Research Article

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Frequency amelioration of an interconnected microgrid system

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Abstract: This article validates the operational effectiveness of a fuzzy-based multistage cascaded proportional integral derivative fractional filter (PIDFN) controller which enhances the frequency regulation of an interconnected islanded microgrid system. The effect of the ambiguous nature of renewable energy resources and test cases concerning different load variations are applied to verify the robustness of the proposed controller. The superiority of the proposed controller upon proportional-integral-derivative (PID), fractional-order PID (FOPID), and Fuzzy FOPID controller in minimizing frequency alteration has been verified through MATLAB/SIMULINK environment.

Keywords: renewable energy sources, wind turbine generator system, diesel engine generator system, fuel cell, ultracapacitor, fractional-order PID controller, proportional-integral-derivative filter constant

1 Introduction

In the modern era of power system, renewable energy source (RES) efficiently replaces a greater amount of conventional power generation in terms of energy requirement. These sources are amply available, economical, situated at the vicinity of the load, and curtails the transmission and distribution losses in the system. The renewable source with the ability to function at low as well as medium voltage levels that can be operated in integration with the distributed generation sources, controllable units, loads along with the energy storage systems embodying in a small network is designated as a microgrid (MG). Resilience, power system reliability, decrement in the feeder capacity, power quality improvement, and transmission loss reduction are the essential advantages of a microgrid system. The system may operate in grid-connected mode or an islanded mode and maybe a combination of both.

RESs such as solar and wind play an integral source for generating power in a microgrid system. Aberrant wind speed and fluctuation in the intensity of the sun radiation bring disturbance to the efficient operation of the MG. These sources being sporadic in nature results in a discrepancy between the power generation and load demand in the microgrid system. As a consequence, this imbalance affects the deviation of system frequency. So, to maintain the system frequency within its prescheduled values, a load frequency control scheme is included in the microgrid system.

Multitude control techniques are available in the literature to control the frequency in a MG system [1,2]. Mohanty et al. have implemented integral (I), proportional-integral (PI), and proportional-integral-derivative (PID) controllers for enhancement of the frequency profile implementing an HVDC link in the system [3]. Owing to the incompetency of the conventional controllers, various advanced controllers are incorporated in the literature. Bevrani et al. have implemented an H-∞ and μ-synthesis controller for minimizing the deviation in frequency in an islanded MG [4]. With the operational advantages, various configurations of fractional-order PID controller are implemented to mitigate the frequency deviation in a multi-area power system [5–8]. Moreover, the system performance can be improved with fuzzy logic-based fractional-order PID controller [9–13]. Ahmadi et al. have proposed a fuzzy-based PID controller for frequency regulation and control in a multi-source power system [14]. A cascaded scheme of fuzzy-based PID controllers can enhance the system performance for a hybrid power system [15,16]. So, contemplating all the above spheres of research of load frequency control (LFC) in an interconnected MG, a new fuzzy multistage cascade PIDFN controller is considered

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Thus, the contributions made by this article are

1. An interconnected islanded MG system is incorporated comprising photovoltaic (PV), wind, diesel engine generator (DEG), and ultracapacitor.
2. A fuzzy multistage cascade PIDFN-based controller is included in the system to improve the system's frequency control.
3. To evidence the superior operative performance of the proposed controller upon PI, FOPID, and fuzzy FOPID, the dynamic performance of LFC has been explored through MATLAB/Simulink environment contemplating various loading conditions and irregularities in wind and PV power generation.

The arrangement of the article is as follows: Section 2 describes the structure of the proposed MG system and the function of the various components. The control techniques implemented in the system are described in Section 3. Section 4 describes the supremacy of the proposed fuzzy multistage cascade PIDFN controller over other controllers. The robustness of the proposed controller in improving the frequency control is described in concluding Section 5.

2 Description of MG system

The structural representation of an interconnected islanded MG system is depicted in Figure 1. Area 1 is exemplified by DEG, PV, ultracapacitor (ULC), and load whereas area 2 represents wind turbine generator (WTG), ULC, and DEG. A controller is designed to minimize the frequency deviation and attain a steady state when the system is subjected to various disturbances.

Whenever the non-conventional sources break down to supply the desired power to the load, then the DEG acts as a substitute. Ultracapacitor acts as a backup and improves the system stability. The generated load balance is achieved by the DEG and fuel cell (FC). In each MG system, the controller output is connected to the DEG, ULC, and storage unit to diminish the frequency deviation. The elements of the islanded MG system are represented in Table 1. The models of the various components of the hybrid MG system are illustrated in the following sub-sections.

2.1 DEG

Variation in solar intensity and wind speed results in the alteration of generated power. DEGs functions as a backup in isolated MG as they hold the capacity to run with higher efficiency, minimal maintenance, and fast speed. Adding to this, it has the ability to atone the power supply to the load due to the alteration of RESs in the MG. The transfer function model representation of DEG is described in Figure 2.

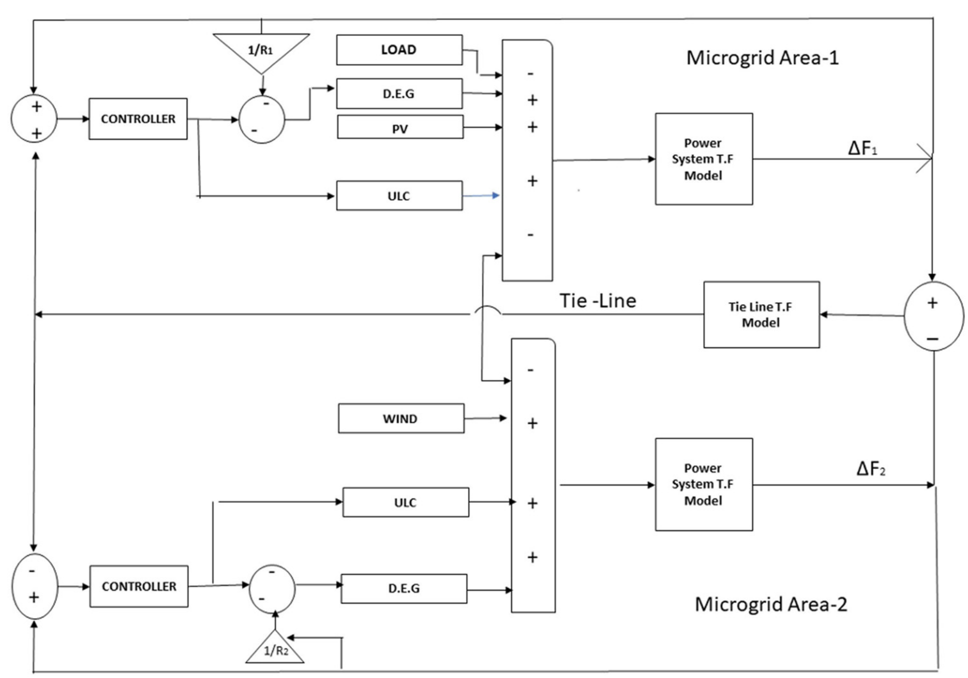

Figure 1: Proposed microgrid model.

Table 1: System model transfer function and parameter

Model	Transfer function	Parameters
Diesel engine generator	$K_{DG}/(ST_{DG} + 1)$	$K_{DG} = 0.03$ and $T_{DG} = 2$
Wind turbine	$K_{WTG}/(ST_{WTG} + 1)$	$K_{WTG} = 1$ and $T_{WTG} = 1.5$
PV	$K_{PV}/ST_{PV} + 1$	$K_{PV} = 1$ and $T_{PV} = 0.03$
Ultracapacitor	$1/(ST_{ULC} + 1)$	$T_{ULC} = 0.08$
Synchronizing coefficient	K_{12}/s	$K_{12} = 0.56$

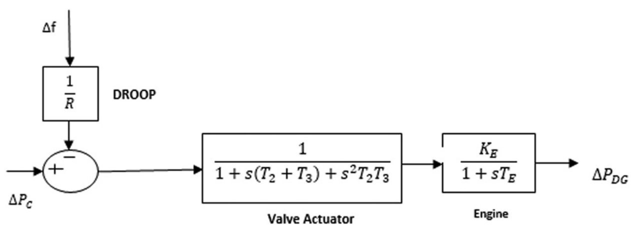

Figure 2: Transfer function model of DEG.

2.2 PV system

A PV system is an aggregation of various PV modules connected in series or parallel. The solar radiation and temperature being erratic in nature produces volatile power from the PV system. The extracted power from the PV cell is calculated as

$$P_{PV} = \eta S\phi\,(1 - 0.005(T_a + 25)), \quad (1)$$

where η = PV array efficiency, S = area of the photovoltaic array, ϕ = solar radiation intensity, and T_a = surrounding temperature.

The transfer function of the PV system is represented as

$$TF_{PV} = \frac{K_{PV}}{1 + sT_{PV}}, \quad (2)$$

where K_{PV} = Gain of PV array and T_{PV} = time constant of PV array.

2.3 WTG system

The electrical energy produced in the WTG depends on the kinetic energy extracted from the wind. The generated power from the wind turbine system is expressed as,

$$P_{WTG} = \frac{1}{2}\rho A C_p(\lambda\ ,\ \beta)\ V_w^3, \quad (3)$$

where ρ = density of air (kg/m^3), λ = turbine tip speed ratio, V_w = wind velocity (m/s), C_p = power coefficient, A = area swept by the turbine blade (in m^2), and B = pitch angle of the turbine blade.

2.4 ULC

It is a component that has the ability to store charge electrostatically. It can combat thousands of cycles as compared to batteries. The storage unit has faster charge and discharge characteristics. It has negligible resistance and has faster response to power disturbance in the system. The transfer function is expressed as

$$TF_{ULC} = \frac{1}{1 + sT_{ULC}}. \quad (4)$$

2.5 MG system

The power needed to supply the load is supplied from all the sources and the corresponding relationship between alteration in frequency with corresponding power demand is expressed in equation (5) as

$$\frac{\Delta f}{\Delta P} = \frac{K_{PS}}{1 + sT_{PS}}, \quad (5)$$

3 Controller design

Discrepancy in the nature of the wind and sun radiation leads to power disturbance which further distorts the system frequency, so a controller is designed to curtail the frequency deviation. In this article a fuzzy multistage cascade PIDFN controller is proposed which improves the system performance in an interconnected islanded MG system. The controller performance is further compared with other conventional controllers under various conditions.

3.1 PI controller

This controller is an amalgamation of proportional and integral controller, and has a faster response. The PI controller minimizes the divergence in frequency and attains

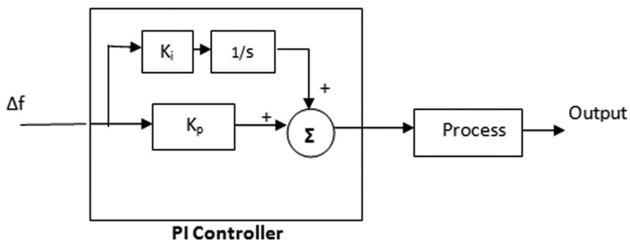

Figure 3: PI controller.

a stable response. The simplified diagram is represented in Figure 3.

3.2 Fractional-order PID controller (FOPID)

FOPID is a distinct PID controller where the derivative and integral orders are fractional and the parameters λ and μ represent integrator and derivative order, respectively. The controller possesses a better performance and is represented as

$$C(s) = K_p\left(1 + \frac{K_i}{s^\lambda} + K_d s^\mu\right), \tag{6}$$

where K_p = proportional gain, K_i = integral gain, and K_d = derivative gain.

3.3 Fuzzy FOPID

Fuzzy-tuned FOPID controller is an extension of conventional FOPID controller. In this scheme, the parameters of the FOPID controller are altered by using fuzzy inference system. There are two fuzzy inputs i.e., frequency deviation (Δf) and variation in load (ΔP) which update the scaling factors of the proportional gain (K_p), integral gain (K_I), and derivative gain (K_D) [14]. The final values of the FOPID controller are computed as

$$K_P = K_P + \Delta K_P\,, \tag{7}$$

$$K_I = K_I + \Delta K_I, \tag{8}$$

$$K_D = K_D + \Delta K_D\,. \tag{9}$$

In the above equations, the FOPID controller's initial gain value is represented by K_P, K_I, and K_D and the scaling factor calculated from the fuzzy logic controller (FLC) are ΔK_P, ΔK_I, and ΔK_D. The fuzzy inference system (FIS) has six membership functions for change in frequency and three membership functions for change in load. The fuzzy logic controller rules are represented in Table 2.

Change in frequency has six membership functions such as low negative (LON), big negative (BGN), medium negative (MDN), low positive (LOP), big positive (BGP), and medium positive (MDP). For alteration in load, there are three membership functions such as low (LO), big (BG), and medium (MD).

3.4 Proposed fuzzy multistage cascade PIDFN controller

In the proposed work, an efficient controller which is a combination of PIDFN-FOPIDFN is connected in series as shown in Figure 4. The controller parameters are tuned by fuzzy inference system for an interconnected MG. The FIS has the same rules as in Table 2. The output of the FIS is given as input to the cascaded controller and its performance is studied in Section 4. The gain values of the PID, FOPID, and filter constant (FN) are selected. Fuzzy logic is used to reduce the deviation in frequency by tuning the parameters of the PIDFN controller (Figure 4).

Table 2: Rules of fuzzy logic controller

$\Delta f/\Delta P$	LON	BGN	MDN	LOP	BGP	MDP
LO	LON	BGN	MDN	LOP	MDP	LOP
BG	BGN	BGN	BGN	MDP	MDP	MDP
MD	MDN	BGN	BGN	LOP	MDP	MDP

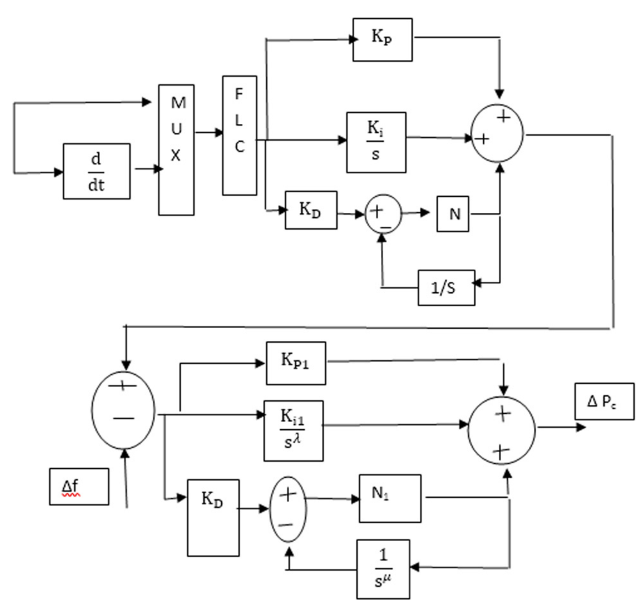

Figure 4: Schematic representation of the proposed controller.

4 Results and discussion

Faster response and dynamic stability are the required features of a control system. The effectualness of the proposed controller is examined on an interconnected MG system under different operating conditions. The MG system is simulated in MATLAB software. The proposed multistage controller is analyzed on an isolated and multi-area MG system. The predominance of the suggested controller under different scenarios is studied and comparative analysis with other controllers in existing literature is studied.

4.1 Scenario 1 – Individual MG-step load

A single MG system comprising of PV, WTG, DEG, FC, and ULC is subjected to a step load increment of 0.01 p.u at time $t = 20$ s. A relative comparison of the dynamic responses in frequency with PI, FOPID, and fuzzy FOPID are shown in Figure 5, respectively.

It is depicted from Figure 5 that with PI, FOPID, and fuzzy FOPID, the frequency deviation could be reduced with the settling times of 32, 24, and 20 s, respectively. However, with the proposed fuzzy multistage cascade PIDFN controller, the frequency deviation is effectively improved and system attained steady state in 21 s. The comparative analysis of the dynamic response in terms of undershoot, overshoot, and settling time is given in Table 3.

The comparison of undershoots, overshoots, and settling times with PI, FOPID, fuzzy FOPID and proposed multistage cascade PIDFN controllers presented in the Table 3 clearly evidenced the robustness of the proposed controller.

Table 3: Comparative analysis of system response for scenario 1

Parameters	Controllers			
	PI	FOPID	Fuzzy FOPID	Proposed controller
Settling time	32	30	24	21
Peak overshoot	0.23	0.15	0.12	0.03
Peak undershoot	−0.22	−0.08	−0.03	−0.01

4.2 Scenario 2 – Individual MG-multiple load disturbance

The MG system is administered to a multiple load disturbance which encompasses a 3% step load increase at $t = 10$ s and 1% step load decrease at $t = 20$ s. A comparative performance of the dynamic performance of frequency is represented in Figure 6.

It can be noticed that the system's response with PI, FOPID, and fuzzy FOPID controller became more oscillatory and required a larger settling time. However, with the proposed fuzzy multistage cascade PIDFN controller, the damped oscillations are significantly alleviated and the system attains stability faster than the other three controllers. The comparative analysis of the dynamic response in terms of undershoot, overshoot, and settling time is given in Table 4.

Table 4 verified the role of the proposed controller in lessening the settling time and adding to system stability faster than other suggested controllers even with a multistep load perturbation.

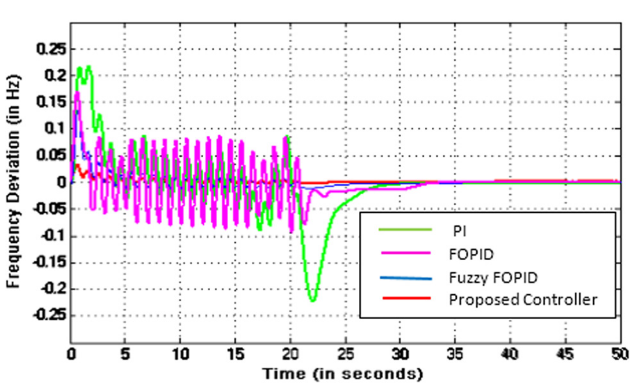

Figure 5: Frequency deviation during step load.

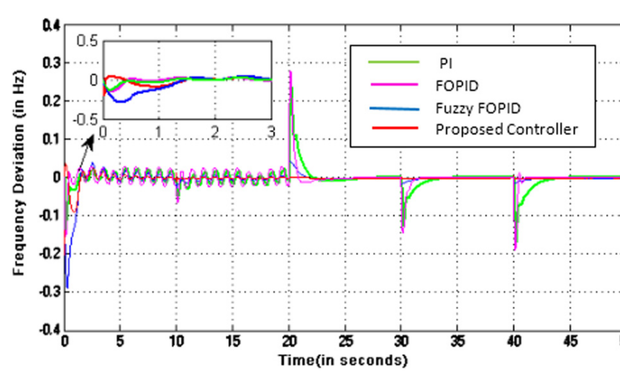

Figure 6: Frequency deviation during multiple load disturbance.

Table 4: Comparative analysis of system response for scenario 2

Parameters	Controllers			
	PI	FOPID	Fuzzy FOPID	Proposed controller
Settling time	25	24	22	20
Peak overshoot	—	—	—	0.2
Peak undershoot	−0.21	−0.27	−0.3	−0.05

4.3 Scenario 3 – Interconnected MG-step load disturbance

In this system the MG-1 comprises of PV, DEG, FC, and ULC and MG-2 consists of WTG, DEG, FC, and ULC. The two MG system is connected to a tie-line and MG-1 is subjected to a 1% step load increase at $t = 20$ s. A relative comparison of the dynamic responses established for differences in frequency ΔF_1 and ΔF_2 and change in exchange power through tie line ΔP_{TIE} with PI, FOPID, fuzzy FOPID, and fuzzy multistage cascade PIDFN controller are shown in Figure 7(a)–(c), respectively.

It is depicted from Figure 7(a) that with PI, FOPID, and fuzzy-tuned FOPID controllers, the frequency deviation of area-1 could be reduced with the settling times of 25, 24, and 23 s, respectively. However, with the proposed fuzzy multistage cascade PIDFN controller, the deviation in area-1 frequency is effectively improved and the system attained steady state in 21 s.

In Figure 7(b), the frequency of area-2 with a PI, FOPID, and fuzzy FOPID controller results in an oscillatory response, while with the proposed controller, the frequency response at area-2 is improved and reached steady state in 14 s.

From Figure 7(c) it is observed that with PI, FOPID, and fuzzy FOPID controllers, the tie line power flow between the control areas have declined and also failed to attain their prescheduled value. The proposed controller is robust enough to bring down the tie line power deviation with a settling time of 21 s. The comparative analysis of the dynamic response in terms of undershoot, overshoot, and settling time is given in Table 5.

The divergence of peak undershoots, overshoots, and settling times with PI, FOPID, fuzzy FOPID, and proposed fuzzy cascade PIDFN controllers presented in the Table 5 clearly evidenced the robustness of the suggested controller.

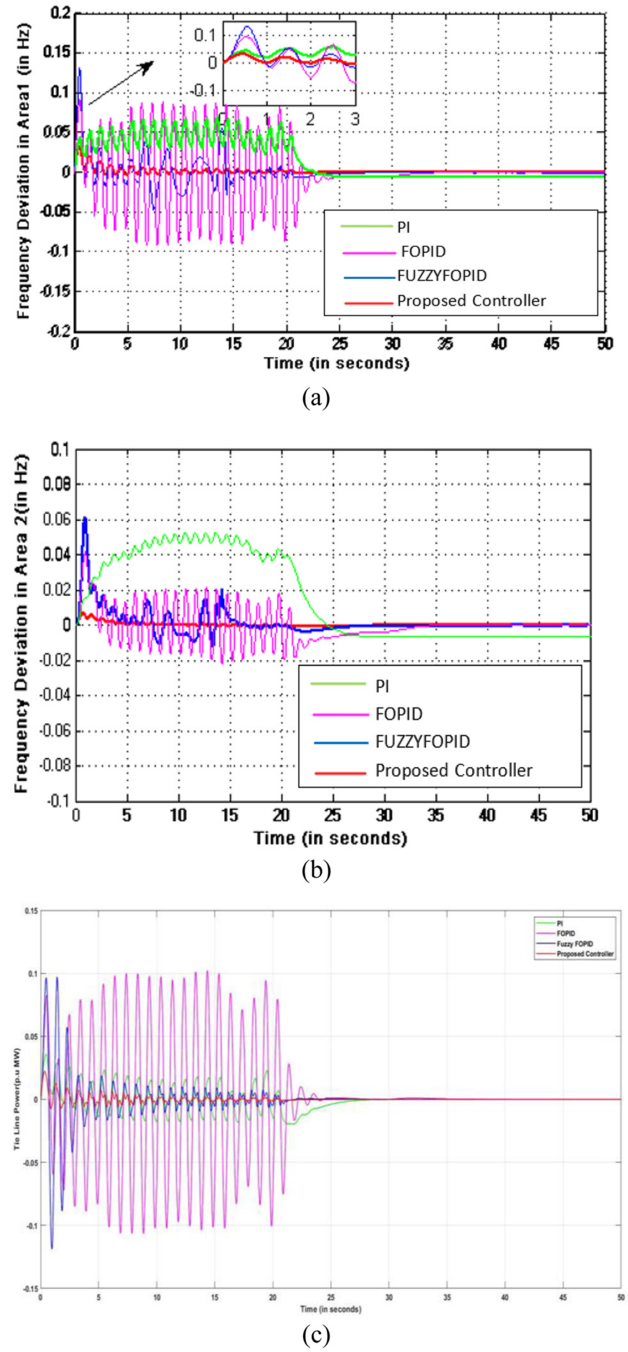

Figure 7: Frequency deviation in multi-microgrid for step load disturbance. (a) Frequency deviation in area 1; (b) frequency deviation in area 2; (c) frequency deviation in tie line.

4.4 Scenario 4 – Interconnected MG-multiple load disturbance

In this case, MG-1 is subjected to a variable step load perturbation at $t = 20$ s. The frequency response of various controllers is represented in Figure 8(a)–(c), respectively.

Table 5: Comparative analysis of system response for scenario 3

	Parameters	Controllers			
		PI	FOPID	Fuzzy FOPID	Prop. controller
Area 1	Settling time	25	24	23	21
	Peak overshoot	0.03	0.08	0.12	0.02
	Peak undershoot	—	−0.02	−0.015	−0.01
Area 2	Settling time	33	30	22	14
	Peak overshoot	—	0.041	0.043	0.005
	Peak undershoot	—	−0.026	−0.0012	—
Tie line	Settling Time	28	24	23	21
	Peak overshoot	0.04	0.07	0.08	0.02
	Peak undershoot	−0.01	−0.06	−0.12	−0.005

From Figure 8(a)–(c), it is observed that although the investigated system is put through a multistep load variation, the proposed controller is able to operate persistently with sustained oscillations. The values of undershoots, overshoots, and settling times of the system responses are tabulated in Table 6.

Table 6 verified the role of the proposed controller in lessening the settling time and adding to system stability faster than the other suggested controllers in area 1, area 2, and tie line even with a multi-step load perturbations.

4.5 Scenario 5 – Interconnected MG-constant RES in MG-1

In this scenario, the wind power generation is assumed to be constant in MG-1. Step load disturbance occurs in MG-1 due to variation in the nature of solar intensity frequency deviation in the system. The suggested controller is predominant over other controllers and has better response as shown in Figure 9(a)–(c).

It is illustrated from Figure 9(a)–(c) that the frequency deviation in area 1 and area 2 are reduced with step load variation in the MG system. The values of undershoots, overshoots, and settling times of the system responses are tabulated in Table 7.

From Table 7 it is evident that with the test scenario 5 established for constant wind speed in area 1, the proposed controller can function reliably adding to system stability.

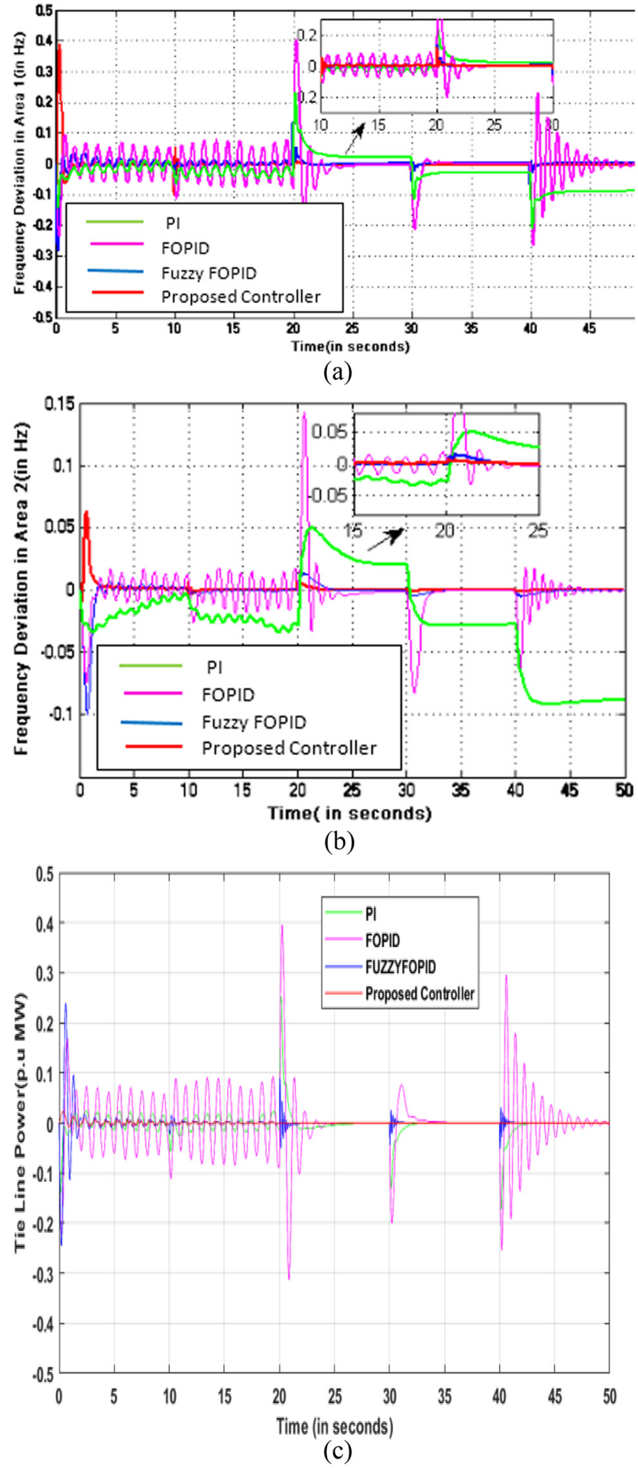

Figure 8: Frequency deviation in multi-microgrid for multiple load disturbance. (a) Frequency deviation in area 1; (b) frequency deviation in area 2; (c) frequency deviation in tie line.

Table 6: Comparative analysis of system response for scenario 4

	Parameters	Controllers			
		PI	FOPID	Fuzzy FOPID	Prop. controller
Area 1	Settling time	28	23	20	18
	Peak overshoot	—	—	—	0.32
	Peak undershoot	−0.18	−0.24	−0.26	−0.02
Area 2	Settling time	35	25	14	12
	Peak overshoot	—	—	—	0.06
	Peak undershoot	−0.01	−0.07	−0.1	−0.005
Tie line	Settling time	27	24	22	20
	Peak overshoot	—	−0.15	0.23	0.002
	Peak undershoot	−0.13	−0.23	−0.21	−0.01

Table 7: Comparative analysis of system response for scenario 5

	Parameters	Controllers			
		PI	FOPID	Fuzzy FOPID	Prop. controller
Area 1	Settling time	18	12	10	8
	Peak overshoot	0.05	0.1	0.12	0.02
	Peak undershoot	—	−0.01	—	—
Area 2	Settling time	15	14	12	10
	Peak overshoot	0.07	0.045	0.025	0.01
	Peak undershoot	—	−0.002	—	—
Tie line	Settling time	14	23	8	6
	Peak overshoot	0.04	0.08	0.09	0.02
	Peak undershoot	−0.02	−0.05	−0.06	—

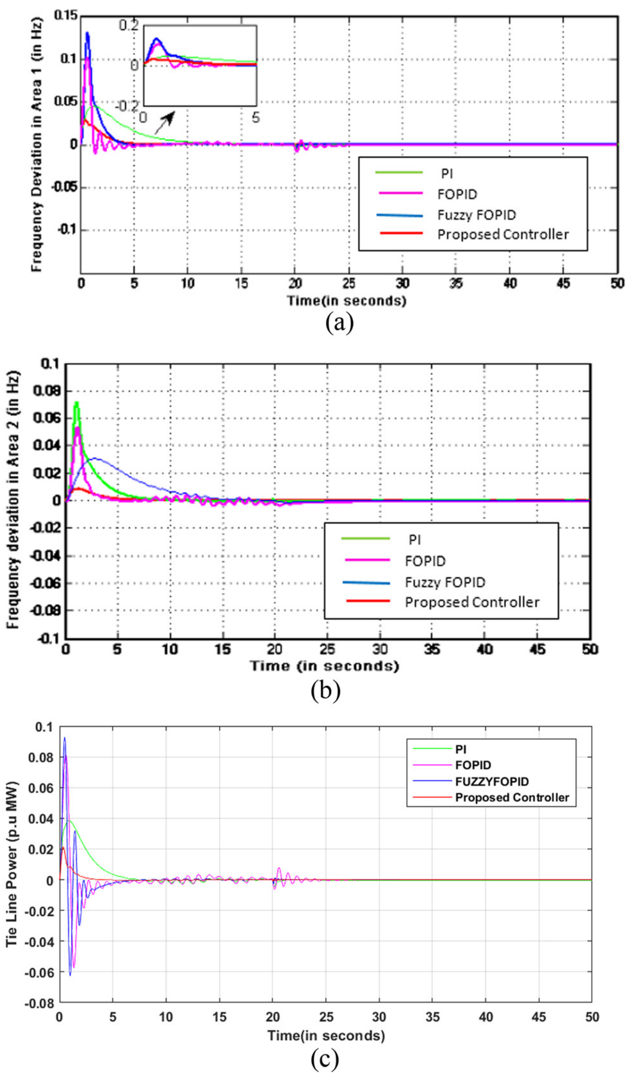

Figure 9: Frequency deviation in multi-microgrid for constant RES in area 1. (a) Frequency Ddeviation in area 1; (b) frequency deviation in area 2; (c) frequency deviation in tie line.

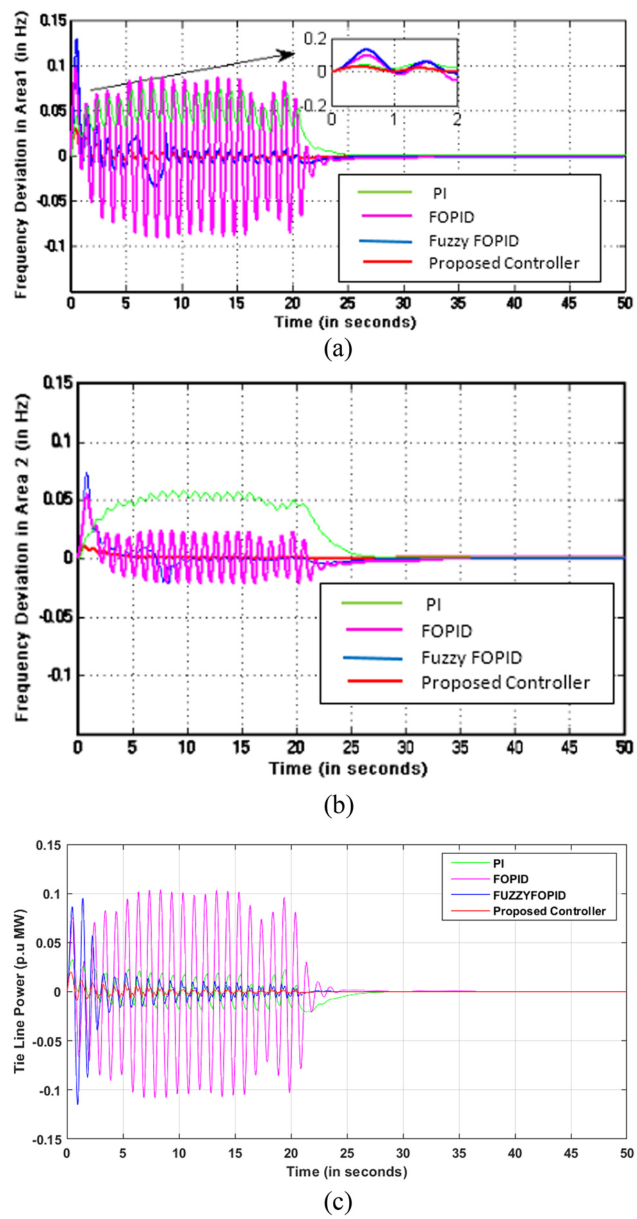

Figure 10: Frequency deviation in multi-microgrid for constant RES in area 2. (a) Frequency deviation in area 1; (b) frequency deviation in area 2; (c) frequency deviation in tie line.

Table 8: Comparative analysis of system response for scenario 6

	Parameters	Controllers			
		PI	FOPID	Fuzzy FOPID	Prop. controller
Area 1	Settling time	26	25	23	20
	Peak overshoot	0.08	0.12	0.1	0.02
	Peak undershoot	—	−0.04	−0.02	−0.01
Area 2	Settling time	29	27	25	15
	Peak overshoot	0.06	0.07	0.05	0.001
	Peak undershoot	−0.04	−0.03	−0.02	—
Tie line	Settling time	27	25	23	20
	Peak overshoot	0.04	0.08	0.07	0.01
	Peak undershoot	−0.06	−0.05	−0.01	−0.001

4.6 Scenario 6 – Interconnected MG-constant RES in MG-2

In this case, the MG-2 system has constant solar intensity and MG-1 system has fluctuating wind power generation. To verify the supremacy of the proposed controller, the frequency response is depicted in Figure 10(a)–(c).

From Figure 10(a)–(c), it is observed that although the investigated system is put through variation in wind speed in area 2, the proposed controller is able to operate persistently with sustained oscillations. The values of undershoots, overshoots, and settling times of the system responses are tabulated in Table 8.

Table 8 verified the role of the proposed controller in lessening the settling time and adding to system stability faster than other suggested controllers even with a perturbation in wind power.

5 Conclusion

A fuzzy-based multistage cascaded PIDFN controller has been proposed in this article to reduce the system's frequency deviation when the interconnected isolated MG is encountered with distinct load variations. In addition to this, alteration in solar radiation and fluctuation in wind speed have been considered to get a deep insight into the LFC analysis. The efficacy of the proposed controller in enhancing dynamic responses in terms of overshoot, undershoot, and settling time has been compared with PI, FOPID, and Fuzzy-based FOPID controllers. The proposed fuzzy-based multistage cascaded PIDFN controller is robust enough in minimizing frequency deviation at area-1 to settle at 21 s, in area-2 at 14 s, and tie-line power response at 20 s, only when subjected to step load perturbation. The detailed analysis of the dynamic performance of the proposed controller is represented in Tables 3–8, respectively. The comparative analysis of the simulation results for different test scenarios with the proposed controller confirmed its robustness of it.

Conflict of interest: Authors state no conflict of interest.

Data availability statement: All data generated or analyzed during this study are included in this research article.

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