Improvement of load frequency control performance for shipboard microgrid system

Cong-Trang Nguyen[1], Nguyen Nghia Tin[2], Thai Pham Thien Hao[2], Phan Tan Liem[2]
[1]Power System Optimization Research Group, Faculty of Electrical and Electronics Engineering, Ton Duc Thang University, Ho Chi Minh City, Vietnam
[2]Faculty of Electrical and Electronics Engineering, Ton Duc Thang University, Ho Chi Minh City, Vietnam

Article Info

Article history:

Received Jan 21, 2025
Revised Sep 10, 2025
Accepted Sep 27, 2025

Keywords:

Fuzzy control
Load frequency control
Renewable energy sources
Shipboard microgrid system
Storage systems

ABSTRACT

This research studies the shipboard microgrid (MG) scheme's frequency fluctuations problem contrary to the impulsiveness of renewable resources, load instabilities, and the uncertainty of the parameters in the ship MG plant. A shipboard MG system consists of some of the renewable energy resource s (RESs) such as photovoltaic (PV), wind turbine generator (WTG), battery energy storage system (BESS), ship diesel generator (DG), fuel cell (FC), aqua electrolyzer (AE), and loads. A new fuzzy proportional integral derivative (FPID) controller is established to attain the desired frequency stability for the shipboard MG system. Additionally, various scenarios are executed in this research to validate the robustness of the anticipated controller to various load disturbances, parameter changes of plant, and fluctuations of solar irradiance and wind speed. The numerical simulation results obtained in three scenarios compared with those of the conventional PID controller and the existing time-varying derivative fractional order PID (TVD-FOPID) controller in literatures to validate the high usefulness and applicability of the planned control strategy. In brief, the established load frequency controller (LFC) based on FPID technique can improve frequency deviation in shipboard MG plant effectively.

Corresponding Author:

Cong-Trang Nguyen
Power System Optimization Research Group, Faculty of Electrical and Electronics Engineering
Ton Duc Thang University
Ho Chi Minh City, Vietnam
Email: nguyencongtrang@tdtu.edu.vn

1. INTRODUCTION

Maritime transport is one of the prominent ingredients of international business. World business and economic maturation are profoundly supported by shipment. In the marine industry, because the amount of conventional diesel generators (DGs) used is so large, emission of ships needs to be reduced by using renewable energy resources (RESs). In recent years, scientists are increasingly focusing on developing shipboard microgrid (MG) systems that use RESs such as wind, wave power, and solar. However, the challenge of the frequency instability on the shipboard MG systems is the biggest concern today. The load frequency control (LFC) of a electricity plant is a significant direction of electricity quality. The frequency irregularity arrives zero in changed control region demarcated in power systems [1]-[3]. To improve the maritime power system's dependability and enhance the quality of the power, the energy storage systems (ESSs) including batteries, flywheels, or aqua electrolyzer (AE) have been supplemented to shipboard MG system. In addition, the LFC for the shipboard MGs is significant direction of power quality. Therefore, the LFC problem of onboard MGs, along with other control systems, has received significant attention in numerous recent studies published in internationally well-known journals [4]-[12] and in the associated references therein.

In practical shipboard MG systems, LFC is very important issue since it adjusts the balance between creation of energy and load demand [13]. LFC includes controlling and monitoring to certify that the frequency of the ship's MG structure is within a safe operating range [14]. Several control methods have been proposed to establish a LFC with enhanced performance to possess the frequency within the values described as [13], [15]-[20]. Double stage controller was utilized by combining the optimization algorithm with proportional integral derivative (PID) in maritime MG plant based on hybrid wind-ocean wave power [13]. A LFC based on a novel modified PID with filter was presented for marine MG system integrated with renewable energy sources [15]. Based on the meta-heuristic optimization algorithms, researchers in [16] developed a PID controller for regulating frequency in standalone marine MG system. A fractional-order dynamic output feedback controller was established for shipboard MGs [17]. A robust fractional-order PID controller was proposed to regulate frequency of islanded MG [18]. A new robust model predictive controller was created by utilizing the linear matrix inequality (LMI) approarch for controlling a MG on the shipboard in the presence of disturbances and the uncertainty of its parameters [19]. In order to optimize the fractional-order LFC's parameters for an isolated MGs, PI controller was developed based on modified sine cosine algorithm in [20]. Nevertheless, the LMI controllers and fractional order controllers in the above studies have very complex designs which lead to very large elapsed times and may not be feasible in practical control systems. Since the operating conditions of LFC vary greatly, the traditional PID controller that is usually tuned under nominal conditions cannot operate normally under other conditions. Therefore, to overcome the shortcomings of these studies, fuzzy logic (FL) can optimally regulate the constraints of the PID controller. The FL control technique is currently widely used in power systems [21]-[23]. Based on the advantages of FL technique, in this study we use the FL approach to optimize the PID controller parameters, which means that the PID structure is extended to the fuzzy-PID structure (FPID). Compared with PID technique, FPID increases reliability and robustness. Based on FPID method, recent studies [10], [11], [24] have proposed different controllers to solve the frequency control problem in shipboard MGs. A novel fuzzy fractional-order PI controller was investigated for the secondary LFC of the shipboard MG [10]. Grasshopper optimization algorithm tuned fuzzy-based PID through filter control procedure was anticipated to explore the performance of the LFC structure for the marine power systems [11]. Recently, the authors in [24] used the time-varying fractional derivative technique to design a PID controller (TVD-FOPID) to achieve the desired frequency stability in a shipboard MG system. This study considers the frequency oscillation problem of the shipboard MG system against load uncertainty and variability of renewable energy sources. However, the overshoot and frequency deviation amplitude are still quite large. So, the key improvements of this investigation are as follows:

- An innovative FPID controller based on FL technique is anticipated as the secondary load frequency regulation problem of the shipboard MG plant.
- The anticipated FPID controller is associated with the typical PID controller and the recent TVD-FOPID controller in [24] considering different variations of renewable resources (wind power and solar power), load disturbances, and the uncertainty of the parameters in the ship MG plant to demonstrate the efficiency of the technique.
- Simulation and robustness analysis of the suggested FPID controller are performed via three numerical scenarios of the shipboard MG system.

The rest of this creation is systematized as follows: section 2 handles modelling of shipboard MG plant including ship DG, battery energy storage system (BESS), electrolyzer-based fuel cells (FCs), and renewable energy sources such as photovoltaic (PV) and wind turbine generator (WTG). The main achievements of the paper are represented in section 3, which the controller is designed and its performance is also analyzed in detail. In section 4, the simulated responses of the LFC problem are inspected and evaluated explicitly containing a comparison of the controller performances under different disturbance conditions. Lastly, the ends of this study are offered in section 5.

2. MATHEMATICAL MODEL OF SHIPBOARD MICROGRID SYSTEM

A shipboard MG system is modeled in this section. Figure 1 displays the transfer function of the modeling ship MG plant. The shipboard MG system includes PV, WTG, DG, FC, AE, and energy storage elements [e.g., BESS]. These components can be particularly planned on-board a marine power vessel to supply its local loads connected to the shipboard MG power bus. All components of the shipboard MG system are assumed as linear models using the first-order transfer functions. The parameters of shipboard MG system are described in [24].

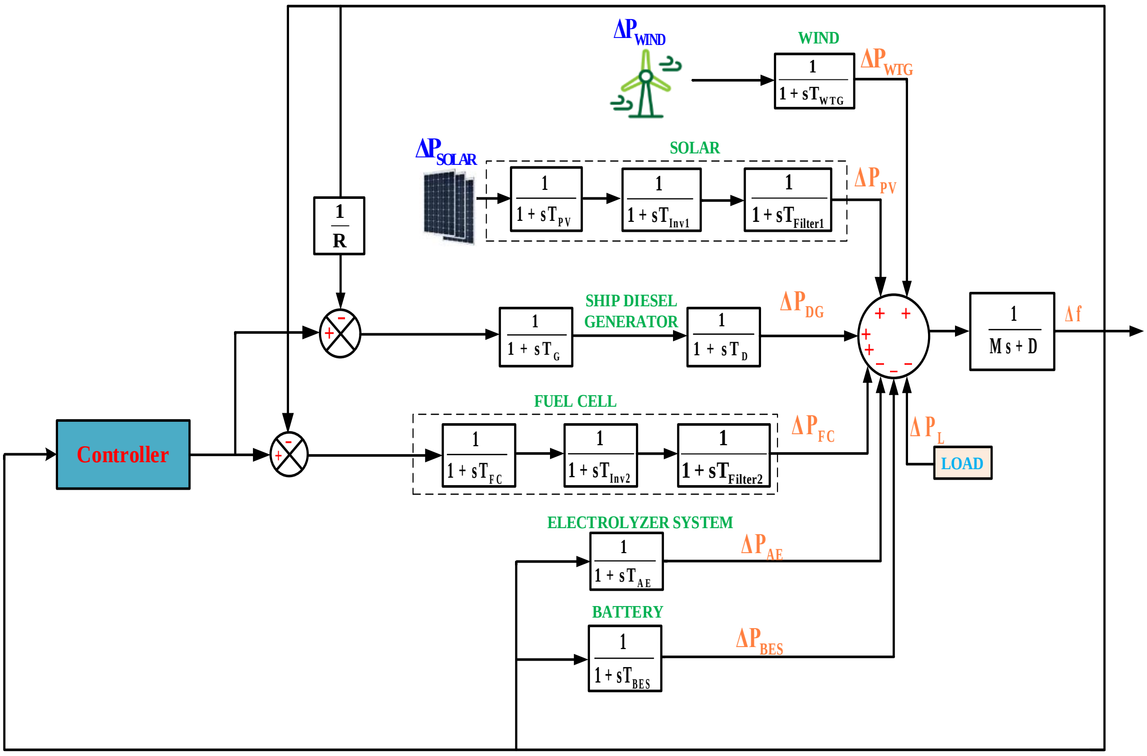


Figure 1. Mathematical model of investigated shipboard MG system

For the shipboard MG system to operate stably, the renewable energy sources supplying the MG plant such as solar and wind sources must be effectively controlled to gratify the demand of the ship's MG system.

So, some techniques for power control based on source power and load power are extensively used and are shown in (1) [20]. From Figure 1, applying the energy conservation principle total energy is as (1):

$$\Delta P_{LOAD} = \Delta P_{PV} + \Delta P_{WTG} + \Delta P_{DG} + \Delta P_{FC} \pm \Delta P_{AE} \pm \Delta P_{BESS}. \quad (1)$$

In shipboard MG system, due to the change of load and renewable energy sources, the grid frequency deviation can be stated as (2):

$$\Delta f = \frac{1}{Ms+D}(\Delta P_{PV} + \Delta P_{WTG} + \Delta P_{DG} + \Delta P_{FC} - \Delta P_{AE} - \Delta P_{BESS} - \beta\Delta f - \Delta P_L). \quad (2)$$

Here M is the inertia constant with the value of 0.2 and D is the damping constant with the value of 0.12.

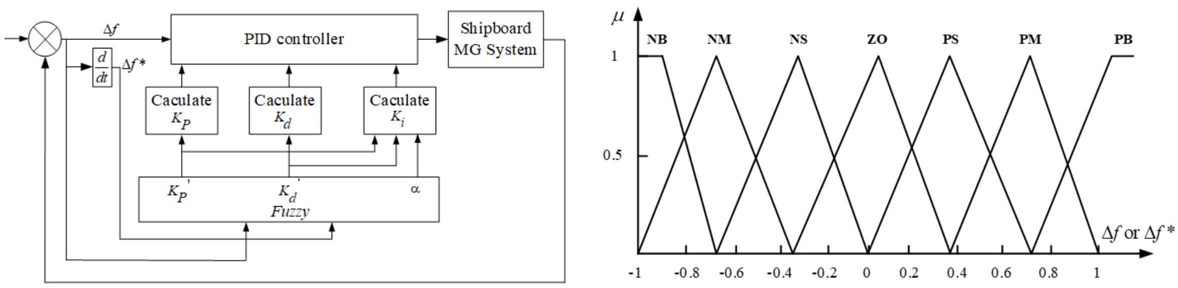
3. DESIGN OF THE FUZZY PROPORTIONAL INTEGRAL DERIVATIVE CONTROLLER

The main purpose of the research is to design a controller to stabilize the load frequency for the shipboard MG system under load changes and uncertainties of renewable energy sources. In fact, PID technique is quite popular and chosen by many control engineers because it has some advantages such as good reliability and cost effective. The PID controller [25] is categorized by three constraints: K_p, K_d, and K_i. Arrogant that K_p and K_d are always in the variety $[K_{pmin}, K_{pmax}]$ and $[K_{dmin}, K_{dmax}]$ it is sensible to express (3) and (4):

$$K_d' = (K_d - K_{dmin})/(K_{dmax} - K_{dmin}), K_p' = (K_p - K_{pmin})/(K_{pmax} - K_{pmin}),$$
$$K_i = K_p/\alpha T_d = K_p^2/(\alpha T_d) \quad (3)$$

$$K_{pmin} = 0.32\,K_u, K_{dmin} = 0.08\,K_u, T_u, K_{pmax} = 0.6\,K_u, K_{dmax} = 0.15\,K_u, T_u, \quad (4)$$

where $T_i = \alpha T_d$, K_u, and T_u are, respectively, the gain and the period of the oscillation at the stability limit under P-control. PID structure is extended to FPID structure due to its several benefits. The FPID can enhance its reliability and robustness as compare to PID. The FPID controller uses a fuzzy system to automatically adjust the parameters K_p, K_i, K_d of the PID controller. The fuzzy system will generate adjustment values $K_p^{'}$, $K_i^{'}$, $K_d^{'}$, which are then input into the PID formula to calculate the control signal. Fuzzy variables of two inputs Δf and Δf^* are negative big (NB), negative medium (NM), zero (ZO), negative small (NS), positive small (PS), positive big (PB), and positive medium (PM). The fuzzy variables of the two inputs $K_p^{'}$ and $K_d^{'}$ are S, M respectively for small and big, respectively. Fuzzy variables of α are S, MS, MB, and B correspond small, medium small, medium big, and big. The structure of the FPID controller is showed in Figure 2(a). In addition, the fuzzy controller premeditated with Δf and Δf^*inputs has the membership functions offered in Figure 2(b) and Tables 1-3. Figures 3(a) and (b) illustrates the membership functions of the output scaling factors K_p' and K_d' and the coefficient α, respectively. The outputs of the fuzzy set are $K_p^{'}$, $K_d^{'}$, and α.



(a) (b)

Figure 2. Fuzzy system: (a) structure of FPID controller and (b) the membership functions of Δf and Δf^*

Table 1. Fuzzy rule for $K_p^{'}$

Δf	Δf^* NB	NM	NS	ZO	PS	PM	PB
NB	B	B	B	B	B	B	B
NM	S	B	B	B	B	B	S
NS	S	S	B	B	B	S	S
ZO	S	S	S	S	S	S	S
PS	S	S	B	B	B	S	S
PM	S	B	B	B	B	B	S
PB	B	B	B	B	B	B	B

Table 2. Fuzzy rule for $K_d^{'}$

Δf	Δf^* NB	NM	NS	ZO	PS	PM	PB
NB	B	B	B	B	B	B	S
NM	B	B	B	B	B	B	S
NS	S	S	B	B	B	S	S
ZO	S	S	S	S	S	S	S
PS	S	S	B	B	B	S	S
PM	B	B	B	B	B	B	S
PB	B	B	B	B	B	B	B

Table 3. Fuzzy rule for α

Δf	Δf^* NB	NM	NS	ZO	PS	PM	PB
NB	S	S	S	S	S	S	S
NM	MS	MS	MS	MS	MS	MS	S
NS	M	MS	MS	MS	MS	MS	M
ZO	M	M	M	M	M	M	M
PS	M	MS	MS	MS	MS	MS	M
PM	MS	MS	MS	MS	MS	MS	MS
PB	S	S	S	S	S	S	S

From (3) and (4), (5) can be deduced:

$$K_p = (K_{pmax} - K_{pmin})K_p^{'} + K_{pmin}, K_i,\ K_p^2/\alpha T_d, K_d = (K_{dmax} - K_{dmin})K_d^{'} + K_{dmin}, \qquad (5)$$

The above factors will be applied when running the PID–like FL controller in dealing with the LFC of shipboard MG system. The flowchart of the FPID is presented in Figure 4. In the following section, simulation results and discussions will be offered specifically under different operating conditions.

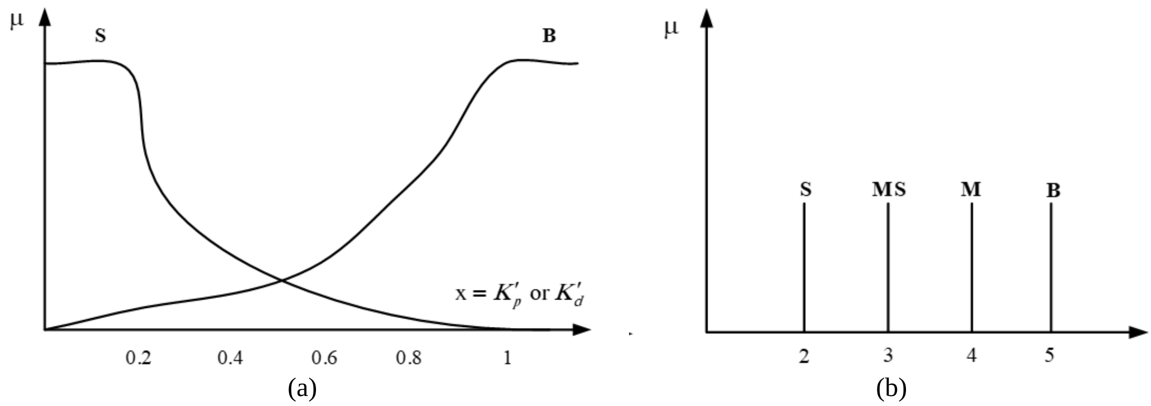


Figure 3. Membership functions: (a) $K_p^{'}$ and $K_d^{'}$ and (b) α

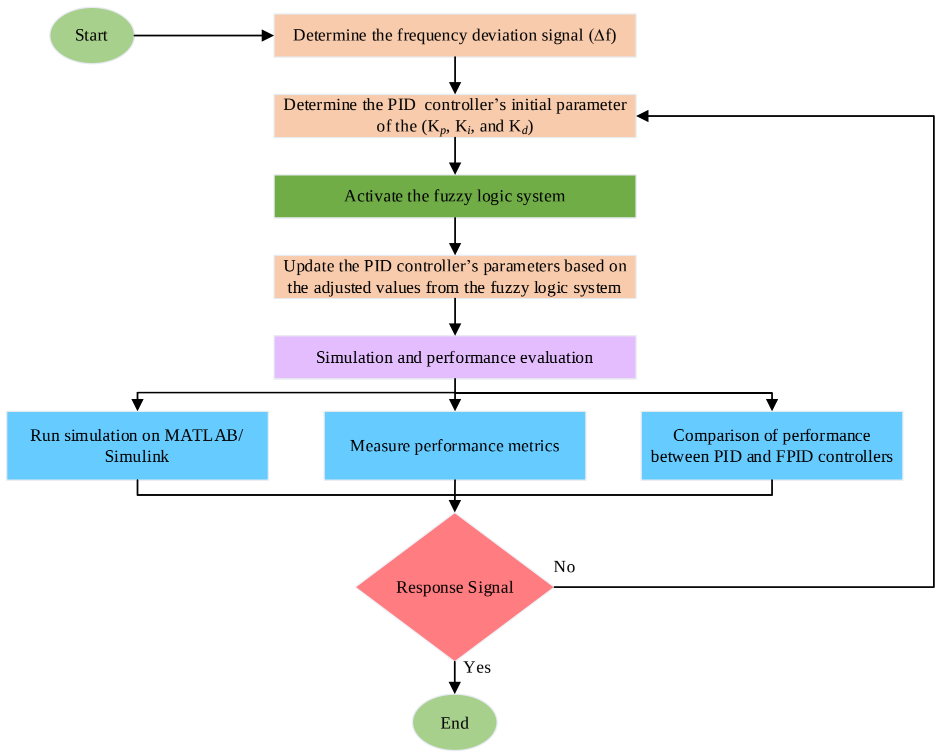


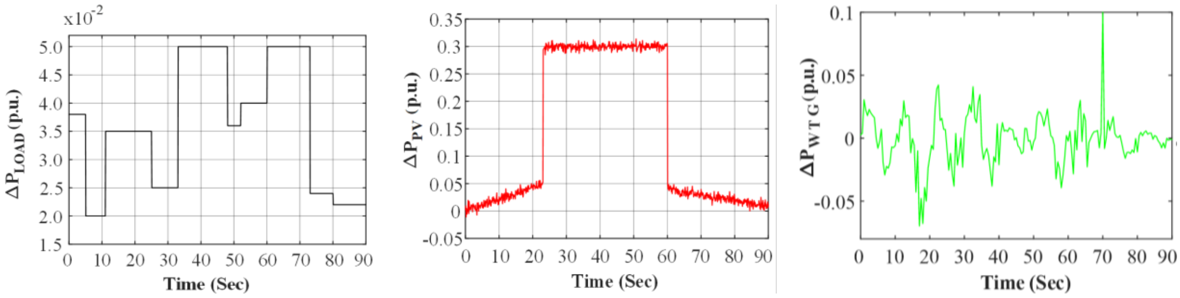
Figure 4. Flowchart for proposed FPID method

4. CASE STUDIES AND RESULTS

In this section, the shipboard MG system is assessed based on FPID controller by using the MATLAB/Simulink software. The feasibility of the suggested FPID controller will be tested through three scenarios. The shipboard MG system's parameters are gotten from [24]. The obtained simulation results will be compared with those of the traditional PID controller and the existing LFC counterparts to prove the high success and applicability of the anticipated control approach.

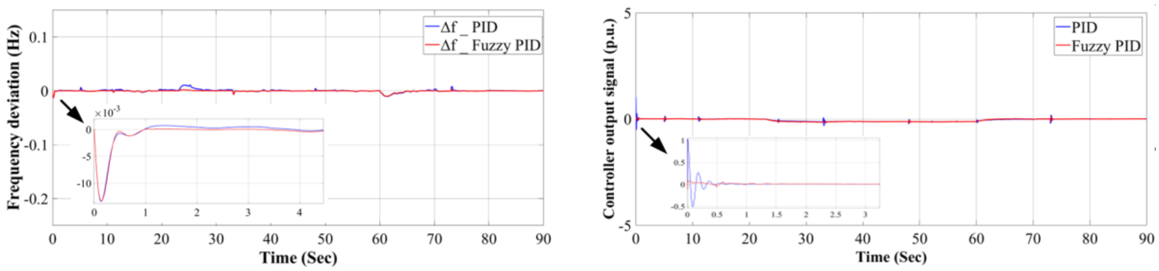
4.1. Scenario 1: performance analysis of the suggested controller with multi-step load perturbations

In this scenario, the performance of the suggested method is cautiously inspected considering multi-step load and the simultaneous perturbations of wind and solar. We examine the load change in a multi-step form and the power vacillations of PV and the wind turbine in Figure 5. Specifically, Figures 5(a), (b), and (c) show the step changes of the load, the active power variations of the photovoltaic (PV) source, and the fluctuating wind turbine power output due to wind speed variations, respectively. The output frequency and controller output curves are displayed in Figures 6(a) and (b), respectively.



(a) (b) (c)

Figure 5. Power fluctuations: (a) step changes of the load, (b) PV, and (c) wind turbines for first scenario



(a) (b)

Figure 6. Response of the first scenario: (a) the system frequency and (b) controller output amplitude

Remark 1: according to Figure 6(a), the FPID controller attains a lower maximum frequency deviation (±0.098 Hz) compared to the PID controller (±0.105 Hz), representing an improvement of approximately 4-7%. The frequency deviation response shows that the FPID controller achieves faster settling and significantly reduced oscillations compared to the conventional PID controller. Furthermore, as shown in Figure 6(b), the FPID significantly reduces the peak controller output signal to approximately ±0.38 p.u., compared to ±0.52 p.u. for the PID controller, corresponding to a reduction of about 27%. This indicates that the FPID controller produces smoother and less oscillatory control signals, enhancing stability and reducing control effort. Thus, we can see that compared with the TVD-FOPID controller in the case 1 of paper [24], the proposed FPID controller offers superior transient performance and improved stability.

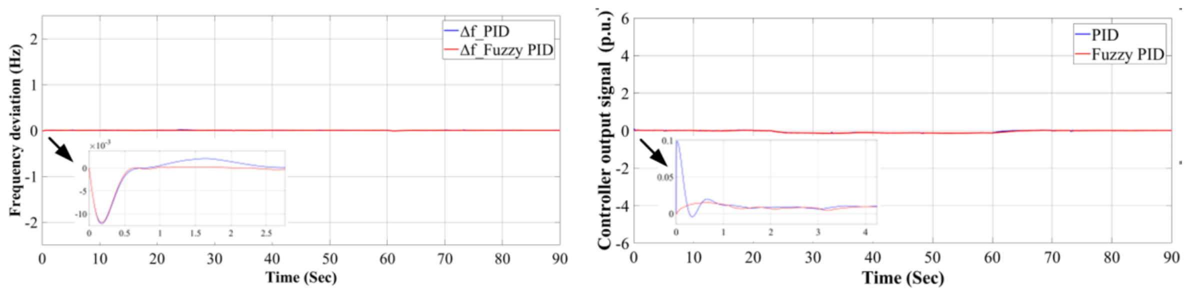
4.2. Scenario 2: sensitivity analysis of the FPID controller to parameter changes of ship MG system

To examine the robustness of the suggested FPID controller, the uncertainty of the parameters in the ship MG plant are wide-ranging by some ranges as exposed in Table 4. The multi-step load and distributed energy resources (wind turbine and PV) have been applied to the ship MG system according to Figure 5, which is similar to the first scenario. Figures 7(a) and (b) depict the frequency and controller amplitude responses of the ship MG system, respectively.

Table 4. The changes in the ship MG system parameters [24]

Parameters	T_g	R	T_{FESS}	T_{BESS}	H	D
Range of variation	+15%	+25%	-15%	+25%	+45%	-15%

Remark 2: as depicted in Figure 7(a), both controllers maintain the frequency deviation within a very slight range under the second scenario. The FPID controller obtains a slightly lower maximum frequency deviation of approximately ±0.0098 Hz compared to ±0.0105 Hz for the PID controller, corresponding to an improvement of about 6-7%. This indicate that the FPID controller achieves a faster settling time and smaller oscillations. In Figure 7(b), the controller amplitude response for the FPID technique is about ±0.072 p.u., whereas for the PID approach it reaches approximately ±0.095 p.u., representing a reduction of around 24%. This shows that the FPID generates more stable and less oscillatory control actions. Compared with the case 3 in research [24], this smoother control effort contributes to enhanced power system stability and reduces unnecessary actuator activity, which is beneficial for long-term operational reliability.

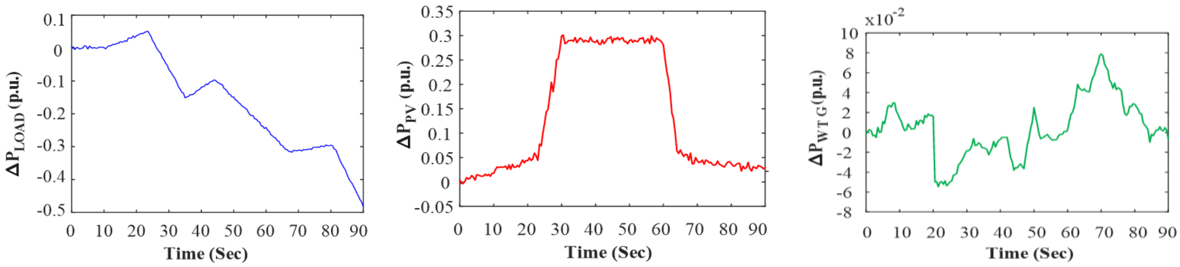


(a) (b)

Figure 7. Response of the second scenario: (a) the system frequency and (b) controller output amplitude

4.3. Scenario 3: investigation of the microgrid system under random load variation and complex disturbance

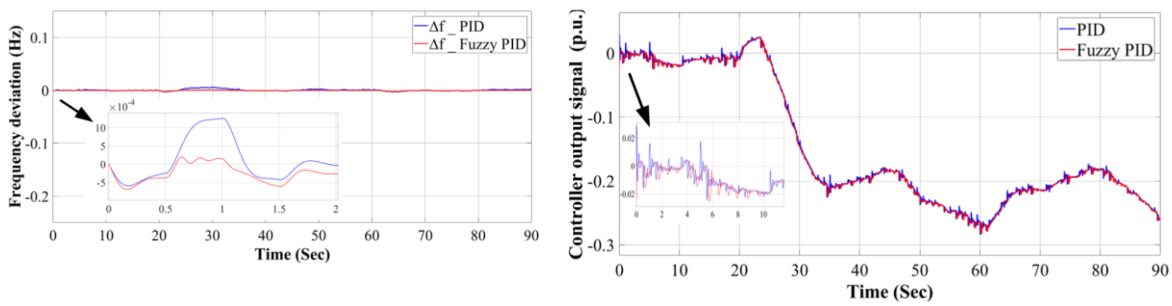
This is the most complex scenario among the three simulation cases. The load is modeled randomly with consideration of disturbances. In addition, the random load is inserted into the simulated plant along with the variation of solar and wind as exposed in Figure 8. Specifically, Figures 8(a) to (c) present the random step changes of the load, the active power variation of the photovoltaic (PV) unit, and the fluctuating power of the wind turbine, respectively. The frequency and controller output responses of the ship MG plant in terms of load disturbances are described in Figures 9(a) and (b), respectively.



(a) (b) (c)

Figure 8. Power fluctuations: (a) step changes of the load, (b) PV, and (c) wind turbines for scenario 3

Remark 3: as illustrated in Figure 9(a), under the third scenario, both controllers maintain the frequency aberration within ±0.00012 Hz. The FPID controller exhibits a slightly smaller maximum deviation of about ±0.00011 Hz compared to ±0.00012 Hz for the PID controller, indicating a marginal improvement in frequency regulation. In Figure 9(b), the controller output response shows that the FPID produces slightly less oscillatory control actions during the transient phase, thereby maintaining system stability while limiting unnecessary control effort. This overall improvement suggests that the FPID provides enhanced dynamic performance and more stable operation.



(a) (b)

Figure 9. Response of the third scenario: (a) the system frequency and (b) controller output amplitude

As can be seen in the above simulation results, the anticipated FPID controller in contrast with the classic PID controller and TVD-FOPID controller [24] has a better response and lower fluctuation and is more robust to parameter uncertainties and external disturbances. Additionally, for TVD-FOPID method, the use of fractional and time-varying parameters increases the complexity of the control structure, which may lead to unstable oscillations. In our paper, the FPID controller is used based on the use of advanced FL with optimally designed membership functions and a high degree of overlap, which not only produces smoother law surfaces than TVD-FOPID but also significantly advances plant stability and dynamic reply characteristics. FPID excels in its ability to intelligently and flexibly adjust PID parameters, which significantly reduces oscillations, shortens response time, and improves the controller performance at higher perturbations. The self-tuning ability of FPID with the support of FL ensures superior performance in maintaining frequency stability and improving system efficiency.

5. CONCLUSION

In this work, the endorsed FPID controller has planned for frequency regulation of the shipboard MG plant in the presence of load fluctuations, the change of wind and solar power sources as well as energy storage devices. In order to provide realistic results, the studied FPID controller has been validated on the three scenarios for the shipboard MG system in which the unpredictability of renewable resources, complex disturbances of the load, and the uncertainty of the parameters in the ship MG plant have also been taken into the consideration. The results have confirmed that the suggested FPID controller is more impressive than other controllers as it results in smaller amplitude and deviation of frequency. Based on the comparision of obtained results between the traditional PID controller and the advanced FPID controller, it has been seen that the suggested method has good performance for solving the stabilization problem of frequency in a ship MG system. Therefore, the proposed technique can contribute to broaden the renewable resource employment into a shipboard grid plant like isolated electricity systems. In future research, by using sliding mode control technique, we will reestablish the shipboard electric grid model by integrating grid-forming inverters together with additional nonlinear components such as saturation effects, switching dynamics, and load-dependent variations. We will also introduce more realistic system constraints, including operational limits of generation units, network stability margins, and safety-critical protection mechanisms. However, incorporating such nonlinearities and constraints is expected to increase the mathematical complexity of the problem. These enhancements aim to better capture the complex operating conditions of shipboard power systems and provide a more accurate basis for optimization.

FUNDING INFORMATION

This research is funded by Ton Duc Thang University under grant number FOSTECT.2025.01.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Cong-Trang Nguyen	✓	✓	✓	✓	✓	✓		✓	✓	✓		✓	✓	✓
Nguyen Nghia Tin		✓		✓	✓	✓		✓	✓	✓	✓	✓		
Thai Pham Thien Hao	✓		✓	✓			✓			✓	✓		✓	
Phan Tan Liem		✓	✓		✓	✓		✓	✓			✓		

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

REFERENCES

[1] H. Bevrani, *Robust Power System Frequency Control*. Cham, Switzerland: Springer International Publishing, 2014, doi: 10.1007/978-3-319-07278-4.

[2] P. Kundur, *Power System Stability and Control*. New York, NY, USA: McGraw-Hill, 1994.

[3] P. T. Nguyen and C. T. Nguyen, "Single phase robustness variable structure load frequency controller for multi-region interconnected power systems with communication delays," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 14, no. 5, pp. 5064–5071, 2024, doi: 10.11591/ijece.v14i5.pp5064-5071.

[4] R. Rajesh, "Optimal tuning of fractional-order proportional–integral–derivative (FOPID) controller based on particle swarm optimization algorithm with reference model for a single conical tank system," *SN Applied Sciences*, vol. 1, no. 7, pp. 1–14, 2019, doi: 10.1007/s42452-019-0754-3.

[5] R. Rajesh and S. N. Deepa, "Design of direct model reference adaptive control augmented with two-degree-of-freedom proportional–integral–derivative–derivative (2 DoF PIDD) controller: An application to speed control of a servo plant," *Journal of King Saud University – Engineering Sciences*, vol. 32, no. 5, pp. 310–320, 2020, doi: 10.1016/j.jksues.2019.02.005.

[6] M. P. E. Rajamani, R. Rajesh, and M. W. Iruthayarajan, "Design and experimental validation of proportional–integral–derivative (PID) controller for buck converter: A multi-objective evolutionary algorithms-based approach," *IETE Journal of Research*, vol. 69, no. 1, pp. 21–32, 2023, doi: 10.1080/03772063.2021.1905564.

[7] R. Ramakrishnan and D. S. Nachimuthu, "Design of state feedback linear–quadratic regulator (LQR) based dual-mode fractional-order PID controller using inertia-weighted particle swarm optimization algorithm for control of an underactuated system," *Journal of the Institution of Engineers (India): Series C*, vol. 102, no. 6, pp. 1403–1417, 2021, doi: 10.1007/s40032-021-00756-x.

[8] M. P. E. Rajamani, R. Rajesh, and M. W. Iruthayarajan, "A proportional–integral–derivative control scheme with enhanced non-dominated sorting genetic algorithm applied to a non-inverting buck–boost converter," *Sādhanā – Academy Proceedings in Engineering Sciences*, vol. 47, no. 4, 2022, doi: 10.1007/s12046-022-02012-z.

[9] C. T. Nguyen, T. H. Chiem, and V. D. Phan, "Observer-based single-phase robustness load frequency sliding mode controller for multi-area interconnected power systems," *Bulletin of Electrical Engineering and Informatics (BEEI)*, vol. 13, no. 5, pp. 3147–3154, Oct. 2024, doi: 10.11591/eei.v13i5.7893.

[10] B. Yildirim, M. Gheisarnejad, and M. H. Khooban, "A robust non-integer controller design for load frequency control in modern marine power grids," *IEEE Transactions on Emerging Topics in Computational Intelligence*, vol. 6, no. 4, pp. 852–866, 2022, doi: 10.1109/TETCI.2021.3114735.

[11] A. K. Choudhary, S. Prakash, M. Sharma, and S. Dhundhara, "Grasshopper optimization-based robust power/frequency regulator for shipboard microgrid," *IET Renewable Power Generation*, vol. 14, no. 17, pp. 3568–3577, 2020, doi: 10.1049/iet-rpg.2020.0849.

[12] R. Alayi, F. Zishan, S. R. Seyednouri, R. Kumar, M. H. Ahmadi, and M. Sharifpur, "Optimal load frequency control of island microgrids via a PID controller in the presence of wind turbine and PV," *Sustainability*, vol. 13, no. 19, art. no. 10728, 2021, doi: 10.3390/su131910728.

[13] A. Latif, S. M. S. Hussain, D. C. Das, and T. S. Ustun, "Double-stage controller optimization for load frequency stabilization in hybrid wind–ocean wave energy-based maritime microgrid system," *Applied Energy*, vol. 282, p. 116171, 2021, doi: 10.1016/j.apenergy.2020.116171.

[14] D. Kumar, H. D. Mathur, S. Bhanot, and R. C. Bansal, "Forecasting of solar and wind power using long short-term memory recurrent neural network (LSTM-RNN) for load frequency control in isolated microgrid," *International Journal of Modelling and Simulation*, vol. 41, no. 4, pp. 311–323, 2021, doi: 10.1080/02286203.2020.1767840.

[15] G. Zhang, I. A. Khan, A. Daraz, A. Basit, and M. I. Khan, "Load frequency control of marine microgrid system integrated with renewable energy sources," *Journal of Marine Science and Engineering*, vol. 11, no. 4, p. 844, 2023, doi: 10.3390/jmse11040844.

[16] S. Alahakoon, R. B. Roy, and S. J. Arachchillage, "Optimizing load frequency control in standalone marine microgrids using meta-heuristic techniques," *Energies*, vol. 16, no. 13, p. 4846, 2023, doi: 10.3390/en16134846.

[17] E. Bahrampour, M. Dehghani, M. H. Asemani, and R. Abolpour, "Load frequency fractional-order controller design for shipboard microgrids using direct search algorithm," *IET Renewable Power Generation*, vol. 17, no. 4, pp. 894–906, 2022, doi: 10.1049/rpg2.12643.

[18] S. Khosravi, M. T. H. Beheshti, and H. Rastegar, "Robust control of islanded microgrid frequency using fractional-order proportional–integral–derivative controller," *Iranian Journal of Science and Technology – Transactions of Electrical Engineering*, vol. 44, no. 3, pp. 1207–1220, 2020, doi: 10.1007/s40998-019-00303-6.

[19] F. Amiri and M. H. Moradi, "Designing of the controller for shipboard microgrid based on linear matrix inequality," *Journal of Applied Research on Electrical Engineering*, vol. 1, no. 2, pp. 175–185, 2022, doi: 10.22055/JAREE.2022.39484.1041.

[20] S. Mishra, R. C. Prusty, and S. Panda, "Performance analysis of modified sine cosine optimized multistage fractional-order proportional–derivative–proportional–integral (FOPD–PI) controller for load frequency control of an islanded microgrid system," *International Journal of Numerical Modelling: Electronic Networks, Devices and Fields*, vol. 34, no. 6, p. e2923, 2021, doi: 10.1002/jnm.2923.

[21] C. C. Lee, "Fuzzy logic in control systems: Fuzzy logic controller – Part I," *IEEE Transactions on Systems, Man, and Cybernetics*, vol. 20, no. 2, pp. 404–418, Mar.–Apr. 1990.

[22] C. C. Lee, "Fuzzy logic in control systems: Fuzzy logic controller – Part II," *IEEE Transactions on Systems, Man, and Cybernetics*, vol. 20, no. 2, pp. 419–435, Mar.–Apr. 1990.

[23] M. Sugeno, *Industrial Applications of Fuzzy Control*. Amsterdam, The Netherlands: Elsevier Science Inc., 1985.

[24] M. Sonalika, P. C. Nayak, R. C. Prusty, and S. Panda, "Design and analysis of time-varying derivative fractional-order proportional–integral–derivative (TVD-FOPID) controller for frequency regulation of shipboard microgrid system," *Electrica – Journal of Electrical Engineering*, vol. 24, no. 2, pp. 392–405, 2024, doi: 10.5152/electrica.2024.2305.

[25] Z. Y. Zhao, M. Tomizuka, and S. Isaka, "Fuzzy gain scheduling of proportional–integral–derivative controllers," *IEEE Transactions on Systems, Man, and Cybernetics*, vol. 23, no. 5, pp. 1392–1398, 1993, doi: 10.1109/21.260670.

BIOGRAPHIES OF AUTHORS

Cong-Trang Nguyen has completed the Ph.D. degree in automation and control from Da-Yeh University, Taiwan. He is currently a member of the Power System Optimization Research Group, Faculty of Electrical and Electronics Engineering, Ton Duc Thang University, Ho Chi Minh City, Vietnam. His current research interests include sliding mode control and optimization algorithm. He can be contacted at email: nguyencongtrang@tdtu.edu.vn.

Nguyen Nghia Tin was born in Vietnam in 2003. Now, he is a student at the Faculty of Electrical and Electronics Engineering at Ton Duc Thang University, Ho Chi Minh City, Vietnam. His research topics interests are in load frequency control for power systems with fuzzy logic and sliding mode control. He is a member of the student research group on "Modern Control Techniques in Power System (MCTPS)". He can be contacted at email: nguyennghiatin2003@gmail.com.

Thai Pham Thien Hao was born in Vietnam in 2003. Now, he is a student at the Faculty of Electrical and Electronics Engineering at Ton Duc Thang University, Ho Chi Minh City, Vietnam. His research interests include renewable energy sources and control systems. He is a member of the student research group on "Modern Control Techniques in Power System (MCTPS)". He can be contacted at email: thienhao270803@gmail.com.

Phan Tan Liem was born in Vietnam in 2003. Now, he is a student at the Faculty of Electrical and Electronics Engineering at Ton Duc Thang University, Ho Chi Minh City, Vietnam. His research interests are the application of modern control methods and intelligent algorithms in power system control. He is a member of the student research group on "Modern Control Techniques in Power System (MCTPS)". He can be contacted at email: liemphan.17082003@gmail.com.