SLP. The delF comparison of area 1 and the tie line power flow comparison of the MA-, DE-, PSO-, and GA-tuned PID controllers are provided in Figures 7 and 8, respectively.
It is evident that the projected technique-tuned MA-PID controller yields superior performance over those of GA-, PSO-, and DE- tuned controllers by time domain specification variables.

Table 4 effectively dispatches the numerical values from Figures 7 and 8 to analyse the performance of the suggested tuning technique-oriented controller in the MMG. The behaviour comparisons in Figures 7 and 8 and Table 4 demonstrated that the projected MA-PID controller improved performance over existing (GA, PSO, and DE optimization) methods. The deviation settling times of \(\Delta F_1\) (22 s > 19 s > 19 s > 18 s), \(\Delta F_2\) (23 s > 19 s > 18.5 s > 18 s), and \(\Delta P_{\text{ti line}}\) (20 s > 19 s > 19 s > 18.5 s) are quicker than those of GA, PSO, and DE controllers. Additionally, peak values, such as peak overshoot (POS) and peak undershoot (PUS), were minimized in the response.
Table 4. Controller parameters of del F₁, del F₂, and del Ptieline.

<table>
<thead>
<tr>
<th>Controlled Parameters/Optimization Technique</th>
<th>del F₁</th>
<th>del F₂</th>
<th>del Ptieline</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ts (10⁻³)</td>
<td>POS (10⁻³)</td>
<td>PUS (10⁻³)</td>
</tr>
<tr>
<td>GA-PID</td>
<td>20</td>
<td>7.5</td>
<td>1</td>
</tr>
<tr>
<td>PSO-PID</td>
<td>19</td>
<td>6.9</td>
<td>0.3</td>
</tr>
<tr>
<td>DE-PID</td>
<td>19</td>
<td>7.0</td>
<td>0.3</td>
</tr>
<tr>
<td>MA-PID</td>
<td>18.6</td>
<td>6.5</td>
<td>0.75</td>
</tr>
</tbody>
</table>

5.2. Case 2: MMG with RLP

In this section, RLP was introduced to the proposed power network in order to analyse the behaviour of the optimization technique in the MMG. The result comparisons of the system frequency and tie line power are plotted in Figures 9 and 10, respectively (del F₁, and del Ptieline).

Figure 9. del F₁ comparison in the MMG with RLP.

Figure 10. del Ptieline comparison in the MMG with RLP.

According to the response comparison of the tie line power and system frequency, they diverged from the nominal values at the start of the abrupt loading condition. The tie-line power and system frequency initially demonstrated some peak values, which were quickly minimized by adopting the proposed MA technique-based MA-PID controller.
6. Robustness Analysis

The robustness investigation was performed in this section in order to verify the performance and effectiveness of the planned MA-PID controller with different loading situations and system parameter variations. In this section two separate robustness analyses are discussed. In the Section 6.1, the system investigated by applying 1%, 2%, 5%, and 10% percentage step load disturbances for rigorous analysis. The test contributed to the higher performance of the MA-PID controller in the investigated system. In Section 6.2, changes in system parameters $T_g$ and $T_s$ ($\pm 50\%$ and $\pm 25\%$) for demonstrating the reliability of the controller.

6.1. 1%, 2%, 5%, and 10% Load

In the robustness analysis, different levels of SLP were applied to area 1. The response comparisons of the system frequency and tie-line power flow between connected areas ($\text{del } F_1$ and $\text{del } P_{\text{tie-line}}$) are plotted in Figures 11 and 12, respectively.

![Figure 11. del F1 comparison for robustness analysis.](image)

![Figure 12. del Ptie-line comparison for robustness analysis.](image)
Figures 11 and 12 clearly illustrate that the smooth operation of the proposed technique-adopted controller (MA-PID) is superior at the time of parameter variations. The controller controlled the deviation in the system frequency under different loading conditions, from which the proposed controller is the most suitable to implement to solve the LFC crisis.

6.2. Sensitivity Analysis

A sensitivity examination was conducted with different ranges of system parameter variations of governor time constant ($T_g$) and turbine time constant ($T_s$) (±50 and ±25%) from their nominal values. The response comparison of the system frequency and tie line power flow are presented in Figures 13–16.

**Figure 13.** del $F_1$ comparison for change in $T_g$.

**Figure 14.** del $P_{\text{tie line}}$ comparison for change in $T_g$.
The smooth performance of the MA-PID controller was achieved in all critical situations within system parameters, which is effectively demonstrated in Figures 13–16. From this overall performance analysis, the projected MA-PID controller is the most suitable controller for the proposed power microgrid.

7. Conclusions

This paper presented the design and investigation of a microgrid and multi-microgrid system for the LFC scheme by integrating an MA-PID controller as a secondary controller. Without the secondary controller in the power system, it is too difficult to control frequency oscillation. Thermal, PV, and wind energy are used to power the MG. A variety of tests were carried out in order to establish the superiority of the suggested tuning of secondary controller gain values. The examination results were as follows:

- The MA-PID controller was examined an isolated MG system with 1% SLP. The performance of the projected technique-tuned controller was compared with those of GA, DE, and PSO-PID controllers. The performance of systems del F₁, del F₂, and del P_	ext{tie-line} showed that the projected MA-PID produces a better outcome with minimal settling time (8 s = MA < 10 s = DE < PSO = 10.5 s < GA = 11 s) over GA, PSO, and DE controllers.
• RLP was used to examine the single-area MG system, and the frequency was affected at the initialization time of loading, but it returned to normal operating conditions after 10 s.

• SLP was used to analyse the performance of the projected MA-PID controller in the MMG system. In terms of oscillation control of the system frequency, the MA-PID controller performed more quickly in del $F_1$ (22 s > 19 s > 19 s > 18 s), del $F_2$ (23 s > 19 s > 18.5 s > 18 s), and del $P_{tie line}$ (20 s > 19 s > 19 s > 18.5 s) than GA, PSO, and DE controllers.

• RLP was employed in the MMG to legalize the performance of the MA-PID controller within the MMG’s LFC. It was effectively evident that the MA-PID controller improved performance by reducing the steady-state error in the system frequency with minimal settling time (in del $F_1$ = 20 s).

• Various load disturbance situations and system parameter variations were conducted in the robustness test, and the sensitivity analysis test clearly proved that the projected MA-PID controller functioned admirably under all crucial conditions for solving the LFC crisis.

8. Recommendation and Future Scope

In the proposed work, a standalone and interconnected microgrid power system with a secondary controller (PID) was examined for frequency regulation. The controller parameters were tuned by the Mayfly algorithm, and the response was compared with the responses of the GA, PSO, and DE controllers. The following recommendations and scopes are suggested for future research:

• The system size may vary, and the performance of the secondary controller can be analysed;

• Conduct an investigation by changing the optimization technique and controller.

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Appendix A

$$R_1 = 0.05 \text{ per unit, } R_2 = 0.04 \text{ per unit, } T_{H1} = T_{I2} = 0.4 \text{ s, } T_{g1} = T_{g2} = 0.1 \text{ s, } T_{w1} = T_{w2} = 0.5 \text{ s, } T_{pv1} = T_{pv2} = 1.5 \text{ s, } T_{BESS1} = T_{BESS2} = 0.1 \text{ s, } T_{FESS1} = T_{FESS2} = 0.1 \text{ s, } K_{g1} = K_{g2} = 1 \text{ per unit, } K_{w1} = K_{w2} = 1 \text{ per unit, }$$

$$K_{pv1} = K_{pv2} = 1 \text{ per unit, } K_{BESS1} = K_{BESS2} = 1 \text{ per unit, } K_{FESS1} = 3 \text{ per unit, } K_{FESS2} = 4 \text{ per unit, } K_{WT1} = K_{WT2} = 1 \text{ per unit, } K_{PV1} = K_{PV2} = 1 \text{ per unit, } M_1 = M_2 = 8 \text{ per unit, } D_1 = D_2 = 1 \text{ per unit, } T_{I2} = 1.4, B_1 = 10 \text{ per unit, } B_2 = 12.5 \text{ per unit.}$$

References


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