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Frequency Regulation in an Autonomous Microgrid Using BES based Multistage PID Control Approach

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ABSTRACT- The variability in output power from renewable energy sources (RES), load and system disturbances in autonomous microgrid (MG) can lead to significant frequency deviations. Traditional PID controllers often struggle to perform adequately under these challenging conditions. To address these issues, this paper recommends a multistage PID (MSPID) controller designed explicitly for microgrid frequency management. The parameters of this controller are optimized using a Bald Eagle Search (BES) algorithm. The controller is rigorously tested on an autonomous hybrid microgrid, considering various parametric and systemic disturbances. The results demonstrate notable improvements in error reduction, settling time, and overshoot, highlighting the effectiveness of the proposed controller compared to multilevel PID(MLPID) and traditional PID controllers found in existing literature.

Keywords: Frequency control, Multilevel PID, Multistage PID controller, Microgrid, Bald eagle search optimization.

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1. INTRODUCTION

In present power systems, the rising demand for electrical energy for various applications from conventional sources is becoming environmentally hazardous and cost prohibitive. To tackle the rise in demand, increasing penetration of non-conventional energy sources to the grid would be an alternate solution for modern power systems [1]. Though the power from renewable energy sources is ecofriendly, the RES output power is highly intermittent in nature; this intermittency poses additional technical issues in modern power system, mainly in load frequency control (LFC) [2].

LFC is a critical operational technique in electrical power systems that typically employs a conventional controller to generate the corrective signal at the governor summing point. This process is essential for maintaining the balance between power supply and demand, thereby ensuring system stability. However, several factors can influence the effectiveness of LFC, particularly low system inertia, which refers to the limited ability of the system to resist changes in frequency. Besides that, variable loads, intermittency in RES output power and non-linear characteristics of DEGs can further complicate the control dynamics.

The above factors complicate the MG frequency dynamics, which not only cause large frequency deviations but also affect the power system's reliability. Improved control and coordinate strategies are required. Several researchers proposed various intelligent-based PID controllers for MG frequency control in response. In [3], El-Fergany et al. proposed a social spider optimization (SSO) based PID controller, [4] C S Ratnam et al. proposed Grey Wolf Optimization (GWO) based PID controller and in [5] Annamraju et al. proposed a GOA-PID controller for MG frequency control. Intelligent PID controllers generally demonstrate satisfactory performance across a variety of operating conditions. However, one area for potential improvement lies in achieving a more effective balance between the derivative and integral components, as this could enhance overall performance.

Numerous innovative multistage PID controllers have been introduced in the literature, aiming to effectively overcome the limitations of conventional PID controllers in LFC for microgrids (MG) and to enhance frequency dynamics. For instance, Khadangha et al. developed a multistage PD-PI controller [6], which demonstrates potential for improved performance. Similarly, Annamraju et al. have contributed significantly with fuzzy-based multistage PD-PI controller [7] and a multilevel PD-PI controller [8] and Khokkar et al. proposed different cascade structures specifically tailored for

MG frequency control [9-10]. These advancements incorporate operating scenarios and test conditions that align well with previous research, ensuring a relevant comparison. The outcomes of these studies indicate that the proposed configurations significantly enhance frequency responses compared to traditional PID controllers, offering promising results in environments rich in renewable energy sources. This progress represents a meaningful step forward in the pursuit of more efficient control solutions for microgrids.

This paper presents a comprehensive evaluation of multilevel and multistage PID controllers for LFC in MGs, aiming to identify the most effective solution. To facilitate a fair comparison, the study employs the recently developed Bald Eagle Search (BES) algorithm for the optimization of all controller parameters. This approach not only enhances the reliability of the results but also contributes to the advancement of control strategies in MG applications. The key contributions of this paper are listed below:

1. This paper presents an innovative multistage PID controller specifically designed for LFC analysis in islanded MG. The study includes a comprehensive comparison of the proposed controller's performance against several established techniques in the literature, including BES PID and BES MLPID controllers. This comparative analysis aims to highlight the advantages of the proposed method and contribute to advancements in microgrid control strategies.
2. Significant progress has been made by optimizing the parameters of the multistage PID controller through the use of BES. This initial effort sets a solid foundation for further improvements and refinements.
3. The robustness of the proposed controller is confidently demonstrated through its evaluation against uncertainties from renewable energy sources, microgrids, and energy storage systems in a single controller framework.

2. MATHEMATICAL MODEL OF MICROGRID AND METHOD

Fig.1 illustrates the transfer function model of two-area hybrid MG. The test system consists of DEG, PHEVs, WTGs and PV array. In the present study, DEGs and PHEVs are responsible for MG frequency control in area-1, whereas DEGs are alone responsible for frequency control in area-2. The detailed functioning and description of each component can be found in [8].

In interconnected power systems, the generation and load balance can be expressed in terms of area control error (ACE), it can be articulated as:

$$ACE_1 = \Delta f_1 * \beta_1 + \Delta P_{tie,12}$$

$$ACE_2 = \Delta f_2 * \beta_2 + \Delta P_{tie,21} \quad (1)$$

This study aims to minimize the Area Control Error (ACE) to maintain frequency deviations and tie-line power at their scheduled values. Generally, PID controllers are utilized to achieve Load Frequency Control (LFC) objectives.

2.1. Proposed Multistage PID controller

The literature indicates that while traditional PID controllers are widely used, they may not always achieve optimal performance in renewable energy applications due to suboptimal trade-offs between the integral and derivative components. Fortunately, this challenge can be effectively addressed through the implementation of multilevel PID (MLPID) and multistage PID (MSPID) controllers. Figure 3 presents the structure of the MSPID controller specifically designed for frequency control in power systems. The equation for correcting the change in Area Control Error (ACE) using the MSPID controller can be articulated as follows:

$$U_f = \left(\left(K_P + K_D * \frac{sN}{N+s}\right)\left(\frac{K_I}{s} + K_{PP}\right)\right) * ACE \quad (2)$$

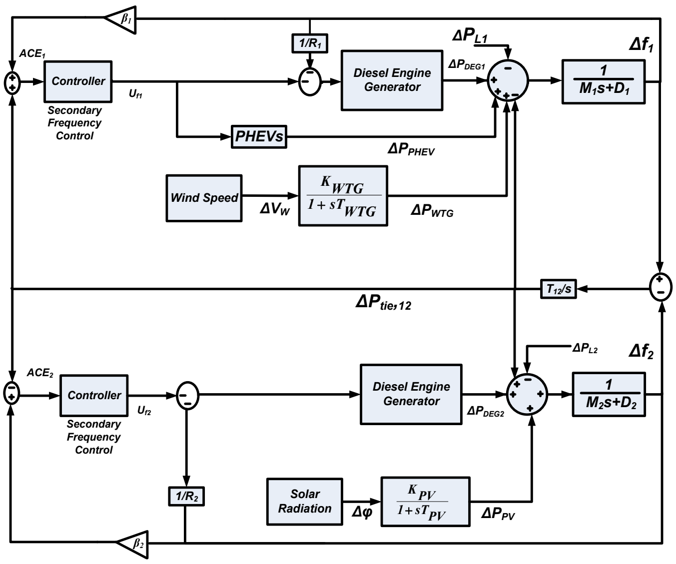
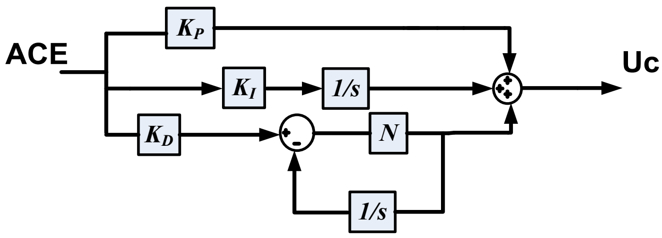
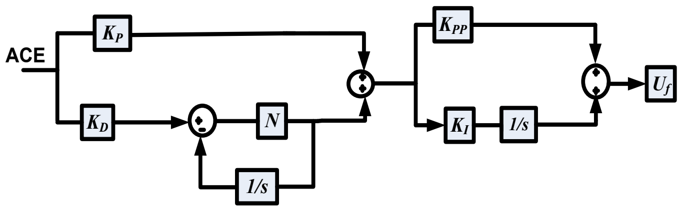


Figure 1. Dynamic model of Microgrid



(a)



(b)

Figure 2. Schematic model of (a) PIDF controller and (b)Recommended MSPIDF controller

3. BES BASED MULTISTAGE PID CONTROLLER

This section describes a brief description of the BES application to suggest MSPIDF controller. The following steps summarize this [11,12]:

Step 1: Initialize the various parameters like number of iterations, number of runs and number of points.

Step 2: Initialize the population randomly and calculate the objective functions using the following equations.

$$P_i = lb + (ub - lb) * rand(1, dim) \quad (3)$$

$$\text{Fitness (IAE)} = \int_0^t |\Delta f_1 + \Delta f_2 + \Delta P_{tie,12}| dt \quad (4)$$

Step 3: Select the search area using following equation

$$P_{new,i} = P_{best} + \alpha * \text{rand}() * (P_m - P_i) \quad (5)$$

Where 'α' is a variable which monitors the position of eagle. Where 'r' denotes random number and 'P_m' denotes all previous gained information. With *eq. (4)* compute the fitness of each population; if the solution is best replacing the old one or else keep the previous one [13].

Step 4: Determine the best location for swooping using the following equation.

$$P_{i,new} = P_i + y(i) * (P_i - P_{i+1}) + x(i) * (P_i - P_m) \quad (6)$$

Step 5: Determine the location of the prey using *eq.(7)*

$$P_{i,new} = rand() * P_{best} + (P_i - c_1 * P_{i+1}) * x_1(i) + (P_i - c_2 * P_{best} * y_1(i) \quad (7)$$

Step 6: Calculate the objective function value and update the best solution obtained (*i.e.* optimal gains of PIDF, MLPIDF and MSPIDF controller gains)

Figure 3 illustrates the BES optimization procedure and how it minimizes the fitness function using IAE.

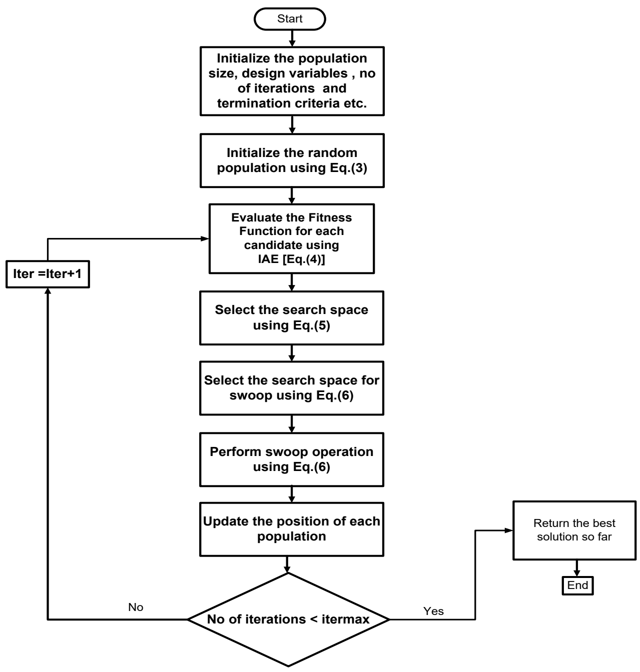


Figure 3. BES flowchart for optimization of MSPIDF controller

4. RESULTS & DISCUSSIONS

This section focuses on the constructive analysis of the time-domain simulation of frequency dynamics in a MG across critical operating scenario using MATLAB/Simulink. The simulation data was sourced from references [3,5] and conducted on a system equipped with 8 GB of RAM and an Intel Core i3 processor within the MATLAB 2016 b environment. This study aims to evaluate the MG's frequency response to several disturbances, including load, solar power, wind power, plug-in hybrid electric vehicles and parameter uncertainties. Furthermore, it examines the effectiveness of a coordinated strategy and the MSPID controller in enhancing the MG's overall performance under these diverse conditions. The performance of the proposed MSPID controller is compared with another type of multilevel PID structure [8] and traditional PID structure [3].

4.1. Step load disturbances in MG

In this scenario, multiple step load disturbances are introduced at various time intervals in Area1 as shown in *figure 4(a)*. This approach allows for a comprehensive observation of the resultant frequency deviations within Area1, treated as an isolated section. *Figure 4(b)* illustrates the frequency response for Scenario1, demonstrating the performance of different controllers. Table 1 provides a detailed dynamic analysis of these controllers at *t=2s*.

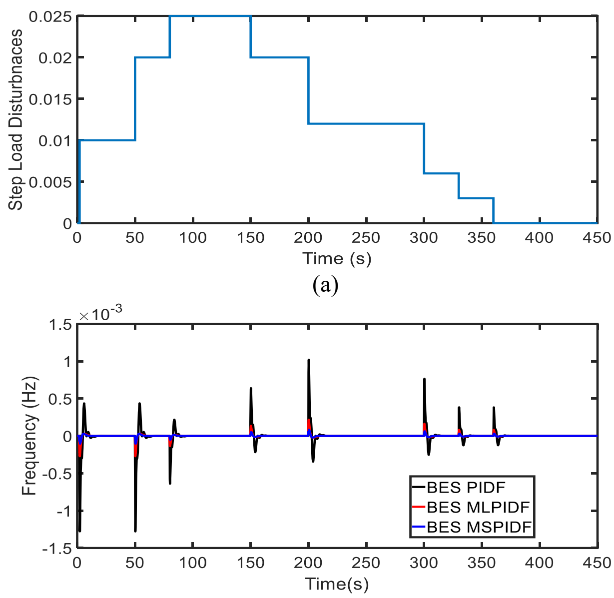


Figure 4. (a) Random load changes in MG, (b) Corresponding MG frequency deviations

Table 1. Performance indices of MG for scenario1

Controller	Peak undershoots (Hz)	Settling time (s)	Error (IAE)
PIDF [3]	-0.00125	22	5.5
MLPIDF [8]	-0.000272	11	4.3
MSPIDF	-0.000105	9.2	2.29

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Remark: The simulation results from scenario1 unequivocally demonstrate that the proposed controller achieves significant enhancements in overshoot reduction, settling time, and Integral of Absolute Error (IAE) values. Proposed MSPIDF controller yields impressive outcomes, reducing overshoot by 61% compared to the MLPIDF controller and by 92% relative to the PIDF controller. Additionally, it effectively decreases settling time by 17% and 41%, respectively.

4.2.Wind power disturbances in MG

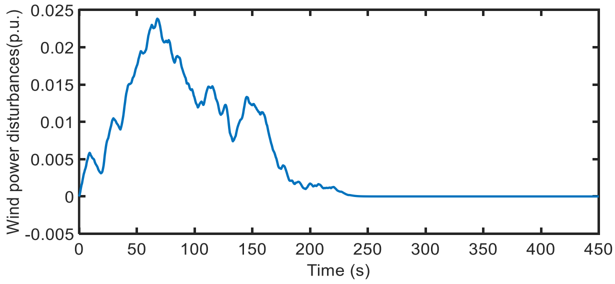
In this scenario, random wind power disturbances are introduced in Area1 as shown in *figure 5(a)*. The frequency deviations within Area1 and Area2 and Tie-line power deviations depicted in *figure 5 (b), 5(c)* and *5(d)* respectively.

Table 2 illustrates dynamic analysis with different controllers.

Table 2. Performance indices of MG subjected to wind power disturbances

Controller Tper	Peak overshoot (Hz)		Peak undershoot (Hz)		Error (IAE)
	Area-1	Area-2	Area-1	Area-2	
PIDF [3]	1.8*e-4	1.7*e-4	-2*e-4	-2.2*e-4	3.63
MLPIDF [8]	0.4*e-4	0.14*e-4	-0.45*e-4	-0.1*e-4	2.92
MSPIDF	0.1* e-4	0.05*e-4	-0.2*e-4	-0.04*e-4	1.45

Remark: The simulation results from scenario2 unequivocally demonstrate that the proposed controller achieves significant enhancements in overshoot reduction, undershoot reduction, and Integral of Absolute Error (IAE) values. proposed MSPIDF controller yields impressive outcomes, reducing overshoot by 75% compared to the MLPIDF controller and by 94% relative to the PIDF controller and undershoot by 56% compared to MLPIDF and 90% compared to PIDF controller in area-1. Additionally, it effectively decreases IAE value by 50.4% and 61%, respectively.



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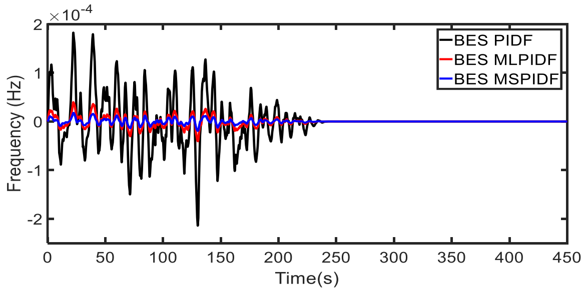

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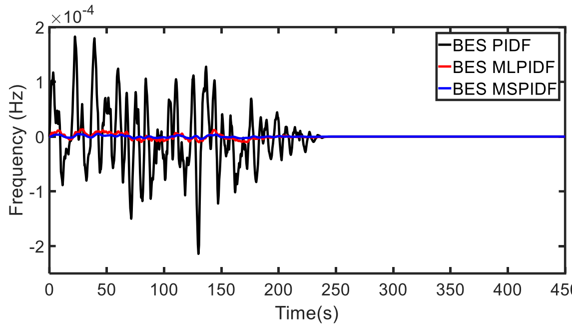

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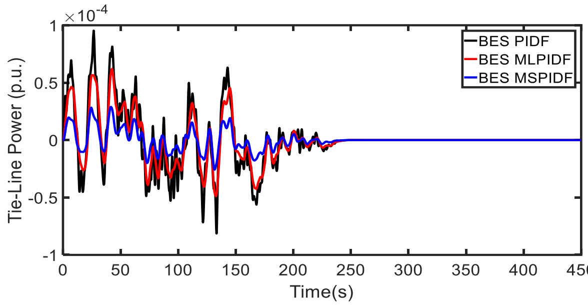
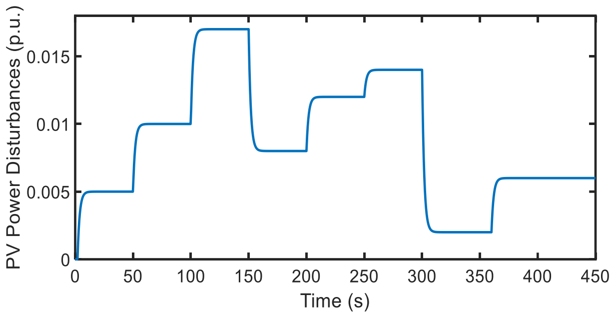


(d)

Figure 5. (a) Random wind power deviations, (b) Frequency deviations in area-1, (c) Frequency deviations between area-1 & area-2, (d) Tie-line power deviations between area-1 &2

4.3. Solar power disturbances in MG

In this scenario, step variant solar power disturbances are introduced in Area2 as shown in *figure 6 (a)*. This approach allows for a comprehensive observation of the resultant frequency deviations within Area1 and Area2 and Tie-line power deviations in between area-1 and area-2. These variations are depicted in *fig. 6(b), 6(c)* and *6(d)* respectively.



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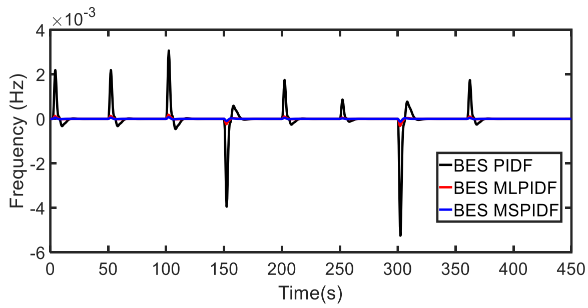

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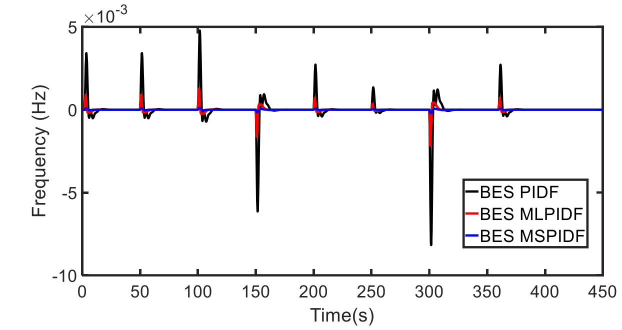

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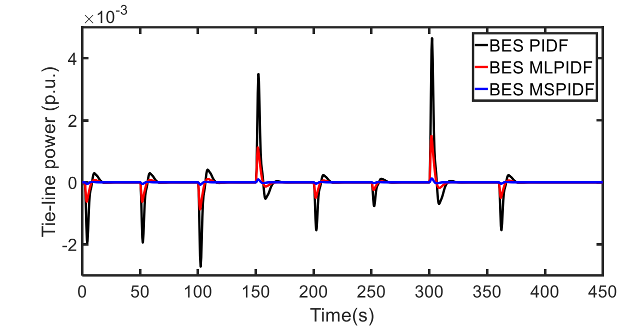
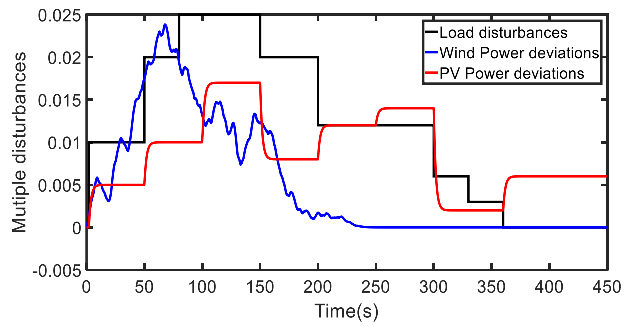


(d)

Figure 6. (a) Random wind power deviations, (b) Frequency deviations in area-1, (c) Frequency deviations between area-1 & area-2, (d) Tie-line power deviations between area-1 &2

4.4. Multiple power disturbances in MG

In this scenario, multiple disturbances like load, solar and wind are introduced in MG simultaneously. In specific, wind and load disturbances are considered in area-1 and solar power disturbances are considered in area-2. Besides that, 50% uncertainty considered in Moment of inertia of the MG. *Figure 7(a)* represents multiple disturbances in MG and *figure 7 (b), (c)* and *(d)* illustrates the corresponding frequency deviation in area-1, 2 and tie-line power deviations between area-1 and area-2. *Table 3* illustrates the optimized gains of various controllers. *Table 4* demonstrates the MG dynamics under scenario4. In this scenario concurrent disturbances in MG and parametric uncertainties are consider to assess the robustness and supremacy of the proposed controller and performance compared with contemporary controllers in the literature *i.e.* MLPIDF and PIDF controllers.



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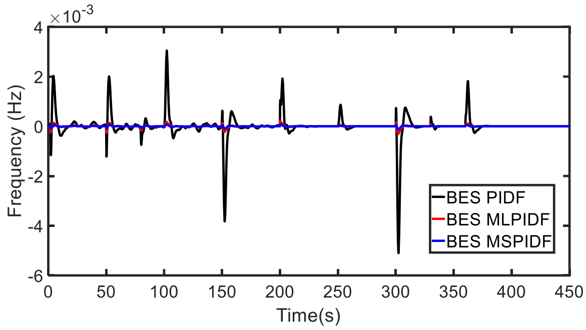

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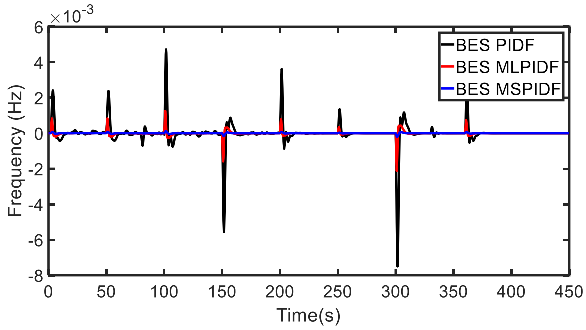

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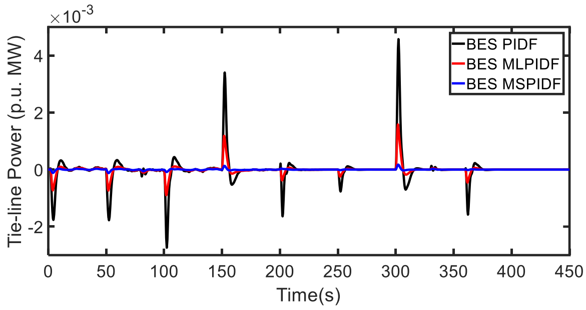

(d)

Figure 7. (a) Random wind power deviations, (b) Frequency deviations in area-1, (c) Frequency deviations between area-1 & area-2, (d) Tie-line power deviations between area-1 &2

Table 3. BES optimized controller gains

Controller parameter	PIDF controller	MLPIDF controller	MSPIDF controller
K_{p1}	4.98	4.97	4.82
K_{i1}	4.963	4.98	5
K_{d1}	1.08	1	4.9963
K_{pp1}	-	4.97	4.99
N_1	167	254	392.7
K_{p2}	4.99	4.995	4.81
K_{i2}	1.67	4.98	5
K_{d2}	3.3	4.92	5
K_{pp2}	387	3.83	4.99
N_2	-	384	393

Table 4. Performance indices of MG subjected to wind power disturbances

Controller Type	Peak overshoot (Hz)		Peak undershoot (Hz)		Error (IAE)
	Area-1	Area-2	Area-1	Area-2	
PIDF [3]	3.1*e-3	4.8*e-3	-5*e-3	-7.6*e-3	35.3
MLPIDF [8]	0.2*e-3	1.1*e-3	-0.3*e-3	-2*e-3	19.81
MSPIDF	0.08* e-3	0.1*e-3	-0.1*e-3	-0.21*e-3	7.36

Remark: The simulation results from scenario4 unequivocally demonstrate that the proposed controller achieves significant enhancements in overshoot reduction, undershoot reduction, and Integral of Absolute Error (IAE) values. *Table 4* demonstrates that proposed MSPIDF controller yields impressive outcomes, reducing overshoot by 80% compared to the MLPIDF controller and by 92% relative to the PIDF controller and undershoot by 83% compared to MLPIDF and 94% compared to PIDF controller in area-1. Additionally, it effectively decreases the IAE value by 44% and 80%, respectively. Furthermore, the proposed controller demonstrates remarkable robustness against concurrent disturbances and parametric uncertainties and is less reluctant compared to other multilevel PID controllers. Quantitative analysis confirms the supremacy and resiliency of the proposed controller against all possible disturbance in microgrid.

5. CONCLUSION

This study proposes a multi-stage control strategy that combines proportional-derivative (PD) and proportional-integral (PI) controllers to enhance a microgrid's load frequency control (LFC) performance. The research findings indicate that adjusting the configuration of the PID controller according to the suggested design significantly improves the microgrid's dynamic frequency response. Various operating scenarios are analyzed to examine the frequency fluctuations in microgrids. The frequency response results show that the proposed controller structure improves overshoot and settling time and substantially reduces the overall error in the system compared to traditional PID controllers. Numerical analysis confirms a minimum of 40% reduction in overall error and a decrease in overshoot/undershoot by 25% compared to multilevel PIDF controller. The study demonstrates that the frequency dynamics of the microgrid can be optimized by implementing a cascading structure and repositioning the integrator component to the second stage of the controller.

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