sustainability

MDPI

Article

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

Boopathi D[1*], Jagatheesan K[2], Anand B[3], Sourav Samanta[4] and Nilanjan Dey[5]

[1] Assistant Professor, Paavai Engineering College, Namakkal, Tamilnadu, India.; boopathime@gmail.com
[2] Associate Professor, Paavai Engineering College, Namakkal, Tamilnadu, India.; jaga.ksr@gmail.com
[3] Professor, Hindustan College of Engineering and Technology, Coimbatore, Tamilnadu, India.; anand.eie@hicet.ac.in
[4] Assistant Professor, University Institute Technology, Burdwan, West Bengal, India.; sourav.uit@gmail.com
[5] Associate Professor, Techno International New Town, Kolkata, India.; neelanjandey@gmail.com

*Correspondence: boopathime@gmail.com;

Abstract: The primary goal of this article is to create a tuned secondary controller to control the system frequency in a networked microgrid system. Renewable energy sources (RES), energy-storing units (ESU), and synchronous generators are all part of the proposed system. The RESs include photovoltaic (PV) and wind turbine generator (WTG) units. The ESU is made up of a flywheel and a battery. Because renewable energy sources are not constant in nature, their value fluctuates from time to time, causing an effect on system frequency and power flow variation in the tie line. To address this situation, a Proportional integral derivative (PID) controller based on the Mayfly Algorithm (MA) is proposed and built. Comparing the response to Genetic algorithm (GA), Differential Evolution (DE), and Particle swarm optimization (PSO) technique-optimized controller performance demonstrates the superiority of MA-tuned controller performance. 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. The robustness analysis test was also performed to determine the effectiveness of the suggested optimization technique (1%, 2%, 5%, 10% Step load perturbation (SLP), ±25%, ±50% variation from nominal governor and reheater time constant).

Keywords: Mayfly algorithm, load frequency control, secondary control, frequency deviation, PID controller.

Citation: To be added by editorial staff during production.

Academic Editor: Firstname Lastname

Received: date
Revised: date
Accepted: date
Published: date



Copyright: © 2023 by the authors. Submitted for possible open access publication under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

The installation of renewable energy sources solves the problems caused by conventional energy sources in the environment during electric power generation and matching sudden load demand situations. Pollution is a big issue in the environment, and one of the sources of pollution is electric power generation. The traditional techniques of generating electricity cause environmental degradation. 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 shortage of fossil fuels. The inclusion of RESs is a difficult undertaking because RESs are typically non-linear power-generation sources. When incorporating RES into the electricity grid, numerous quality challenges arise, notably 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 secondary controller is required to implement in the scheme to preserve frequency stability [1], [2], [5]. Especially it maintains the frequency stands and important parameters in the frequency (settling time and stability). Settling time is the time required to bring the

frequency oscillation into a predefined value. Stability is maintaining the predefined values in frequency at sudden loading conditions.

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

In [12], the author investigates PV and energy storage systems combined with microgrids using the virtual area control error approach. The performance of the Grey wolf optimization (GWO) approach adjusted PID controller has implemented to a microgrid is integrated with the thermal power plant in [13], genetic algorithm, PSO, and ACO technique tuned PID controller result was compared with the proposed controller. In [14], multivariable generalized predictive control theory was used to implement LFC in MG (wind + EV), this study also includes the performance of PID and fuzzy controller for supremacy of the proposed controller. The author [15] presented a mouth flame optimization method-based FPID controller for a microgrid, for the fusibility of MFO – FPID controller results was compared with classical controllers. In [16], an Imperialist Competitive Algorithm (ICA) tuned cascade controller (c-PIDF) was implemented as a supplementary controller in a microgrid. To justify the efficacy of the ICA – cPIDF controller, the performance was compared with genetic algorithm and cuckoo search algorithm - based controllers. PSO - PID controller was used to study RESs integrated multi-source power grid in [17]. To justify the improvement of the PSO – PID controller, results have been compared with the conventional PID controller. A cascade PI-TID controller deployed as a supplementary controller in an isolated microgrid consisting of wind, biogas, and biodiesel using Harris hawk's optimization technique in [18], also the results have been compared with TID and PID controller performance. In [19], MPC was used to examine the LFC in a wind energy-based MG and conventional PID controller performance was compared with MPC controller performance. In [20], the performance of a hybrid microgrid was investigated by a biogeography-tuned PID controller, also the performance was compared with the conventional method PID controller. In [21], a wind power-based hybrid power system with a moth swarm algorithm-based PID controller is examined for LFC, this study extended to with/without SMES performance analysis. In [22], the MA - PID controller is implemented to a standalone power network as a tributary controller. The superiority of the Mayfly algorithm is justified by the result comparison of the GA and

PSO techniques. The Mayfly algorithm is used in a variety of applications, including proton exchange membrane fuel cell modelling [23], [24]. In [25], MPC was used to forecast the microgrid. [26] uses the WHO approach to maintain voltage stability in the power supply. In [27], ANN is used to improve the stability of a wind-form integrated power grid. [28] used hPSO and GWO to analyze the performance of a PV panel.

The response of a multi microgrid evaluated by the atom search optimization (ASO) adjusted PID controller and the results was compared with GA and PSO - PID controllers by the author in [29]. In [30] the Ziegler Nichols approach tuned PID controller is used as a subordinate controller for a stand-alone microgrid system with wind and an MPPT-based solar plant. SSO - FPID controller developed in [31] for the LFC of a microgrid made up of solar PV, wind turbine, bio-gas, and bio-diesel to regulate system frequency. The performance was superior to that of a traditional PID controller. In [32], the author constructed a PID controller tuned by the Honey Badger Algorithm (HBA) for a microgrid that includes PV, wind turbine, bio-gas, and bio-diesel unit. A law-based sliding mode controller is constructed for the LFC of a microgrid (wind/hydrogen/battery DC microgrid), and a comparison study demonstrates the dominance of the suggested controller. [33]. A comparative literature survey is dispatched in Table. 1, attempt to analyze the research gap in the LFC of microgrids.

Table 1: Comparative literature survey

Ref. No	Optimizer	Controller	Control area	Source	Comparative study
[6]	Artificial Sheep algorithm	PI	Microgrid	Pumped storage, RESs	Robustness study
[9]	Chaotic crow search algorithm	PID	two areas MG	Thermal, solar, wind, EV, ESS	Conventional I controller
[10]	Particle swarm optimization	PID	Isolated MG	PV, wind, FC, BESS	Conventional PID
[11]	Black hole optimization	FPID	Isolated MG	Wind, PV, flywheel, EV	Multi- objective PID
[13]	Grey wolf optimization	PID	hybrid MG	Thermal, PV, BESS, wind	GA-PID, PSO-PID
[16]	Imperialist Competitive Algorithm	PID	multi MG	Thermal, DEG, FESS, BESS	GA and CSA - PID
[17]	Particle swarm optimization	PID	Single area	Thermal, solar, wind	Conventional PID
[18]	Harris hawks optimization	PI	Isolated MG	PV, wind, biogas, biodiesel	GOA, CSA and GA - PID
[20]	Biogeography optimization	PID	hybrid MG	Wind, PV, diesel, FESS, ESS	Conventional - PID
[21]	Moth swarm algorithm	PID	Single area	Wind	Effect of SMES
[22]	Mayfly Algorithm	PID	Single area	Thermal, hydro, gas	GA, PSO - PID
[40]	Atom search optimization	PID	Multi MG	PV, wind, diesel	GA, PSO - PID
[41]	Ziegler Nichols	PID	Single area	Wind, Solar	Conventional-PID
[42]	Slap swarm optimization	FPID	Isolated MG	PV, wind, biogas	SSO - PID
[43]	Honey Badger Algorithm	PID	Isolated MG	PV, wind, biogas, biodiesel	Conventional-PID
[44]	Quick reaching law	PID	Isolated MG	Wind, battery	Conventional-PID

The process of identifying gaps in 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 increased in recent days. The implementation of the 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 are suggested for optimization of the controller's 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 for generating the required electric power for all consumers with good quality. But in recent days because of air pollution and shortage of raw material power generation moved from the conventional source to renewable energy sources for generating electric power for consumers. Also, renewable-based generating power is included with conventional power by designing a microgrid system to balance load demand. All these are discussed and shown in the above literature review section as well as Table 1. Whenever rapid load demand arises in the microgrid, fluctuations in system frequency and produced voltage impact the quality of generated electricity. To overcome these issues several secondary controllers and energy storage techniques are designed and effectively implemented. The same design of the controller also utilized several optimization techniques to design controller gain values with a suitable cost function. To overcome the drawbacks of conventional power systems and the requirement of a secondary controller in this proposed article micro grid system is designed (conventional + Renewable Energy Source + Energy Storage system) with a secondary (PID) controller for frequency stabilization during emergency load situations.

The foremost objective of these studies presented in the literature review section is to reduce time domain specification parameters (settling time, steady state error, peak over, and undershoot) in the power generating systems during unexpected load changing situations. Based on that still, any algorithm-based controller doesn't provide better-controlled response. For that, the design of a suitable controller with superior optimization is required for better LFC performance in power systems during sudden load demand conditions.MA algorithm is a recently developed optimization technique and it is an easily implemented method for solving both continuous and discrete problems. Similarly, this algorithm rarely gets stuck in local optimum points [38]. The advantage of proposed the MA is MA has fast convergence and convergence rate. The nuptial dance, and random flight improve the balance among exploration and exploitation. Based on this potential the MA technique is motivated for the design of PID controller in the proposed microgrid/multi microgrid for performance improvement.

1.2. Innovation of the article

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

1.3. The main Contribution of the article

- Towards developing a microgrid and multi microgrid incorporated with RESs (PV and wind) and energy storage system.
- To develop a suitable secondary controller (PID) for the proposed power system.
- Utilize the projected Mayfly Algorithm for controller gain parameters tuning to regulate the system operation during sudden load demand situation.

- To explain the enhanced response of the MA optimized controller (Over GA, PSO, and DE method designed controller).
- To conduct the robust and sensitivity analysis for showing the supremacy of proposed algorithm for tuning of gain values of controller in situations.

1.5 Implication of the article

- RESs based microgrid is investigated.
- Mayfly algorithm utilized to optimize the proposed auxiliary controller.
- Both SLP and Random load pattern (RLP) load interruption is provided to the system and supremacy is verified by the response comparison with GA, PSO, and DE technique and robustness test.

2. Proposed System Modelling

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

2.1 Micro grid (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 contains the nominal parameters of the proposed system model [34]. The mathematical function of the proposed system model is given in equations 1 to 7, and the transfer function model of the investigated system is shown in figure 2 [34]. In figure 2, B denotes the biasing constant, R represents the regulator constant, del P is small load disturbance, f represents system frequency and Δf denotes the change in frequency.

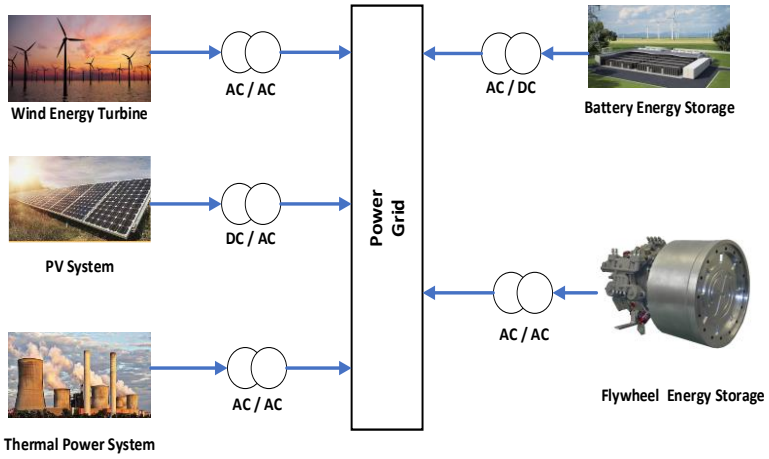


Figure. 1. The general structure of an AC microgrid

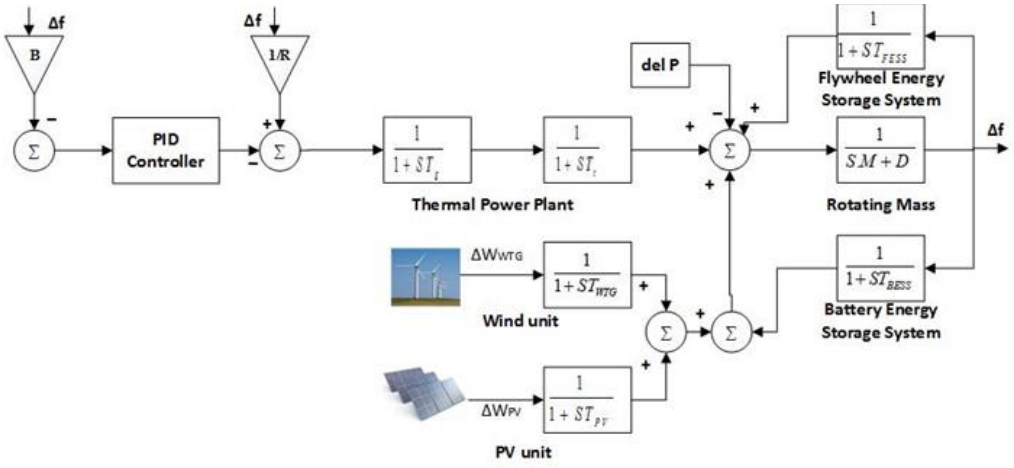


Figure. 2. Transfer function model of MG.

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 given in equations 1 and 2 In that Tg and Tt are denoted as the governor and turbine time constant respectively.

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

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

2.3 Wind farm

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 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 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 3TWTG represents the wind turbine generator time constant in equation 3.

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

2.4 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 request 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 TPV in equation 4.

$$\text{PV system} = \frac{1}{1+sT_{PV}} \quad (4)$$

2.5 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 to store the energy during nominal/minimal load demand conditions. The transfer functions are given in equation 5 and 6.

$$\text{Battery energy storage system} = \frac{1}{1+sT_{BESS}} \quad (5)$$

$$\text{Flywheel energy storage system} = \frac{1}{1+sT_{FESS}} \quad (6)$$

In above equation, TBESS is time constant of the battery energy storage system and TFESS represents time constant flywheel energy system respectively.

2.6 Multi MG

To increase the system's power capacity, MGs are linked together 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 [34] depicts the mathematical function of the multi MG.

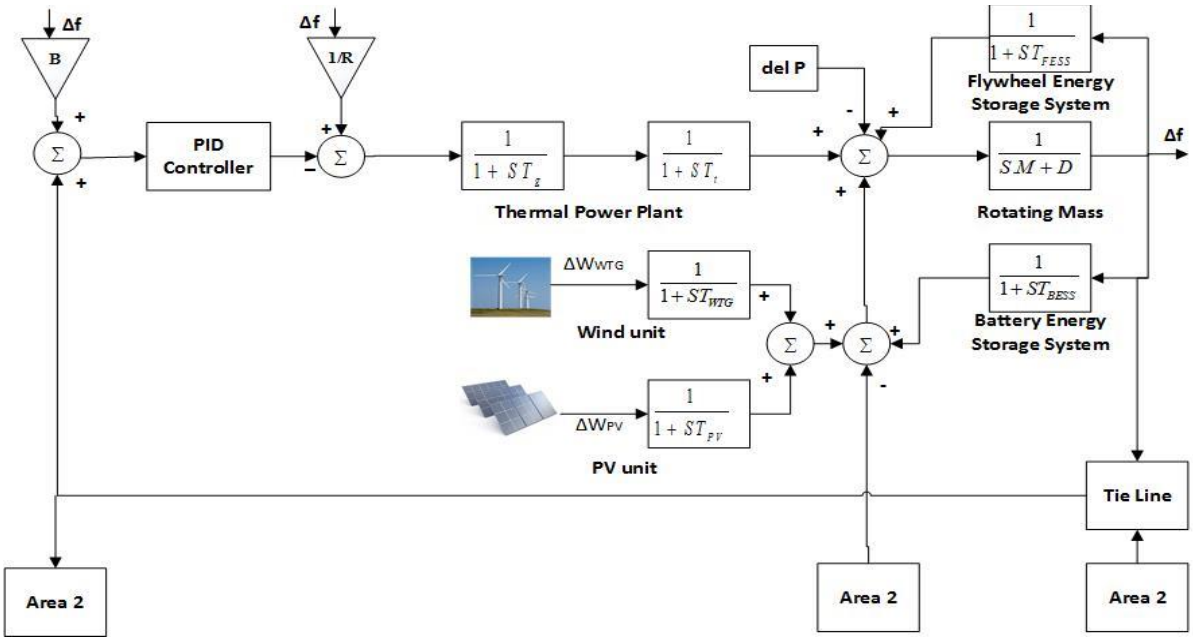


Figure. 3: Transfer function model of the multi-MG.

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, it is not always reliable in loading circumstances. When unexpected loading occurs in the power system, it takes a long time to stabilize the system. To address the 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 of 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 given in equation 7.

$$G_{PDS}(S) = K_p + \frac{K_i}{s} + K_d s \qquad (7)$$

Where the K_p, K_i, K_d are the proportional, integral and derivative controller gain parameters.

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 (crossover, mutation, swarming, nuptial dance, and random walk). Two sets of mayflies are initially generated at random to represent the male and female populations, respectively. In the second phase, the velocity of each male fly is updated, and then files are ranked depending on the velocity. In the end, the highest-ranking fly's mate with female flies. likewise, the gain values are tweaked using this algorithm. Whereas Figure. 4 depicts the MA's functional flow [23].

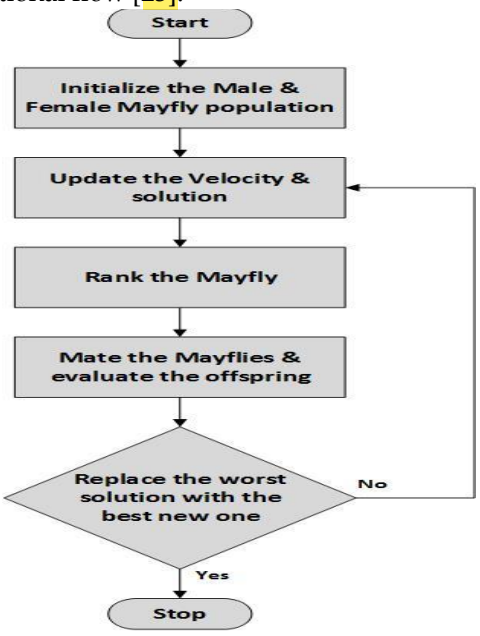


Figure. 4: Functional flow of MA

Male Mayfly movement

The group of male mayflies adjusts its position with respect to its own and neighbour position. x_i^t is the present position of the ith mayfly in the search space at time t. The position changing is by adding velocity v_i^{t+1} is expressed in equation 8 and 9 [37].

$$x_i^{t+1} = x_i^t + v_i^{t+1} \qquad (8)$$

Speed of the male mayfly

$$v_{ij}^{t+1} = v_{ij}^t + a_1 e^{-\beta r_p^2}(Pbest_{ij} - x_{ij}^t) + a_1 e^{-\beta r_p^2}(gbest_i - x_{ij}^t) \qquad (9)$$

Where

v_i^{t+1} = Velocity of Mayfly (ith at time t).
ij = Dimension in search space.
x_i^t = Fly position at time t.
a1, a2 = Co-efficients of social effects.

Pbestij = Local best value.
Gbestj = Best location of Mayfly.

The best mayflies in the group change its speed continually to improve its global best. Updated velocity in equation 10. Dance coefficient represented as d and r is random number in between -1 to 1[37].

$$v_{ij}^{t+1} = v_{ij}^{t} + d + r \quad (10)$$

Female mayfly movement

The female fly updated its position by increasing the speed, y_i^{t+1} is the ith mayfly position at time t.

$$y_i^{t+1} = y_i^{t} + v_i^{t+1} \quad (11)$$

The process of attraction happens by random, the first ranked female attracted by best males. Remaining files attracted accordingly their fitness. For minimization problem, the velocity is expressed as follows. rmf is distance between male and female fly [37].

$$v_{ij}^{t+1} = \{v_{ij}^{t} + a_2 e^{-\beta r_{mf}^2}(x_{ij}^{t} - y_{ij}^{t}), if \rightarrow f(y_i) > f(x_i),$$
$$v_{ij}^{t} + f_1 * r, if \rightarrow f(y_i) > f(x_i) \quad (12)$$

Most of the popular optimization methods required zero derivative points. For solving non-linear problems more variables are used for dimension in the search space, and also search space is increased. The numerical solving methods may be stuck at the point of local optimum. So, no guarantee to find the best global optimum solution. To overcome the shortfalls of numerical methods, more metaheuristics algorithms are used to solve complex optimization problems. The Mayfly algorithm can be easily implemented for both continuous and discrete problems. Also, this method rarely gets stuck in local optimum points [38].

The major advantage of the MA [38]:

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

The MA is suggested in the research work to maximize the recommended secondary controller parameters such as K_p, K_i, and K_d. Table 2 displays the optimised controller parameters.

Table 2. MA Optimized controller gain parameters.

System modelling / Optimized gain parameter	Controller 1			Controller 2		
	(K_p)	**(K_i)**	**(K_d)**	**(K_p)**	**(K_i)**	**(K_d)**
Microgrid (SLP)	0.9750	0.9999	0.0017	-	-	-
Microgrid (RLP)	0.9999	0.9999	0.0624	-	-	-
Multi MG (SLP)	0.9805	0.9998	0.1456	0.6691	0.8088	0.0747
Multi MG (RLP)	0.9999	0.9999	0.3037	0.9999	0.9999	0.9999

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. The performance is evaluated using the MATLAB simulation tool. In Case 1, the system's response is investigated using SLP and in Case 2, the system's reaction is 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 behavior in the LFC crisis. To test the suggested technique tuned controller's ability, one percent step load disturbance is applied. The responses of the system GA, PSO, and DE - PID controllers are compared to demonstrate the superiority of the projected MA algorithm - based PID controller. Figure.5 depicts the outcome comparison of system frequency.

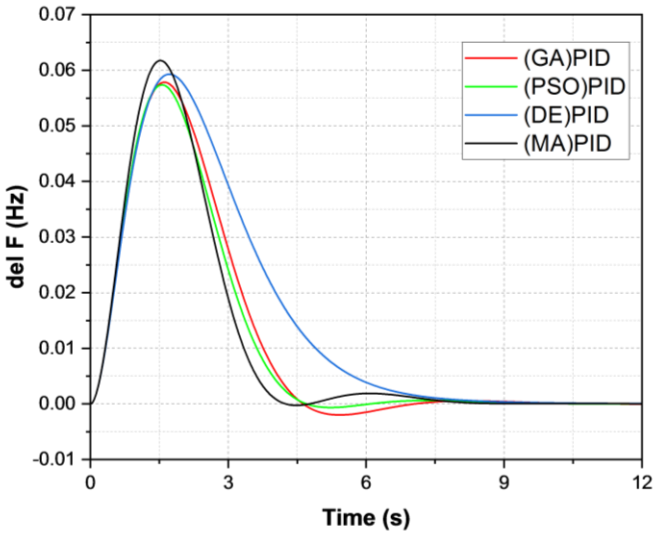


Figure. 5: del F comparison of MG for SLP

Figure 5, shows the projected MA technique designed controller is superior to alternative methods for resolving frequency oscillations during unexpected load demand. It quickly settles the oscillation (8s) compared to GA and PSO method - based controllers (8s=MA < 10s = DE < PSO = 10.5s < GA = 11s) 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 F1.

Controlled parameters / Optimization Technique	Ts	POS	PUS
GA – PID	12	0.057	2 X 10-3
PSO – PID	11	0.057	0.6 X 10-3
DE – PID	10	0.060	0
MA – PID	08	0.062	2.5 X 10-4

4.2 Case 2: MG with RLP

The suggested system is tested in this part using a random load pattern to evaluate the performance of the projected MA method- based PID controller. A random load

applied to the proposed system is ± 0.01 as the maximum and minimum. Frequency deviation comparison with RLP is clearly shown in figure.6.

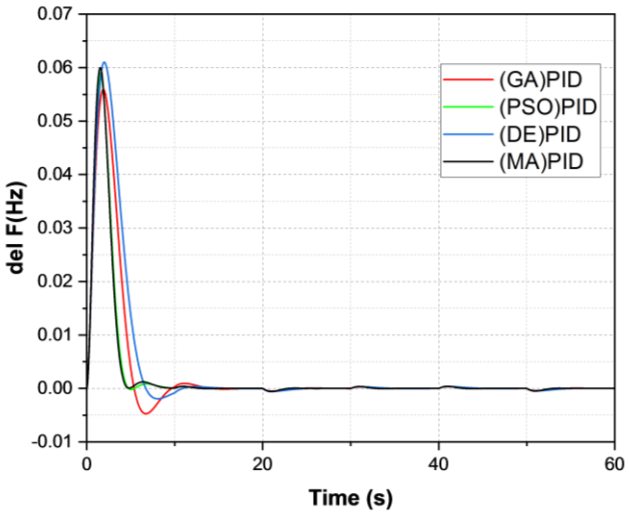


Figure. 6: del F comparison of MG for RLP.

When RLP is applied to the proposed system, the first system frequency has a maximum peak value of 0.06 Hz, as shown in Figures 7 and 9. After a while, the peak values are lowered to 1 X 10^{-3} Hz, and the error is reduced to zero. When the load changes, the frequency deviates somewhat from the nominal values, which is 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 is investigated by applying 1% SLP and an RLP to the system to study the behaviour of the projected MA - PID controller. The performance is examined by considering the following two scenarios (case 1 is with SLP and case 2 is 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 comparisons of MA, DE, PSO, and GA – tuned PID controller is given in figures 7 & 8 respectively.

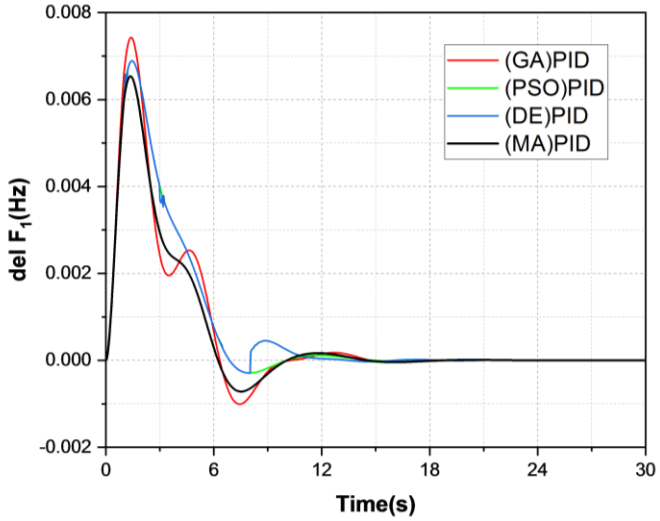


Figure. 7: del F_1 comparison of MMG for SLP.

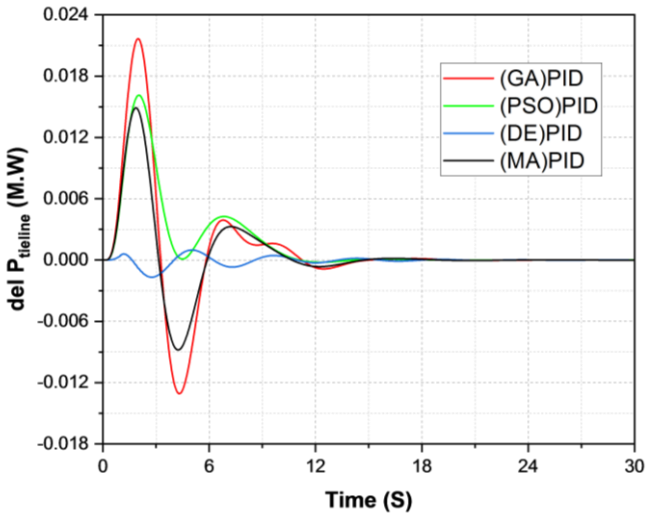


Figure. 8: del $P_{tieline}$ comparison of MMG for SLP.

It is evident that the projected technique-tuned MA-PID controller yields super performance over GA-, PSO- DE- tuned controller performance by time domain specification variables.

Table 4: Controller parameters of del F1, del F2, and del Ptieline.

Controlled parameters / Optimization Technique	del F1			del F2			del Ptieline		
	Ts	POS (10^{-3})	PUS (10^{-3})	Ts	POS (10^{-3})	PUS (10^{-3})	Ts	POS (10^{-3})	PUS (10^{-3})
GA – PID	20	7.5	1	21	6.1	0.7	20	0.021	0.013
PSO – PID	19	6.9	0.3	18.5	6	0.1	19	0.016	0.0002
DE – PID	19	7.0	0.3	18.5	6.2	0.1	19	0.001	0.001
MA – PID	18.6	6.5	0.75	18	5.8	0.6	18	0.015	0.007

Table 4 effectively dispatches the numerical values from figures 7 and 8 to analyses the performance of the suggested tuning technique-oriented controller in the MMG. The behavior comparisons of figure7 and Figure 8, and table 3 demonstrated that the projected MA- PID controller improved the performance over existing (GA, PSO and DE optimization) methods. The deviation settling time of del F1 (22s > 19s > 19s > 18s), del F2 (23s > 19s > 18.5s > 18s), and del Ptieline (20s > 19s > 19s> 18.5s) are quick than GA, PSO and DE. Also, minimize the peak values like Peak Over Shoot (POS) and Peak Under Shoot (PUS) in the response.

5.2 Case 2: MMG with RLP

In this section, RLP is introduced to the proposed power network to analyze the behavior of the optimization technique in the MMG. The result comparison of the system frequency, tie line power is plotted in figure 9 and figure 10 respectively (del F1, and del $P_{tieline}$).

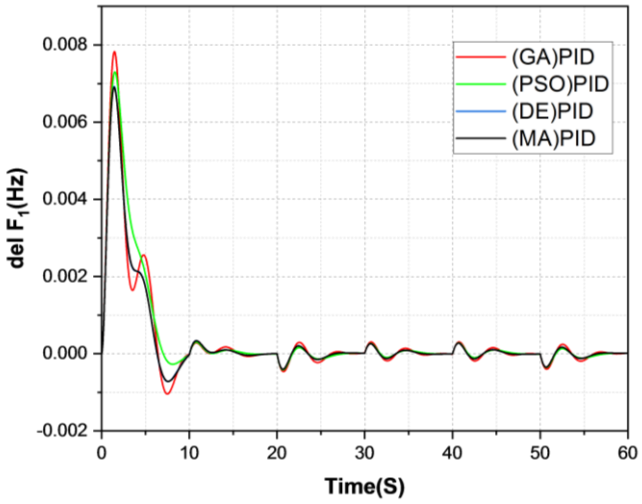


Figure. 9: del F1 comparison of MMG for RLP.

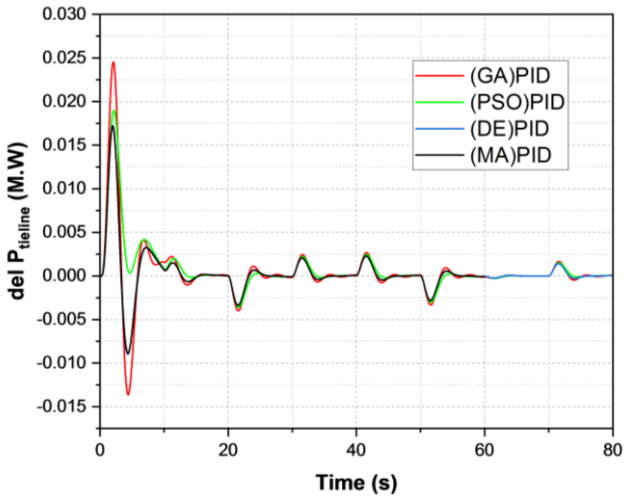


Figure. 10: del Ptieline comparison of MMG for RLP.

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

6. Robust Analysis

A robust investigation was performed in this section to verify the performance and effectiveness of the planned MA - PID controller with different loading situations and system parameter variations. This section discusses two separate robust analyses. The system investigated system is analyzed by applying 1%, 2%, 5%, and 10% percentage step load disturbance for rigorous analysis in section A. The test contributes to the higher performance of the MA-PID controller in the investigated system. In section B, changes in system parameters (±50%, and ±25%) are also verified (Tg and Ts) for conducting robust test analysis.

6.1 1%, 2%, 5%, and 10% load

In the robust analysis, different level of SLP is applied to area 1. The response comparison of system frequency and tie- line power flow between connected areas (del F1, and del Ptieline) is plotted in figures 11 & 12 respectively.

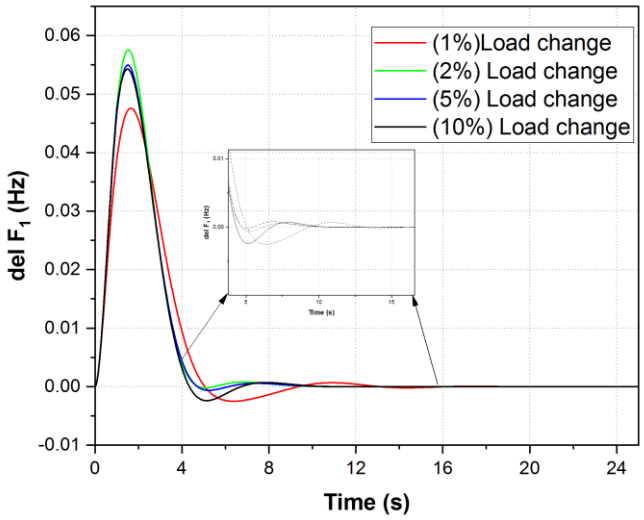


Figure. 11: del F1 comparison for robust analysis.

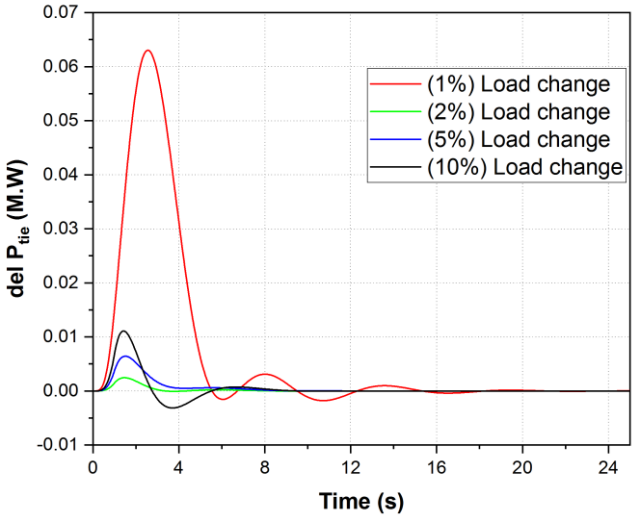


Figure. 12: del Ptieline comparison for robust analysis

Figures 11 & 12 clearly explained 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 in different loading conditions, from this the proposed controller is the best and most suitable one to implement to solve the LFC crisis.

6.2 Sensitivity Analysis

A sensitivity examination is conducted with different ranges of system parameter variations (governor time constant (Tg), and turbine time constant (Ts)) by changing ±50, and ±25 percentages from its nominal value. The response comparison of system frequency and tie-line power flow is given in figure 13 to figure 16.

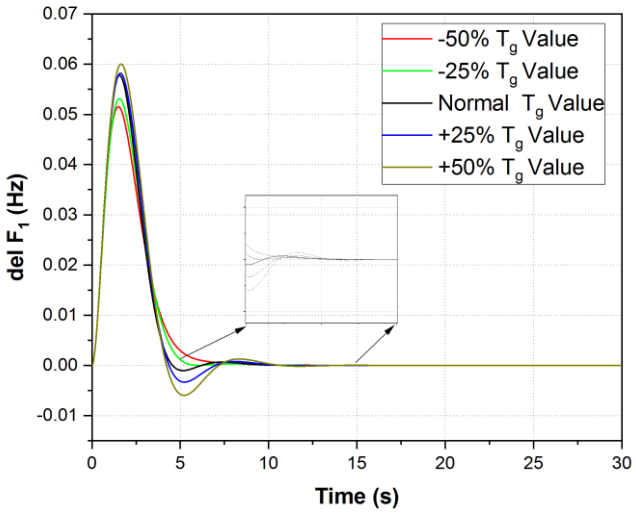


Figure. 13: del F1 comparison for change in Tg

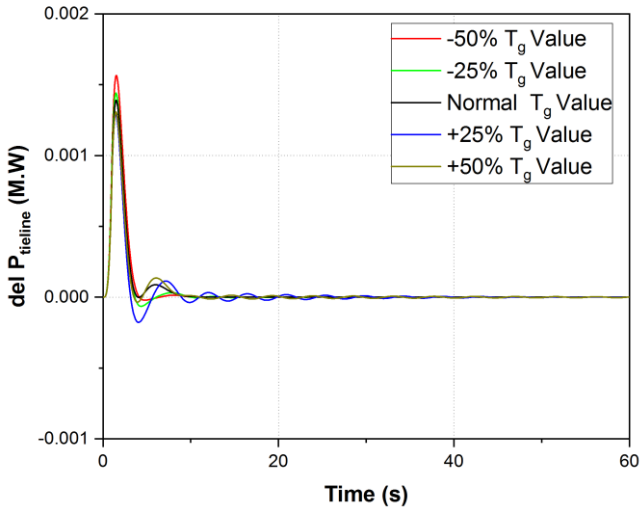


Figure 14: del Ptieline comparison for change in Tg

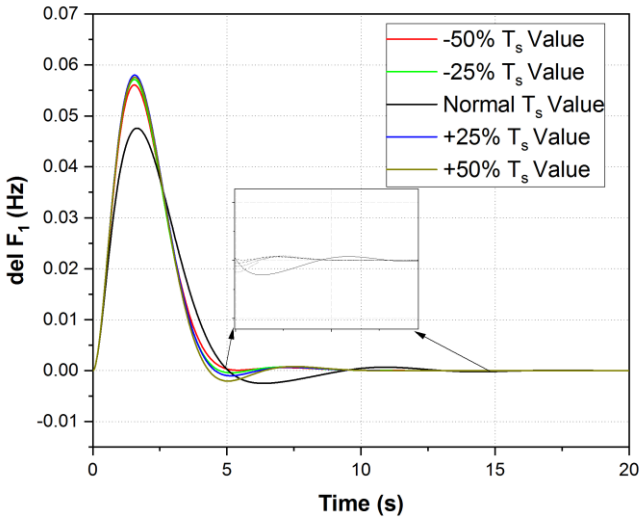


Figure 15: del F1 comparison for change in Ts

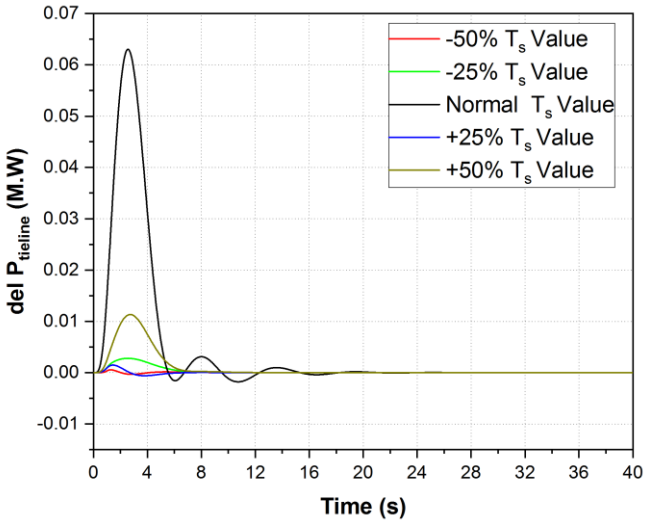


Figure. 16: del Ptieline comparison for change in Ts

The smooth performance of the MA – PID controller is achieved in all critical situations in system parameters and it is effectively demonstrated in Figures 13 – 16. From this overall performance analysis, the projected MA – PID controller is the perfect and suitable controller for the proposed power microgrid

5. Conclusion

This paper designed and investigates a microgrid, multi-microgrid system for the LFC scheme by integrating projected technique tuned MA - PID controller as a secondary controller. Thermal, PV, and wind energy are used to power the MG. A variety of tests are carried out to establish the superiority of the suggested tuning of secondary controller gain values. The examination results are as follows:

- MA - PID controller with 1% SLP examines an isolated MG system. The performance of the projected technique-tuned controller was compared with GA, DE, and PSO - PID controllers. The performance of systems del F1, del F2, and delP$_{tieline}$ is evident that the projected MA - PID produces a better outcome by minimal settling time (11s) over GA, PSO and DE.
- RLP is used to examine the single area MG system and frequency was affected at the initialization time of loading, but it returns to normal operating conditions after 10 seconds.
- SLP is used to analyze the performance of the projected MA - PID controller in the MMG system. In terms of oscillation control of system frequency, the MA - PID controller performed better. (area 1 settled around the 15s to 20s).
- RLP was employed in MMG to legalize the performance of the MA-PID controller in MMG's LFC. It is effectively evident that MA - PID controller improves performance by reducing steady-state error in system frequency with minimal settling time duration (in del F1 = 20s).
- The various load disturbance situations and system parameters variations are conducted in the robust test, and sensitivity analysis test clearly proved that projected MA -PID controller functions admirably under all crucial conditions for solving LFC crisis.

Supplementary Materials: Not applicable.

Author Contributions:

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix

R_1 = 0.05 per unit, R_2 = 0.04 per unit, T_{t1} = Tt2 = 0.4s, T_{g1} = T_{g2} = 0.1s, T_{w1} = T_{w2} = 0.5s, T_{pv1} = T_{pv2} = 1.5s, T_{BESS1} = T_{BESS2} =0.1s, T_{FESS1} = T_{FESS2} = 0.1s, K_{t1} = K_{t2} = 1 per unit, K_{g1} = K_{g2} = 1 per unit, K_{BESS1} = -3 per unit, K_{BESS2} = -4 per unit, K_{FESS1} = -1.5 per unit, K_{FESS2} = -2 per unit, K_{WT1} = K_{WT2} = 1 per unit, K_{PV1} = K_{PV2} = 1 per unit, M_1 = M_2 = 8 per unit, D_1 = D_2 = 1 per unit, T_{12} = 1.4, B_1 = 10 per unit, B_2 = 12.5 per unit

References

1. Kumar, M., & Hote, Y. V. (2021). Maximum sensitivity-constrained coefficient diagram method-based PIDA controller design: Application for load frequency control of an isolated microgrid. Electrical Engineering, 103(5), 2415-2429.
2. Gheisarnejad, M., & Khooban, M. H. (2019). Secondary load frequency control for multi-microgrids: HiL real-time simulation. Soft Computing, 23(14), 5785-5798.
3. Patel, S., Mohanty, B., & Hasanien, H. M. (2020). Competition over resources optimized fuzzy TIDF controller for frequency stabilization of hybrid micro-grid system. International Transactions on Electrical Energy Systems, 30(9), e12513.
4. Khokhar, B., Dahiya, S., & Singh Parmar, K. P. (2020). A robust cascade controller for load frequency control of a standalone microgrid incorporating electric vehicles. Electric Power Components and Systems, 48(6-7), 711-726.
5. Ramesh, M., Yadav, A. K., & Pathak, P. K. (2021). Intelligent adaptive LFC via power flow management of integrated standalone micro-grid system. ISA transactions, 112, 234-250.
6. Xu, Y., Li, C., Wang, Z., Zhang, N., & Peng, B. (2018). Load frequency control of a novel renewable energy integrated micro-grid containing pumped hydropower energy storage. Ieee Access, 6, 29067-29077.
7. Veronica, A. J., Kumar, N. S., & Gonzalez-Longatt, F. (2020). Design of load frequency control for a microgrid using D-partition method. International Journal of Emerging Electric Power Systems, 21(1).
8. Sahoo, B. P., & Panda, S. (2021). Chaotic multi verse optimizer based fuzzy logic controller for frequency control of microgrids. Evolutionary Intelligence, 14(4), 1597-1618.
9. Ali, H., Magdy, G., & Xu, D. (2021). A new optimal robust controller for frequency stability of interconnected hybrid microgrids considering non-inertia sources and uncertainties. International Journal of Electrical Power & Energy Systems, 128, 106651.
10. Boopathi, D., Saravanan, S., Jagatheesan, K., & Anand, B. (2021). Performance estimation of frequency regulation for a micro-grid power system using PSO-PID controller. International Journal of Applied Evolutionary Computation (IJAEC), 12(2), 36-49.
11. Khooban, M. H., Niknam, T., Shasadeghi, M., Dragicevic, T., & Blaabjerg, F. (2017). Load frequency control in microgrids based on a stochastic noninteger controller. IEEE Transactions on Sustainable Energy, 9(2), 853-861.
12. Mohammadi, F. D., Ghorbani, M. J., Feliachi, A., & Choudhry, M. A. (2014, July). Novel load frequency control approach based on virtual area error in a microgrid including PV and battery. In 2014 IEEE PES General Meeting | Conference & Exposition (pp. 1-5). IEEE.
13. Jagatheesan, K., Samanta, S., Boopathi, D., & Anand, B. (2021, December). Frequency Stability Analysis of Microgrid interconnected Thermal Power Generating System with GWO tuned PID controller. In 2021 9th IEEE International Conference on Power Systems (ICPS) (pp. 1-5). IEEE.
14. Yang, J., Zeng, Z., Tang, Y., Yan, J., He, H., & Wu, Y. (2015). Load frequency control in isolated micro-grids with electrical vehicles based on multivariable generalized predictive theory. Energies, 8(3), 2145-2164.
15. Prusty, U. C., Nayak, P. C., Prusty, R. C., & Panda, S. (2020, December). Impact of Vehicle to Grid mode Electric Vehicles in standalone Microgrid for frequency regulation. In 2020 IEEE International Symposium on Sustainable Energy, Signal Processing and Cyber Security (iSSSC) (pp. 1-6). IEEE.
16. Nayak, P. C., Prusty, U. C., Prusty, R. C., & Panda, S. (2021). Imperialist competitive algorithm optimized cascade controller for load frequency control of multi-microgrid system. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 1-23.
17. Kumarakrishnan, V., Vijayakumar, G., Jagatheesan, K., Boopathi, D., Anand, B., & Kanendra Naidu, V. (2022). PSO Optimum Design-PID Controller for Frequency Management of Single Area Multi-Source Power Generating System. In Contemporary Issues in Communication, Cloud and Big Data Analytics (pp. 373-383). Springer, Singapore.
18. Sahoo, B. P., & Panda, S. (2020, January). Load frequency control of solar photovoltaic/wind/biogas/biodiesel generator based isolated microgrid using harris hawks optimization. In 2020 First International Conference on Power, Control and Computing Technologies (ICPC2T) (pp. 188-193). IEEE.
19. Pahasa, J., & Ngamroo, I. (2014). Coordinated control of wind turbine blade pitch angle and PHEVs using MPCs for load frequency control of microgrid. IEEE Systems Journal, 10(1), 97-105.

20. Kumar, R. H., & Ushakumari, S. (2014, March). Biogeography based tuning of PID controllers for Load Frequency Control in microgrid. In 2014 International Conference on Circuits, Power and Computing Technologies [ICCPCT-2014] (pp. 797-802). IEEE.
21. Magdy, G., Mohamed, E. A., Shabib, G., Elbaset, A. A., & Mitani, Y. (2018). SMES based a new PID controller for frequency stability of a real hybrid power system considering high wind power penetration. IET Renewable Power Generation, 12(11), 1304-1313.
22. Muthukumar, T., Jagatheesan, K., & Samanta, S. (2022). Mayfly Algorithm-Based PID Controller for LFC of Multi-sources Single Area Power System. In Intelligence Enabled Research (pp. 53-64). Springer, Singapore.
23. Shaheen, M. A., Hasanien, H. M., El Moursi, M. S., & El-Fergany, A. A. (2021). Precise modeling of PEM fuel cell using improved chaotic MayFly optimization algorithm. International Journal of Energy Research, 45(13), 18754-18769.
24. Wei, D., Ji, J., Fang, J., & Yousefi, N. (2021). Evaluation and optimization of PEM Fuel Cell-based CCHP system based on Modified Mayfly Optimization Algorithm. Energy Reports, 7, 7663-7674.
25. Hu, C., Bi, L., Piao, Z., Wen, C., & Hou, L. (2018). Coordinative optimization control of microgrid based on model predictive control. International Journal of Ambient Computing and Intelligence (IJACI), 9(3), 57-75.
26. Selim, A., Kamel, S., Jurado, F., & Nasrat, L. (2020). Voltage stability assessment of radial distribution systems including optimal allocation of distributed generators.
27. Kamel, S., Jurado, F., Rashad, A., Ibrahim, Y., & Nasrat, L. (2019). Performance Enhancement of Wind Farms Using Tuned SSSC Based on Artificial Neural Network.
28. Rezk, H., Arfaoui, J., & Gomaa, M. R. (2021). Optimal parameter estimation of solar PV panel based on hybrid particle swarm and grey wolf optimization algorithms.
29. Mishra, S., Nayak, P. C., Prusty, R. C., & Panda, S. (2022). Performance analysis of multistage PID controller for frequency regulation of multi microgrid system using atom search optimisation. International Journal of Ambient Energy, 1-16.
30. Nisha, G., & Jamuna, K. (2022). Frequency Stabilization of Stand-Alone Microgrid with Tuned PID Controller. ECS Transactions, 107(1), 773.
31. Mahakur, A., & Mohanty, D. (2022). Frequency Control of SPV/Wind/Biogas/Biodiesel-Based Microgrid Using Fuzzy-Aided PID Controllers. In Sustainable Energy and Technological Advancements (pp. 611-624). Springer, Singapore.
32. Nikhil, M., Ruchitha, B. N., Gotur, P., Ravinand, M. P., & Reddy, G. H. (2022, April). Frequency Control of Renewables/Biodiesel/Biogas/Battery Energy Storage based Isolated Microgrid using the Honey Badger Algorithm. In 2022 4th International Conference on Energy, Power and Environment (ICEPE) (pp. 1-6). IEEE.
33. Armghan, H., Yang, M., Ali, N., Armghan, A., & Alanazi, A. (2022). Quick reaching law based global terminal sliding mode control for wind/hydrogen/battery DC microgrid. Applied Energy, 316, 119050.
34. Mishra, S., Patel, S., Prusty, R. C., & Panda, S. (2020). MVO optimized hybrid FOFPID-LQG controller for load frequency control of an AC micro-grid system. World Journal of Engineering.
35. Boopathi, D., Jagatheesan, K., Anand, B., Kumarakrishnan, V., & Samanta, S. (2022). Effect of Sustainable Energy Sources for Load Frequency Control (LFC) of Single-Area Wind Power Systems. In Industrial Transformation (pp. 87-98). CRC Press.
36. Kothari, D.P. and Nagrath, I.J. (2003) Modern Power System Analysis. McGraw Hill Education, New York.
37. Liu, C., Li, Q., Tian, X., Wei, L., Chi, Y. and Li, C., 2022. Multi-Objective Mayfly Optimization-Based Frequency Regulation for Power Grid With Wind Energy Penetration. Frontiers in Energy Research, 10, p.848966.
38. Zervoudakis, K. and Tsafarakis, S., 2020. A mayfly optimization algorithm. Computers & Industrial Engineering, 145, p.106559.