

Optimizing Filter Integrated Fuzzy-PID Controller for Frequency Regulation in an Isolated Microgrid

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Abstract- The imbalance between power generation and load requirements often causes frequency fluctuations in a unified power system. Secondary controllers are integrated into the generator control loop to quickly reduce these fluctuations and maintain synchronization. This study introduces a first-order filter within a Fuzzy-PID controller, creating a Fuzzy-PIDF (FPIDF) controller, to regulate frequency in an islanded microgrid model. The microgrid model includes various generation sources such as thermal, wind, aqua electrolyzer (AE), battery energy storage system (BESS), fuel cell (FC), and diesel engine generator (DEG). Optimal values for the FPIDF controller's gains are obtained using Mountain Gazelle Optimization (MGO), considering a 5% load deviation in the microgrid model. The Integral Time Absolute Error (ITAE) is used as the fitness function for the tuning process. To validate the effectiveness of the proposed FPIDF controller, the model's load is varied arbitrarily, and frequency stability is examined and confirmed. Additionally, the performance of the FPIDF controller is compared with that of the Fuzzy-PID and PID controllers, both tuned using the same MGO techniques. Through evaluation based on positive peak, settling time, and negative peak responses, it is shown that the FPIDF controller performs better than the Fuzzy-PID and PID controllers. Furthermore, the effectiveness of the FPIDF controller is demonstrated under random variations in load and wind power. The stability of the model is also verified using pole-zero plot and bode plot analysis.

Keywords Microgrid, Frequency Regulation, Controller Tuning, Mountain Gazelle Optimization, Fuzzy control technique.

1. Introduction

The Frequency of a unified power network primarily depends on the equilibrium between power generation and load demand [1]. The uncertain variation of load demand results in the deviance of the network's frequency. The unified network will be in synchronism as long as the frequency of the all unified control areas remains constant. In order to regulate the frequency of the unified network secondary control schemes are engaged in the generator control loop. Damping out of the oscillations of the frequency deviances is the leading role of the secondary controllers.

Adaptive controllers [2] are implemented as secondary controllers by many researchers for frequency regulation in unified power system. Secondary frequency control can be achieved by numerous control strategies. Diverse frequency regulation techniques are explained in the review paper [3]

by Shayeghi et al. PID controller [4-5] remains the first preference of the researchers for regulation of frequency during load perturbations in a unified network. In AC microgrid, the frequency regulation is necessary to damp out the disturbances using a robust adaptive controller [6]. The secondary controller also takes a multi-stage [7] form implemented in the microgrid network to regulate the system frequency. A fuzzy-logic [8] based controller was considered by many authors for examining the frequency deviance control in the network. The power system configuration also affects the strategy of frequency regulation by secondary controllers. Parmar et al. [9] examined a multi-generation model for examining frequency regulation by an effective control strategy. In article [10], frequency regulation was investigated in a nonlinear type network with a fuzzy secondary controller. Photovoltaic units are considered in the paper [11] for the regulation of voltage in a unified network. Fractional calculus-based secondary controllers [12] can also be implemented in the model for effective regulation of

frequency. Robust methodologies [13] are also adapted by the researchers for the investigation of LFC in the network model. E. S. Ali [14] described one of the simplest ways of frequency regulation by PID regulator in a unified network where the constraints were adjusted by the BFO technique. The sliding mode technique [15] was also found suitable in the LFC examination in the interconnected networks. Double-layer capacitor and fuel cell based model [16] is taken for analysing the LFC in the paper [16] with hybrid generation units. Dipayan Guha [17] considered the GWO tuning method for adjusting the constraints of the secondary controller for examining frequency regulation. Robust linear quadratic integral regulator [18] is realised in the microgrid network for examining LFC with virtual inertia control. To overcome the demerits of conventional energy units, researchers engaged sustainable power generating units [19] for LFC investigation. Additionally, EV [20-21] and PHEV [22] can be implemented in the model along with other sources for the effective LFC examination. PID regulator with multi-stage configuration was adapted in the research work [23] for frequency regulation analysis. Sliding mode controller [24] can be considered to adjust the effective balance of frequency in the unified model. Intelligent PI/PD dual mode regulator is engaged in the article [25] for secondary frequency regulation in unified network. Delay [26] in the control phases can be introduced in the model to get a more practical view of the analysis. Fuzzy adaptive [27] regulation technique effectively regulates the frequency in the unified network during load imbalances. Microgrid model with multiple sustainable sources is considered in the article [28] for frequency regulation study. The Mountain Gazelle Optimizer, as discussed in article [29], has been adopted by many researchers to solve various optimization problems. The Type-2 based fuzzy controller described in article [30] is used in a hybrid source network with different distributed generation sources to effectively regulate frequency. Article [31] considers time delays for analyzing Load Frequency Control (LFC) in a more practical approach within a hydro-thermal unified network. Recently, a tuning algorithm called the Black Widow Optimization Algorithm, detailed in article [32], has been applied for frequency regulation in a microgrid model.

From the above survey, it is observed that numerous control approaches are adopted by the researchers to regulate the frequency of the unified network in different models. In our research, we used a filter-based Fuzzy-PID controller to regulate the frequency of a microgrid network. Our main contributions are:

- i. To create a MATLAB model of a microgrid that includes various power sources like thermal, wind, aqua electrolyzer (AE), fuel cell (FC), battery energy storage system (BESS), and diesel engine generator (DEG).
- ii. To develop a filter-based Fuzzy-PID controller and fine-tune its parameters using Mountain Gazelle Optimization.
- iii. To compare the performance of the projected controller (FPIDF) with other controllers like FPID and PID using simulation results from the microgrid model and to show that FPIDF outperformed the others.

- iv. To test the robustness of our controller (FPIDF) by randomly changing the load pattern and varying wind power levels.

2. System Modelling

The microgrid model examined in this research, depicted in Figure 1, encompasses various generation sources. A simplified transfer function-based model, illustrated in Figure 1, is utilized for analysis. The microgrid incorporates multiple generation sources, including both conventional and renewable sources such as thermal, wind, aqua electrolyzer (AE), battery energy storage system (BESS), fuel cell (FC), and diesel engine generator (DEG). The modeling of this isolated microgrid, along with its nominal parameters, is based on the article [22], while the constraints of the model are detailed in the Appendix section. As shown in Figure 1, two distinct controllers (FPIDF/FPID/PID) are implemented in the model to examine the frequency control capabilities of the secondary controllers. The simplified transfer functions of the wind, AE, FC, BESS, and DEG are provided below.

$$G_{WTG}(S) = \frac{\Delta P_{WTG}}{\Delta P_{WP}} = \frac{K_{WTG}}{1 + sT_{WTG}} \quad (1)$$

$$G_{AE}(s) = \frac{\Delta P_{AE}}{u_2} = \frac{K_{AE}}{1 + sT_{AE}} \quad (2)$$

$$G_{FC}(s) = \frac{\Delta P_{FC}}{u_2} = \frac{K_{fc}}{1 + sT_{fc}} \quad (3)$$

$$G_{BESS}(s) = \frac{\Delta P_{BESS}}{u_2} = \frac{K_{BESS}}{1 + sT_{BESS}} \quad (4)$$

$$G_{DEG}(s) = \frac{\Delta P_{DEG}}{u_2} = \frac{K_{DEG}}{1 + sT_{DEG}} \quad (5)$$

Here K and T are source element constant and time coefficient of corresponding generating source units.

The thermal unit considers reheat type turbine. The transfer function of governor, turbine and reheat component is considered as follows.

$$G_{gov}(s) = \frac{K_g}{1 + sT_g} \quad (6)$$

$$G_{tur}(s) = \frac{1}{1 + sT_t} \quad (7)$$

$$G_{reheat}(s) = \frac{1 + sK_r T_r}{1 + sT_r} \quad (8)$$

ΔP_L in the figure 1 depicts the load perturbation applied in the microgrid. The system's frequency is oscillating due to load disturbances, causing instability. In the initial

investigation the ΔP_L is taken as 0.05 per unit. The transfer function of the power system is considered as:

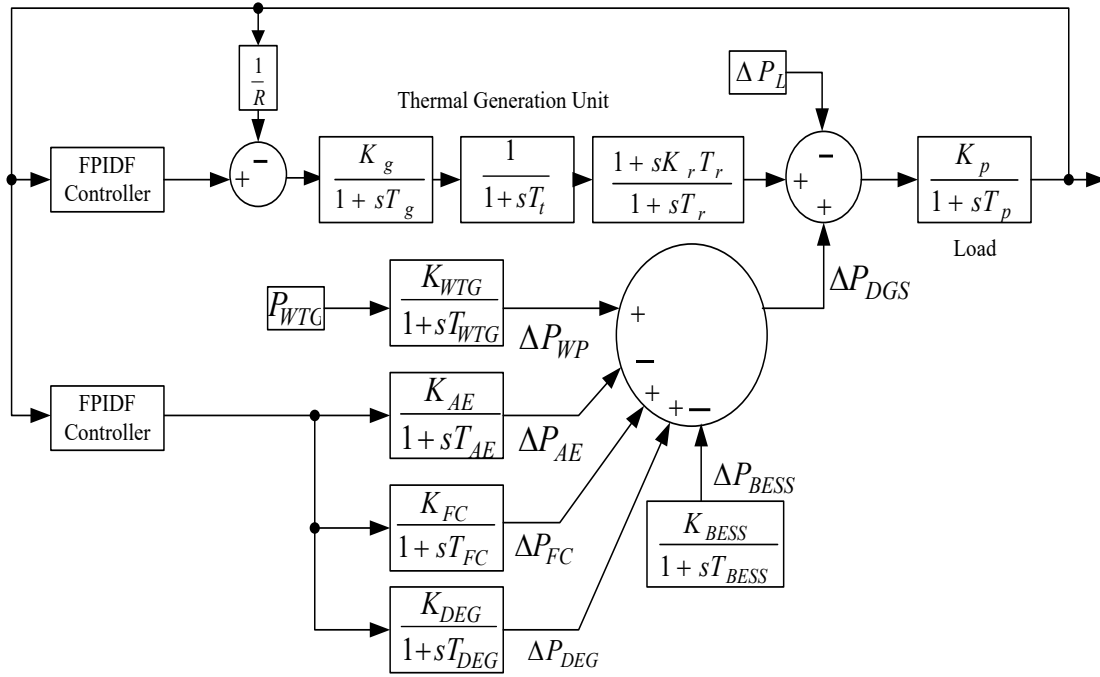


Figure 1. Microgrid model with different sources represented by transfer function.

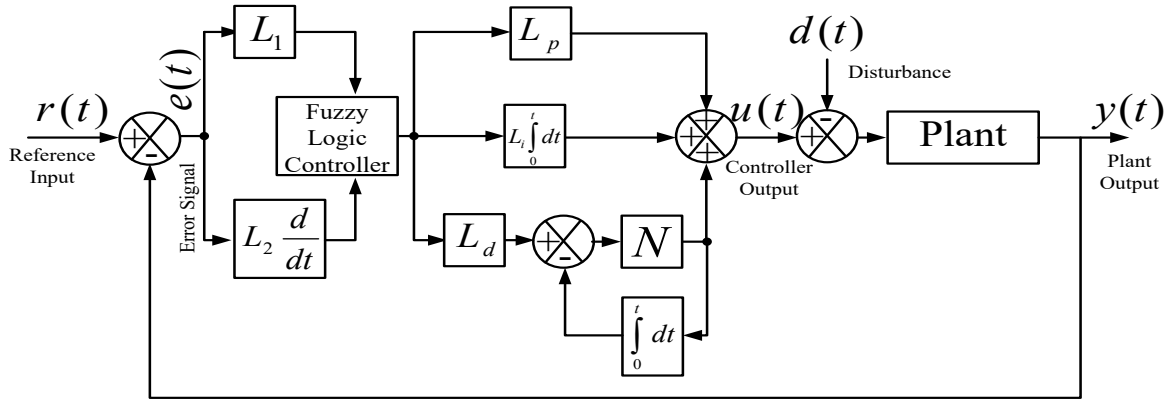


Figure 2. FPIDF controller's configuration.

$$G_{ps}(s) = \frac{K_p}{1 + sT_p} \quad (9)$$

All the system constraints are defined in the appendix.

3. Control Approach

3.1 Mountain Gazelle Optimization:

Inspired by the heirarchy and social activity of mountain gazelles, the MGO [29] was introduced to help in the tuning or optimizing process to attain the global optimum results. The behaviour of gazelles are formulated mathematically to tune the constraints of the fitted controller of the microgrid

model. The tuning process depends on the four life stages of the mountain gazelles, namely maternity herd (MH), solitary territorial male herd (STM), bachelor male herd (BMH) and adult male gazelle (AMG). The best solution is nominated as adult male gazelle. During the process of optimization any gazelle can be part of the above mention herds. The BMH is the gazelle with lowest fitness. The number of iteration, population size, variable dimension detrmnes the computation time. At begining a random population is genarated denoting the gezelles(G_i). For the gezelles in the STM, territory is calculated as follows.

$$STM = m_g - |\delta_1 * Y_m - \delta_2 * X(t) * F| * Cof_r \quad (10)$$

$$Y_m = X_{ra} * [r_1] + M_{pr} * [r_2], r_a = \left\{ \frac{N}{3}, \dots, N \right\} \quad (11)$$

$$F = N_1(D) * \exp(2 - iter * \left(\frac{2}{MI} \right)) \quad (12)$$

$$Cof_i = \left\{ \begin{array}{l} (a+1) + r_3 \\ a * N_2(D) \\ r_4(D) \\ N_3(D) * N_4(D)^2 * \cos((r_4 * 2) * N_3(D)) \end{array} \right\} \quad (13)$$

$$a = -1 + iter * \left(\frac{-1}{MI} \right) \quad (14)$$

Here, in these equations, N= total no of gazelles, r_1 & r_2 = any number between 0-1. m_g = male gazelle population. δ_1 & δ_2 are integers having assigned values either 1 or 2. Y_m = Young male Population, Cof_r = arbitrarily produced coefficient vector, renewed after every iteration. MI = max no of iteration to be carried out. $iter$ = iteration index at a particular time.

The maternity herd comprises female gazelles responsible for birthing new offspring and engaging in reproduction, consequently yielding robust male gazelles. Conversely, adolescent males participate in the endeavor of securing territories within female juvenile gazelle groups. The following equation governs the generation of mother and child herd (MH).

$$MH = Y_m + Cof_{1,r} * (\delta_3 * m_g - \delta_4 * X_{rand}) * Cof_{1,r} \quad (15)$$

X_{rand} is the location vector which is chosen from the entire population. Mountain gazelles exhibit highly territorial behavior, driven by their regular foraging activities. This prompts them to engage in seasonal migrations, moving from one location to another in search of abundant food resources. They selectively settle in habitats where ample sustenance is readily available, showcasing their adaptive behavior in response to changing environmental conditions. The following equation governs the food searching behavior of Gazelles.

$$SF = (hl - ll) * r_9 + ll \quad (16)$$

Where, hl is the higher bound and ll is the lower bound of the mentioned system.

The primary role of the male members within the herd is to engage in territorial disputes and assert dominance over territories essential for the reproduction process. Initially, young males participate in these conflicts, vying for control over female gazelles necessary for birthing offspring. Over time, these adolescent males join forces with the mature counterparts, collectively defending land and territory while also asserting control over additional female members of the herd.

$$BMH = (X(t) - D) + (\delta_5 * m_g - \delta_6 * Y_m) * Cof_r \quad (17)$$

$$D = (|X(t)| + |m_g|) * (2 * r_5 - 1) \quad (18)$$

After computing the fitness of STM, MH, BMH, and SF, they are introduced into the habitat. The entire population is then sorted in ascending order based on their fitness scores. The best-performing gazelle is updated, and a specified number of the best gazelles, denoted as NG, are preserved within the population. ITAE as defined in the equation (19) is taken as the fitness function for the tuning process. The procedural steps of the MGO algorithm are outlined below.

MGO Algorithm Steps:

- Specify the input parameters, including the maximum number of iterations (MI) and the population size (NG).
- Generate a random population of gazelles G_i .
- Evaluate the fitness of each gazelle within the population and designate the best-fitted gazelle as the Adult Male Gazelle (AMG).
- Repeat steps v through vii until the stopping criteria are met.
- Iterate the following sub-steps (a-e) for each gazelle.
 - Evaluate STM applying equation (10).
 - Compute MH applying equation (15)
 - Compute BMH applying equation (17)
 - Compute SF applying equation (16)
 - Apply equation (19) and evaluate the fitness of STM, MH, BMH and SF. Integrate them to the population.
- As per fitness scores arrange the population in ascending order.
- Designate the best-fitted solution within the population as the AMG.
- Return the best solution as AMG.

3.2 Configuration of Controller

PID controllers are commonly utilized for managing frequency oscillations within unified systems due to their straightforward architecture. However, researchers favor the Fuzzy-PID controller for its enhanced disturbance management capabilities compared to PID controllers. The conventional structure of Fuzzy-PID controllers involves five gains (L_1, L_2, L_p, L_i and L_d) and an inference engine, generating control signals based on fuzzy IF-THEN rules. Nevertheless, in certain scenarios, traditional Fuzzy-PID controllers may fail to detect unwanted signals in the output. To address this issue, a filter is integrated into the Fuzzy-PID controller, resulting in the Fuzzy-PIDF controller, which performs more effectively than its original counterpart.

The architecture of the FPIDF controller, illustrated in Figure 2, incorporates six parameters (L_1, L_2, L_p, L_i, L_d and N). The inference engine utilized by the FPIDF controller follows the Mamdani type. Within the fuzzy section, there are two input and one output variables. Fuzzification, inference engine operation, and defuzzification constitute the

three phases of fuzzy action. Triangular-shaped membership functions (NB, NS, Z, PS, PB) are defined for both input and output variables, as depicted in Figure 3. Expertly crafted IF-THEN fuzzy rules govern the control output of the fuzzy segment, with twenty-five rules established for the fuzzy section, as shown in Table 1. In the microgrid model, there are two controllers, resulting in twelve constraints for the tuning process. Evaluation reveals that the output of the designed FPIDF controller yields superior control signals compared to FPID and PID controllers. The filter, along with the fuzzy controller, helps dampen frequency oscillations in the microgrid model, maintaining the system's frequency stability.

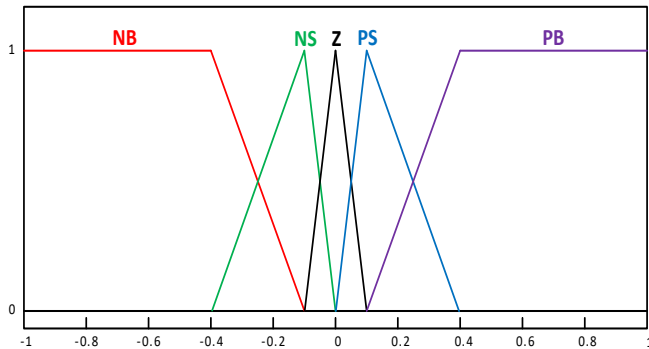


Figure 3. Five Membership functions of FPIDF controller

Table 1. Rule-base defined for FPIDF controller.

ACE	$\dot{ACE}$				
	NB	NS	Z	PS	PB
NB	NB	NB	NB	NS	Z
NS	NB	NB	NS	Z	PS
Z	NB	NS	Z	PS	PB
PS	NS	Z	PS	PB	PB
PB	Z	PS	PB	PB	PB

4. Result and Discussion

The MATLAB software has been utilized for modeling the microgrid network, incorporating two distinct FPIDF regulators as depicted in Figure 1. To assess the control action of the secondary FPIDF controller, a 5% load perturbation is applied, and the MGO technique is employed to fine-tune the constraints of the FPIDF, FPID, and PID controllers using ITAE as the cost function, as described by the following equation.

$$ITAE = \int_0^t (|A_f|) t dt \quad (19)$$

The MGO tuning process employs a population dimension of 100 and runs for 100 iterations. After 20 independent runs, the finest constraints are obtained. Twelve controller constraints associated with the two FPIDF

controllers are indicated in Figure 2. The tuned values of the gains of the FPIDF, FPID, and PID controllers are elaborated in Table 2. With these optimal controller constraints, the microgrid outcomes are plotted in the form of frequency oscillations, as depicted in Figure 4. The responses of FPIDF, FPID, and PID controllers for frequency deviations are superimposed in Figure 4 to assess their comparative performance. Response evaluative indices such as positive and negative peaks and settling time are tabulated in Table 3. The response with lower values of positive and negative peaks and settling time is considered the best performing outcome. In the subsequent stage, the loading of the microgrid model is incrementally increased and decreased by 1%, resulting in step load perturbations of 6% and 4% respectively. Response evaluative indices are recorded for all three controllers: FPIDF, FPID, and PID, and are portrayed in Table 3. The ascendancy of the FPIDF controller over the PID and FPID controllers can be observed from the data presented in Table 3 and Figure 4. Further the following examinations are accomplished to verify the sturdiness of the projected controller.

4.1 Variation of Loading for Robustness Analysis:

Furthermore, robustness analysis is conducted with random loading. The capability of the adjusted FPIDF controller is tested by applying a random loading pattern to the microgrid system, as shown in Figure 5. The outcome, in terms of frequency oscillation of the microgrid model in response to this random load, is depicted in Figure 6. It can be observed that the suggested FPIDF controller successfully dampens the frequency oscillations of the microgrid model even when uncertain load perturbations are applied, supporting the robustness of the applied PIDF controller. The outcomes of the microgrid model for all mentioned controllers, including PID, FPID, and FPIDF controllers, are compared and depicted in Figure 7, further confirming the dominance of the FPIDF controller.

4.2 Sturdiness Analysis with Variable Wind Power:

In this section, the robustness analysis is conducted with variable wind power. The wind power of the wind turbine generator varies throughout the day, and to reflect a more practical scenario, the wind input power of the WTG is varied randomly as depicted in the Figure 8. The frequency oscillations of the microgrid model due to this variable wind input with PID, FPID, and FPIDF controllers are plotted in Figure 9. Here, it can be observed that the response of the FPIDF controller is superior compared to the PID and FPID controllers, confirming the dominance of the FPIDF controller.

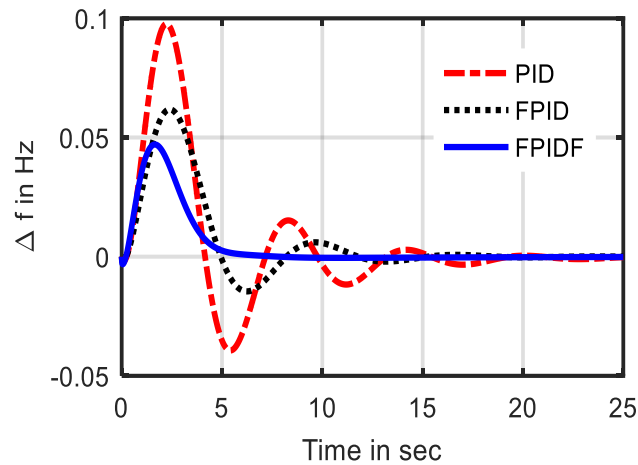


Figure 4. Frequency oscillations of the microgrid due to 5% SLP.

Table 2. Tuned controller constraints attained by MGO.

Controller	Controller 1						Controller 2					
	L_1	L_2	L_p	L_i	L_d	N	L_1	L_2	L_p	L_i	L_d	N
FPIDF	1.612	0.415	1.847	0.201	2.69	156	1.542	0.215	0.487	2.854	2.16	186
FPID	2.772	1.126	1.502	1.210	2.14	NA	1.365	2.984	1.044	2.456	1.98	NA
PID	L_p		L_i		L_d		L_p		L_i		L_d	
	2.4684		2.3518		0.9742		0.9972		2.987		2.0372	

Table 3. Outcome evaluative indices for different controllers with 5%,4% and 6% loading.

Controller	5%SLP			4%SLP			6%SLP		
	U_{sh}	O_{sh}	T_s	U_{sh}	O_{sh}	T_s	U_{sh}	O_{sh}	T_s
PID	-0.0393	0.0976	24.2900	-0.0400	0.0994	24.2800	-0.0387	0.0960	24.3000
FPID	-0.0146	0.0618	17.6500	-0.0148	0.0630	17.6400	-0.0143	0.0606	17.6600
FPIDF	-0.0032	0.0471	6.7800	-0.0024	0.0479	6.7700	-0.0041	0.0463	6.8000

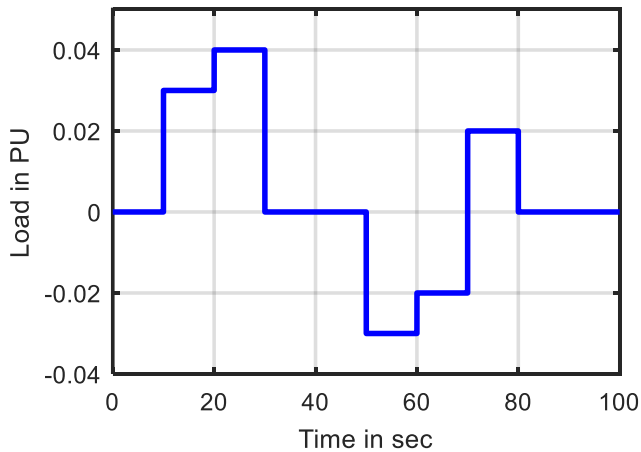


Figure 5. Pattern of the random load applied to the microgrid.

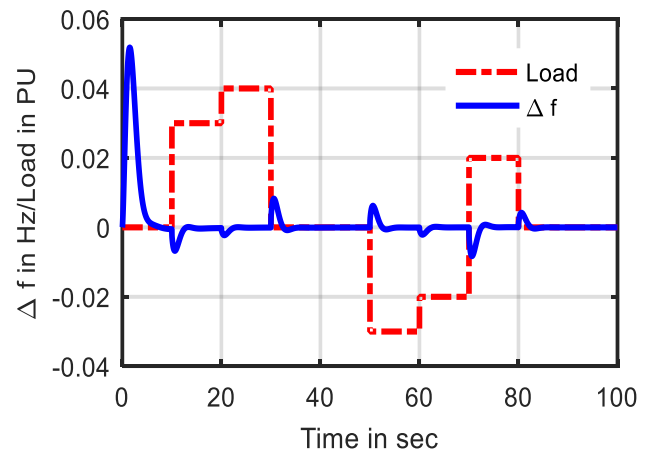


Figure 6. Microgrid frequency oscillations due to

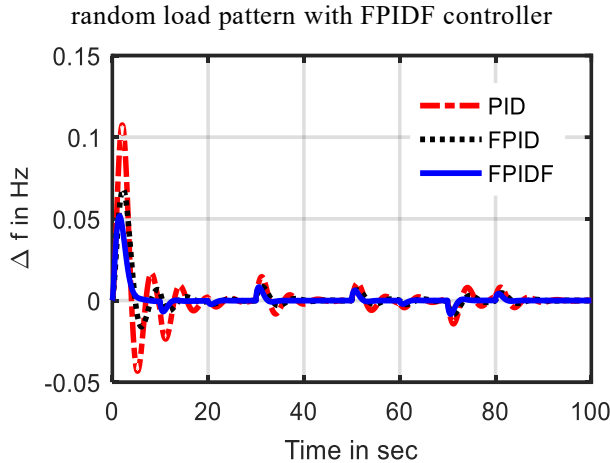


Figure 7. Comparison of frequency oscillations due to random load with all controllers.

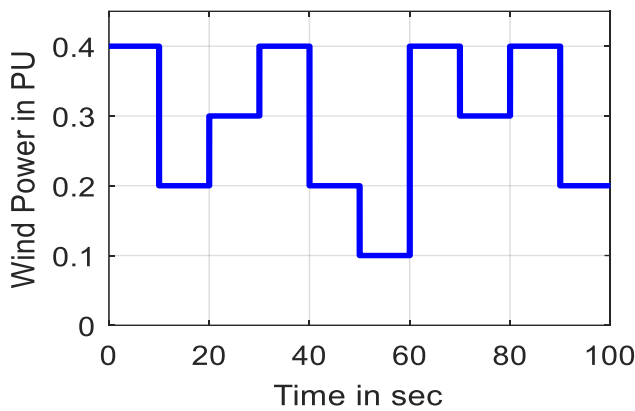


Figure 8. Variation of wind power in per unit.

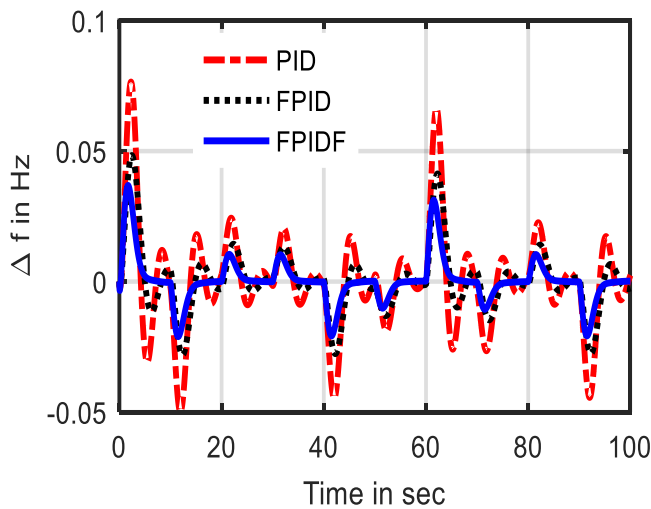


Figure 9. Microgrid frequency oscillations due to variable wind power.

4.3 Stability Analysis with Bode Plot:

Finally, stability analysis is performed using Bode plots. The stability of the microgrid model is verified through pole-zero plots and Bode plots. The pole-zero plot of the scrutinized model with the FPIDF controller is depicted in Figure 10, showing no poles or zeros of the system lying on

the right half of the s-plane, proving that the designed model is stable. Additionally, the Bode plot of the system, depicted in Figure 11, shows a gain margin of 19.7 dB at a frequency of 11.7 rad/sec, further confirming the closed-loop stability of the system.

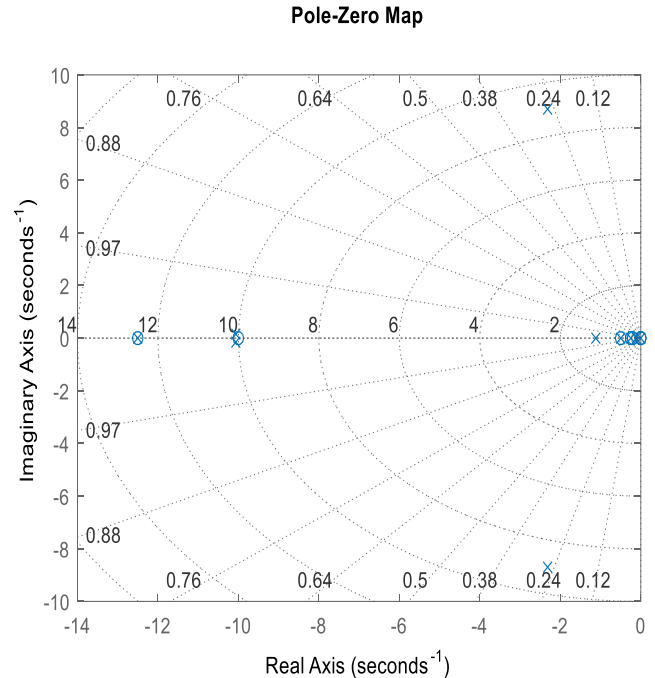


Figure 10. Pole-zero plot of the Microgrid model with FPIDF controller.

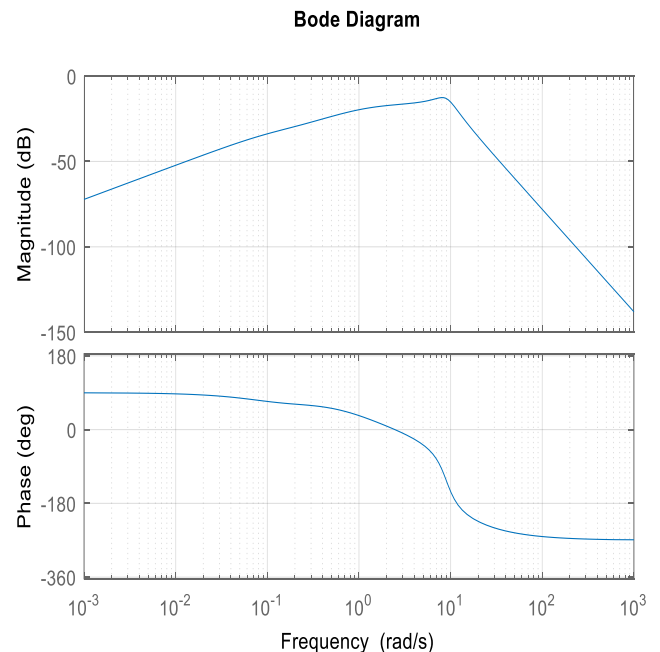


Figure 11. Bode plot of the Microgrid model.

5. Conclusion

This paper investigated frequency regulation within a microgrid model employing the newly introduced filter-fitted Fuzzy-PID (FPIDF) controller. To optimize the controller's performance, Mountain Gazelle Optimization was employed

while varying the load by 5%. The results demonstrate that the FPIDF controller, with its tuned constraints, outperforms both FPID and PID controllers in terms of response. Additionally, the robustness of the FPIDF controller was evaluated by subjecting the microgrid model to a wide range of load deviations, where it efficiently managed frequency regulation even under random load conditions. Furthermore, varying wind power input arbitrarily further established the controller's robustness. Through comprehensive analysis, it is evident that the introduced FPIDF controller effectively regulates the frequency of the microgrid model, showcasing its efficacy in handling dynamic and unpredictable operating conditions. This research underscores the significance of the FPIDF controller in enhancing the stability and reliability of microgrid systems, thus contributing to the advancement of renewable energy integration and grid resilience.

Appendix

Parameters of the Microgrid model:

Parameters of thermal generation unit:

$$K_r = 0.5, K_g = 1, K_p = 120, T_r = 10s, T_g = 0.08s,$$

$$T_p = 20s, T_t = 0.3s, B = 0.425 \text{ MW/Hz}, R = 2.4 \text{ Hz/MW}$$

Parameters of other generation units:

$$T_{WTG} = 1.5s, T_{AE} = 0.5s, T_{BESS} = 0.1s, T_{DEG} = 2s, T_{FC} = 4s,$$

$$K_{WTG} = 1, K_{AE} = 1/500, P_{WTG} = 0.5 \text{ pu}, K_{FC} = 1/100,$$

$$K_{DEG} = 1/300, K_{BESS} = -1/300$$

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N/A

Author Contributions

All authors were responsible for the conceptualization, validation, resources, data curation, software development, and project administration. They jointly contributed to the methodology, formal analysis, investigation, original draft preparation, review and editing, visualization, supervision, and funding acquisition. All authors have read and agreed to the published version of the manuscript.

Conflict of Interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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