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RESEARCH PAPER

Robust frequency control in a wind-diesel autonomous microgrid: A novel two-level control approach

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Volatile nature in renewable power output, stochastic nature of load and continuous change in system structure are the key factors affecting the stable operation of microgrid (MG), particularly in frequency control. Appropriate control schemes are indispensable to reduce the frequency fluctuations in MG under such scenarios. Concerning to these issues; this paper proposes a novel two-level control mechanism approach to mitigate the frequency fluctuations in the wind-diesel standalone MG. In the first level, from wind turbine generator (WTG) side, a fixed wind power command is replaced by an optimum adaptive wind power command based on the power system operating conditions and wind speed conditions. To perform this task, the fuzzy logic approach (FLA) is employed by considering change in wind velocity and frequency deviation as inputs and change in WTG power as output. In the second level, a robust FLA tuned Proportional Integral (PI) controller is proposed to regulate the output power of the diesel engine generator (DEG) for the further reduction in MG frequency fluctuations. With this proposed two-level approach, the MG frequency fluctuations are within the limits in all possible operating conditions, which include some critical operating scenarios. Moreover, the superiority of proposed approach in dynamic performance enhancement against load and wind power changes is proven by comparing with various powerful controllers in the literature.

Introduction

Nowadays, power generation in remote areas generally depends on diesel engine generators (DEG) as a steady and controllable energy source. These DEGs need heavy oil incurs very costly (fuel, transport, and storage cost) and environmentally hazardous. With concerns about issues, renewable energy sources (REs) are envisaged solutions, especially in the microgrid. The microgrid consists of distributed power generators and allied loads. For distributed power generation utilization, depending on the realistic and environmental circumstances, REs, regarded as economical and clean energy sources, viz. solar, wind, biomass, sea, are connected to the isolated microgrid [1]. The connection of RE helps an affordable portion of the power supply thus decreasing the consumption of fuel and transportation costs for DEGs. The microgrid system with REs produces a flexible power supply for isolated remote areas but rich in REs. Among all REs, wind power is regarded as the most propitious because with the ease of present technologies the large-scale power can be generated. Extensive growth in the installation of wind power across the world, introduced technical issues and new challenges for the safe operation of the power system, particularly in microgrids (MGs) [2,3]. Frequency control of MG and active power control from energy sources (DEG and WTG) side are the key issues in MG stability [4].

Frequency fluctuations in the MG is a direct evolution of the discrepancy between the generated power and demand load. The frequency deviance from the rated value (60 Hz or 50 Hz) for the long-term is destructive to the safe operation of the MG. In this regard, Load frequency control (LFC) is of the utmost importance. It functions continuously to balance the frequency between the generated power and load demand [5].

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Many researchers introduced energy storage systems (ESS) based methods [6–8] to smooth out the wind power before supplying to the grid to control the frequency. However, the ESS based method is costly and leads to regular discharging and charging which reduces the life cycle of the battery. This paper principally focuses on MG frequency control based on control of output power of DEG and WTG, without using ESS based method with using the change in wind speed and the MG frequency deviances. For MG frequency control, a novel two level control mechanism approach is employed. The first level control technique is from the WTG side. The second level control technique is from the DEG side. The first level control technique is used to regulate the WTG power command by using wind speed and MG frequency deviations based on power system conditions. To minimize the MG frequency deviations using an optimized wind power command, the authors in [9–11] presented different strategies. In [9–12] authors proposed FLA generated power command for WTG in an MG for smoothing output power based on the MG conditions. However, it has a drawback that it needs two fuzzy logic controllers (FLC) to generate the wind power command. Also, it enhances the difficulty in the calculation. To avoid the above difficulty, in this paper, a unique approach is proposed with only one FLC to generate the WTG power command.

In the last decade, numerous frequency control approaches have been proposed to ensure the reliability and stability of an autonomous microgrid from the DEG side [13–15]. The authors [16,17] focused on existing control strategies [16] of distributed generators in MGs which includes V/F control, droop control, and P/Q control. Various advanced control techniques have been presented recently, such as fuzzy logic [18,19], robust control [20,21], sliding mode control (SMC) [22,23], artificial neural network [24,25], distributed model predictive control [26,27], advanced droop control [28,29]. Moreover, classical PID and PI control techniques are usually employed in MG because of low cost and simple structure. Classical PID/PI techniques are commonly tuned by Ziegler Nichols and, Hit and trial method [30] which is challenging to amend the complexity of MGs such as the varied wind speed, disturbances, and load demand. Yet, the overall system becomes unstable with the inappropriate selection of controller gains. Hence, artificial intelligence techniques viz. genetic algorithm (GA) [31], grasshopper optimization algorithm (GOA) [32], etc. are more attractive to tune the gains of PID controller for LFC problem. Though, these tuning approaches have complex structures and have more calculations that are difficult to implement in a real MG system [33]. Furthermore, the performance of the meta-heuristic methods depends on the suitable selection of their algorithm-specific parameters and improper selection of parameters can lead to divergence of the algorithm. Therefore, it is essential to propose a method that has less calculation, simple in structure, and better effect in frequency control of microgrid.

Unlike traditional control theorems that are essentially based on linearized mathematical models of control plants, intelligent approaches, such as the fuzzy logic control scheme, establish the controller directly based on the measurements, long-term experience, and knowledge of domain experts/operators. Specifically speaking, the principal functionality of fuzzy logic-based LFC is to improve the dynamic frequency performance intended for maintaining the system frequency balanced during sudden load changes. Versatile studies deploying fuzzy logic notions have been conducted for efficient LFC designs in interconnected power systems [34–37]. The authors in [34] provided an overview of fuzzy logic contribution on efficient LFC in multi-area power systems. As well, with the aim of improving the LFC performance in a multi-area power system, the gain scheduling of PI controllers has been undertaken through the fuzzy logic approach [35]. More recently, a heuristically optimized fuzzy logic technique based on a PSO intelligence basis has been utilized for appropriate frequency control in power systems hosting remarkable renewable energy resources [35–37]. As a technical obstacle upon the overall generality of the proposed approaches, the structure of the conventional PI controllers would be changed following the system specification changes [38]. Also, no special care has been devoted to comprehensively analyze and then compare the established methodology with the available literature to direct the research and development in the right stream, spotlighting efficient LFC designs. Additionally, as the artificial intelligent techniques are generally dependent on system-inherent characteristics and expert knowledge, the system behavioral identification precision as well as the learning and corrective plans are engaging an indispensable share in effective LFC synthesis procedures.

To fulfill the stated technical issues discussed in the literature, the present study recruits the fuzzy logic approach to sketch a novel LFC technique. Hence, to do this a complementary fuzzy logic corrective loop (FLCL) is accurately superimposed to the main foundation of the PI controller for adjusting gain values affected by different fault conditions. Therefore, through the prudent design, the structure of the typical PI controller has been conserved as valid under steady-state conditions. And the typical PI controller will not have any change in its structure; that is, the complemented FLCL merely impacts the performance of the PI controller under load disturbances, and hence, no action is performed under steady-state conditions. This method is in principle deploying the cooperation of fuzzy logic features and typical PI controllers to increase the extensibility of the control space studied in the LFC problem.

From the literature review, the FLA is established as a proficient solution for which no accurate mathematical model available. Few authors are stated about the MG LFC design with FLA based gain scheduling of PI controller [38,39]. However, this approach has a drawback that the PI controller structure can change with changes in system specifications that effect system steady state response. To overcome the above issue in this paper, a robust fuzzy tuned PI controller is proposed by retaining the PI controller structure as it is and by extending its robustness through FLA based corrective loop under disturbances to regulate the output power of the diesel engine generator for the further reduction in microgrid frequency fluctuation from DEG side. The vital advantages of this paper are;

- A novel two level control mechanism is proposed to minimize the frequency fluctuations in autonomous wind-diesel microgrid.
- In the first level, an optimum wind power command signal as input to WTG is generated based on MG conditions instead of constant wind command signal.
- In the second level, a robust fuzzy tuned PI controller is proposed for further reduction in the MG frequency fluctuations.

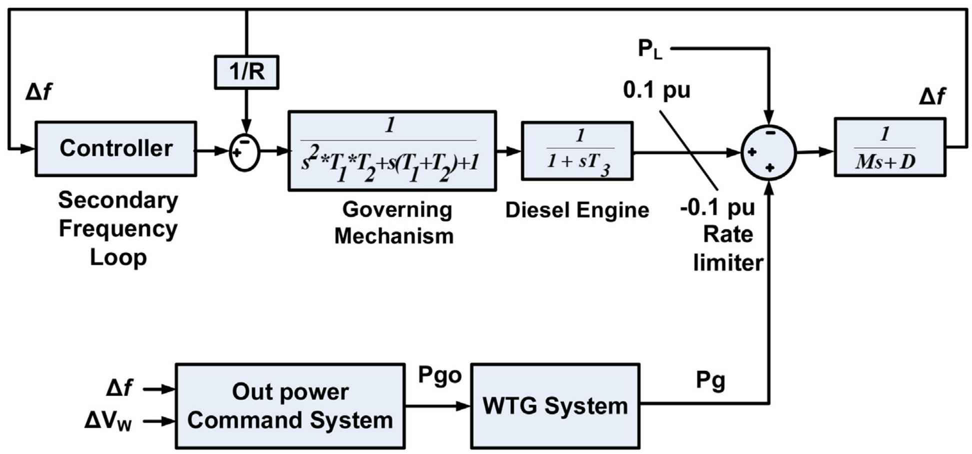

FIGURE 1
Model of autonomous Wind-Diesel MG.

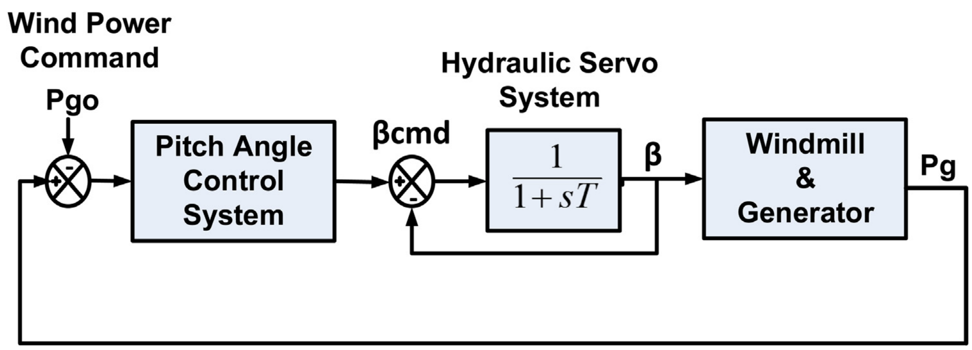

FIGURE 2
Model of the WTG system.

Modelling of MG system

Figure 1 represents the model of autonomous wind-diesel MG [12]. The capacity of autonomous MG is 687.5 KW capacity of WTG is 275 KW and capacity of DEG is 500 KVA. The DEG is used to supply the deficient amount to the load based on wind power availability to imbalance the load-generation in the MG. Each component of the MG system is described below.

Model of WTG

Figure 2 shows the typical model of the WTG system [40]. Where P_{go}*, 'e', β, and Pg in Figure 2 denotes the wind power command generated using FLC, error in output power, pitch angle, and WTG output power. The hydraulic servo system in WTG is used to smooth out the WTG output power. The SQIG is used as a wind generator.

The model of the windmill and generator is presented in Figure 3 [40]. The mechanical output power of the windmill is expressed as:

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

Where 'V_w' is the wind velocity, 'ρ' is air density, 'A' is the swept area, and 'C_p' is power coefficient.

The power coefficient 'C_p' is expressed as:

$$C_p(\lambda, \beta) = 0.22(\frac{116}{\gamma} - 0.4\beta - 5)exp^{-125/_\gamma}$$

$$\gamma = \left[\frac{1}{\lambda + 0.08\beta} - \frac{0.035}{1+\beta^3}\right]^{-1}$$

$$\lambda = \frac{R\omega}{V_\omega} \quad (2)$$

The output power (P_g) of WTG is expressed as:

$$P_g = \frac{-3V^2 s(1+s)R_r}{(R_r - sR_s)^2 + s^2(X_s + X_r)^2} \quad (3)$$

Where's' is the slip of SQIG and it is determined as:

$$s = \frac{\omega_0 - \omega}{w_0} \quad (4)$$

The angular speed (ω) is obtained as:

$$\omega = \sqrt{\frac{2}{J}(P_{wm} - P_g)} \quad (5)$$

Conventional control strategy, WTG output power command kept constant at its rated value $P^*_{go} = 0.4$ pu (pu is per unit value). In traditional strategy, pitch angle control is stimulated if and only if the wind speed is in the region between rated and cut-out. And the pitch angle control is operated constantly at 2° for the wind speed in the region between cut-in & rated speed. However, in this cut-in and rated speed region, the wind power experiences more fluctuations

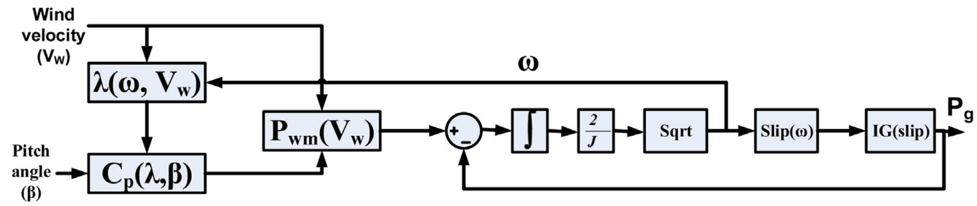

FIGURE 3
Windmill and generator.

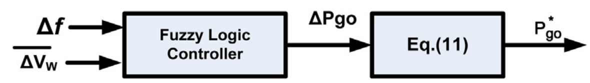

FIGURE 4
FLA based WTG power command signal generation.

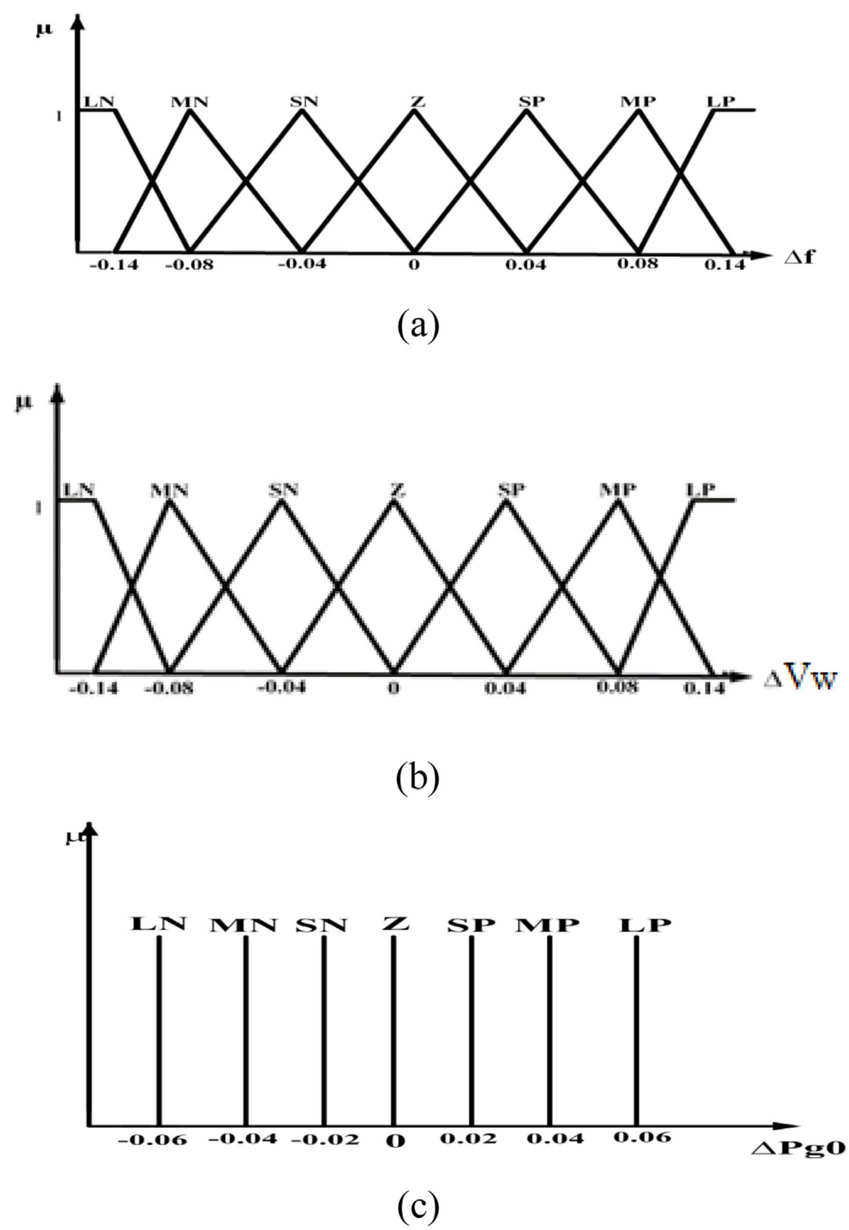

FIGURE 5
a) MF for input frequency deviation, b) MF for input change in wind speed & c) output of FLC of WTG power command system.

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TABLE 1

Rules for output power command system.

ΔP_{go}		Δf						
		LN	**MN**	**SN**	**Z**	**SP**	**MP**	**LP**
ΔV_w	LN	LP	LP	LP	LN	MP	SP	Z
	MN	LP	LP	LP	MP	SP	Z	SN
	SN	LP	LP	MP	SP	Z	SN	MN
	Z	LP	MP	SP	Z	SN	MN	LN
	SP	MP	SP	Z	SN	MN	LN	LN
	MP	SP	Z	SN	MN	LN	LN	LN
	LP	Z	SN	MN	SN	LN	LN	LN

(based on Eq. 1). Therefore, this fluctuating power supplied to MG produces large frequency deviations. Hence, to diminish these frequency fluctuations in MG within acceptable limits, the WTG Output power control has to be operated in all operating regions (i.e. pitch control has to be extended for the region between cut-in & rated wind speed). It's presumable that the proposed method capable to accomplish this task by synchronizing with the pitch angle controller. The cut-in, rated and cut-out wind velocities used for paper are 6, 12, and 27 m/s.

Proposed two-level control mechanism

Concerning the MG stability, a variable WTG power command is generated using FLA instead of the fixed command signal. In this regard, pitch angle control has to be operated in both regions to follow the output power command signal. To achieve this task, the pitch angle is regulated using FLC. Segment 3.1 illustrates the WTG power command signal generation using FLA. Segment 3.2 describes FLA based PI controller.

WTG power command signal generation using FLA

From the last decade, the capability of FLA has been proved in the renewable energy fields [41–43]. The present work essentially focuses to establish an outstanding frequency control of MG with the help of the WTG. Hence in this work, no novel fuzzy is proposed but the novel approach with fuzzy based on frequency deviations and wind velocity for WTG power control is proposed [44].

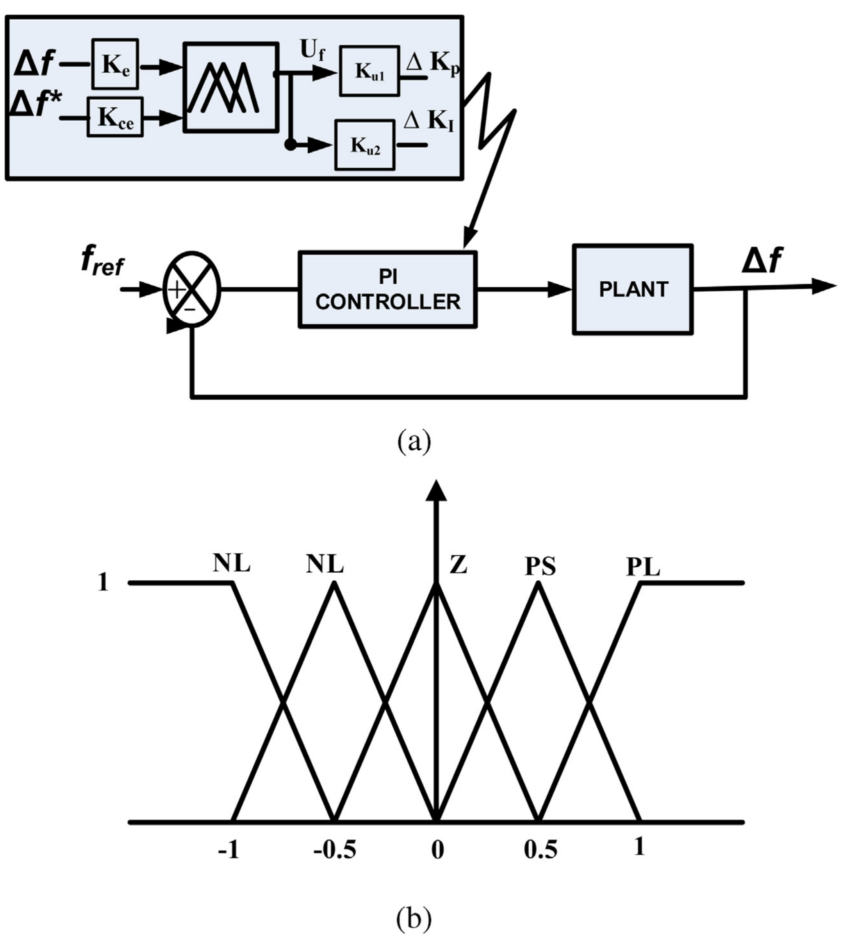

FIGURE 6

(a) FLA-PI controller structure, (b) The inputs and output MF of FLA-PI.

TABLE 2

Fuzzy Rule Base.

U_f		Δf*				
		NL	**NM**	**Z**	**PM**	**PZ**
	NL	NL	NL	NL	NM	Z
Δf	**NM**	NL	NL	NM	Z	PM
	Z	NL	NL	Z	PM	PL
	PM	NM	NM	PM	PL	PL
	PZ	Z	Z	PL	PL	PL

Figure 4 describes the FLA based WTG output power command signal generation (P^*_{go}). The Fuzzy logic-based approach is best suitable for the systems in which high uncertainty present and for mathematical expressions are difficult to derive [6,9,41] and fuzzy logic sinks for the present scenario.

The proposed approach presented in Figure 4 has two inputs that are change in wind speed ($\overline{\Delta V_w}$) and frequency deviation (Δf).

The change in wind speed ($\overline{\Delta V_w}$) can be expressed as:

$$\Delta V_w = \int_{t-T}^{t} V_w dt - V_w \tag{6}$$

$$\overline{\Delta V_w} = \Delta V_w(k-1) - \Delta V_w(k) \tag{7}$$

Where, 'V_W' is the instantaneous wind velocity,' t' is the current time and 'T' is integral time interval which is 20 s. The membership functions (MFs) of proposed approach is depicted in Figure 5 and Table 1 shows the rule base of proposed fuzzy approach.

Based on MG condition ΔP_{go} is controlled by considering the change in frequency as one of the fuzzy input (Δf). In this, the rule base and MFs are selected in such a manner, to stop the further rise in frequency deviation by using trail & error method. The example fuzzy rule is shown below:

Fuzzy rule j: *if* Δf is LN & ΔV_w is SP *then* ΔP_{go} is MP

In rule j, '*if*' part is termed antecedent (ζ_j) and '*then*' part is termed consequent (Q_l).The corresponding defuzzified value (crisp value) from fuzzy reasoning can be determined using Eq. (8):

$$\Delta P_{go} = \frac{\sum_{j=1}^{49} \zeta Q_l}{\sum_{j=1}^{49} Q_l} \tag{8}$$

The WTG power command can be defined using the output of FLC, ΔPgo as:

$$P^*_{go} = P_{rated} - \Delta P_{go} \tag{9}$$

FLA based PI controller

The classical PI controllers have the fixed gains which are tuned by using Ziegler-Nicholas (Z-N) method according to the pre-estimated system operating conditions. However, this PI controller tuned by the Z-N method may not guarantee the optimum response of the system under rapidly changing operating conditions. Therefore, appropriate tuning of gains of the PI controller can produce the optimal performance under rapid changes in MG. To accomplish this task FLA is used in this work.

Figure 6(a) shows the fuzzy logic approach tuning of the proportional-integral controller (PI) structure. In this control configuration, the FLC system is used to adjust the gains of the typical PI controller. The commonly employed PI controller is as follows:

$$U_C = (K_p + U_f * K_{u1}) + (K_I + U_f * K_{u2}) \tag{10}$$

$$e(t) = \Delta f = f_{ref} - f \tag{11}$$

Where K_P is the proportional gain and K_I is the integral gain. K_{u1} and K_{u2} are the scaling factors of proportional and integral gains. The set point, process output, and controller output (generated command signal) are represented as f_{ref}, f, U_C, respectively. For the typical PI controller, the gains *Kp* and *Ki* in Eq. (10) are modified using the operator based on the changes in process condition. In this work, a rule-based intellectual fuzzy coordinate hybrid controller structure is developed to online adjust the scaling factors K_{u1} and K_{u2} according to the changes in output power DEG without much involvement of operator and further, it can increase the performance of classical PI controller for a wide operating range [36].

In Figure 6, frequency deviation (Δf) and change infrequency deviations (Δf*) are FLA inputs and updating factor (U_f) is the FLA output.

Therefore the change in gains of the PI controller (ΔK_P&ΔK_I) according to FLA output is obtained as:

$$\Delta K_p = U_f * K_{u1} \tag{12}$$

$$\Delta K_I = U_f * K_{u2} \tag{13}$$

The used FLC inputs are Δf & Δf*, which are expressed as:

$$\Delta f = f_{ref} - f \tag{14}$$

TABLE 3

Microgrid Parameters.

WTG Parameters	
R(Blade Radius)	14 m
V(Phase Voltage)	400 V
R_s	0.00397
R_r	0.00443
X_s	0.0376
X_r	0.0536
J	62,999 kg-m^2
ρ	1.225 kg/m^2
P_g	275 kw
DEG Parameters	
T_1,T_2(Time constants of governor)	0.1,0.25 s
T_3(DEG Time constant)	5 s
D(Damping coefficient)	0.012 puMW/Hz
M(Inertia Constant)	0.1 puMW/Hz

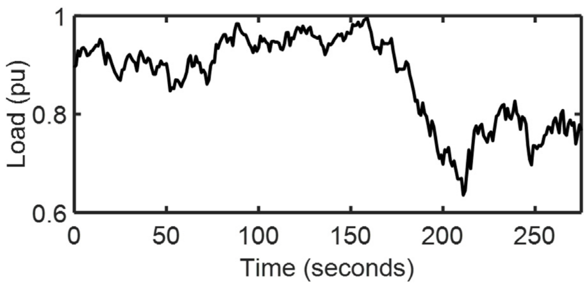

FIGURE 7

Load pattern.

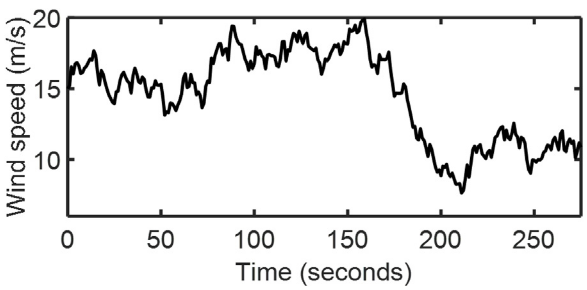

FIGURE 8

Wind Speed.

$$\Delta f^* = \Delta f(k-1) - \Delta f(k) \quad (15)$$

The input and output MFs of FLC are presented in Figure 6(b). Two inputs with five fuzzy sets (5^2), FLA consists of 25 rules to resemble different operating conditions are shown in the Table 2. The sample rule of FLC is defined as:

Sample rule: if 'Δf' is Z and 'Δf ' is PM then U_c is PM*

Using Eq. (16) the output of FLA (UA) from fuzzy reasoning is determined as:

$$U_f = \frac{\sum_{i=1}^{25} \mu_i w_i}{\sum_{i=1}^{25} w_i} \quad (16)$$

Where μ_i is the degree of MF of i^{th} input and w_i is the i^{th} rule weight.

Simulation results and analysis

In this section, the frequency fluctuations of MG have been investigated for all possible operating conditions including certain critical operating scenarios. The efficacy of the proposed two-level control mechanism is examined through simulation results using MATLAB/Simulink. A real-time test system stated in [10] is used for this study. The simulation parameters of the test system are given

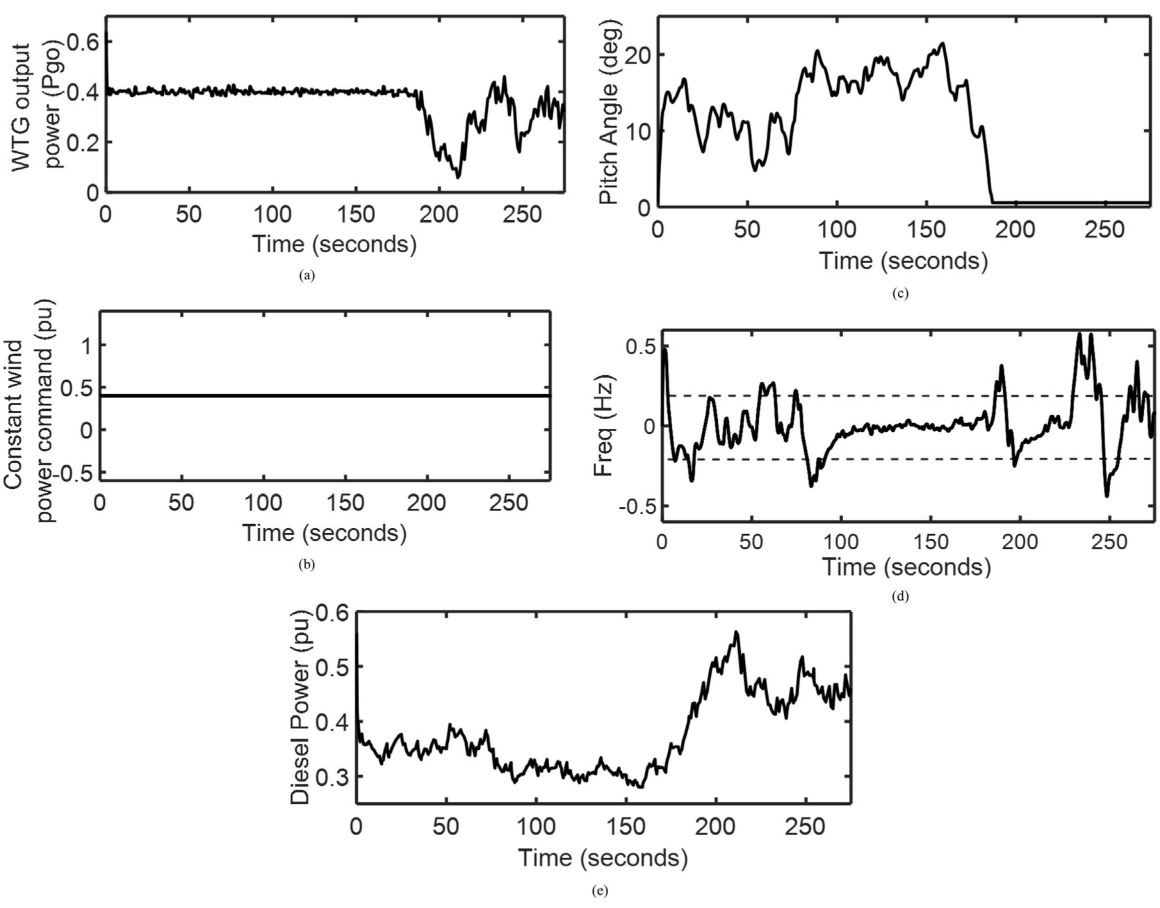

FIGURE 9

Simulation results under Scenario 1 (a) WTG power (P_g) (b) WTG power command signal (c) Pitch angle (d) frequency deviation of MG & (e) DEG output power.

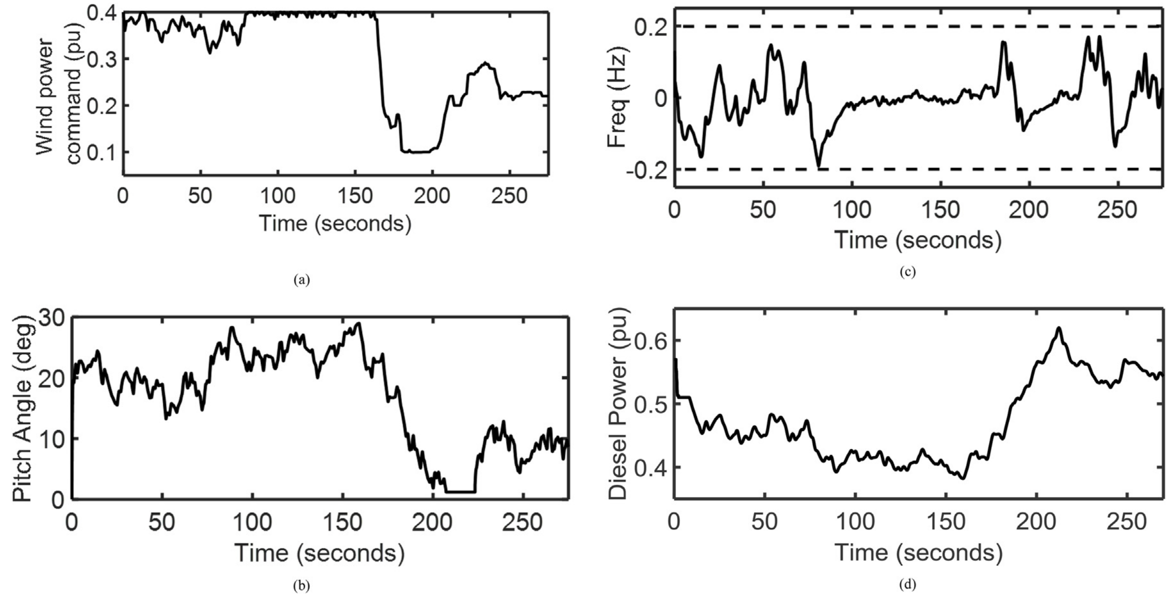

FIGURE 10

Simulation results under Scenario 2 (a) WTG power command signal (b) Pitch angle (c) frequency deviation of MG & (d) DEG output power.

in Table 3. The supremacy of the proposed two-level control mechanism is studied under the following scenarios.

Scenario 1

Objective: This scenario aims to show the frequency deviation of MG with a constant wind power command on the WTG side and a simple integral controller on the DEG side.

In this basic case, a constant wind power command on the WTG side and a simple integral controller on the diesel engine side is considered. A 300 s sample data of wind speed and load are shown in Figures 7 & 8 respectively. In Figure 8 the wind speed from t = 0–180 s shows above rated speed (i.e. 12–28 m/s) and from t = 181–300 s shows below rated speed (6–12 m/s). Figure 9(a) shows the WTG output power P_{go}, Figure 9(b) shows the constant wind power command Pgo and it is kept constant at its rated value (i.e. 0.4 pu) and the pitch angle is between 2°–90°, as shown in Figure 9(c). It is observed that in Figure 9(c), when wind speed is above the rated speed (i.e. t = 0–180 s), the pitch angle is efficiently operated by pitch angle control mechanism and frequency deviation in MG shown in Figure 9 (d) is nearly the acceptable limit (excluding the initial stage) whereas for wind speed is below rated speed (i.e. t = 180–300 s) the pitch angle is operated at 2° results in large WTG output power fluctuations, which leads to large frequency deviations. The diesel power fluctuations for this scenario is presented in Figure 9 (e).

Scenario 2

Objective: This scenario aims to show the frequency deviation of MG with a variable wind power command on the WTG side and a simple integral controller on the DEG side.

Based on scenario 1, to operate the pitch angle in both regions (above rated and below rated speed) in this scenario a constant wind power command on the WTG side is replaced by a variable wind power command and a simple integral controller is kept as it is on the DEG side. In this case, the WTG power command signal shown in Figure 10 (a) is generated according to MG condition and wind speed, prioritizing to stop large frequency fluctuations in MG. Figure10(b) depicts the pitch angle (β) of WTG, it is witnessed that the pitch angle control is extended to two operating regions (i.e. cut in-rated & rated- cut out range) compared to the case in scenario 1 for frequency control in MG. Figure 10(c) shows the frequency deviation of MG, which is within the range of ±0.2 Hz. Figure 10(d) shows DEG output power(ΔPd) and it has been observed that the DEG fluctuations are reduced significantly in this scenario. This is achieved due to the constant wind power command is replaced by a variable wind power command on WTG side.

Scenario 3

Objective: This scenario aims to propose the best controller on DEG side.

In this case, the frequency regulation of the real-time test system is studied with the control mechanism on the DEG side without any controllers on the WTG side. A robust fuzzy tuned PI controller is proposed on the DEG side to regulate the frequency. In this we consider, a step-change in load and wind power of 0.01 pu is applied at t = 20 & 120 s respectively. The instantaneous dynamic

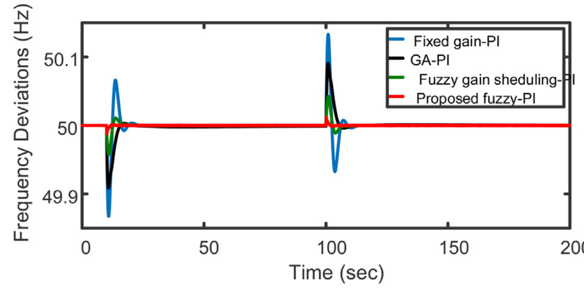

FIGURE 11

Response of MG frequency deviation for Scenario 3.

TABLE 4

Quantitative analysis of scenario 3.

Methods	Performance indices			
	Peak Undershoot (Hz)	Settling Time (s)	Peak Overshoot (Hz)	Settling Time (s)
Fixed gain-PI [ref 10]	49.965	17	50.027	15
GA-PI [ref 31]	49.978	11	50.02	13
Fuzzy gain scheduling-PI [ref 35]	49.985	9	50.015	10
Proposed Fuzzy tuned-PI	49.992	6	50.004	5

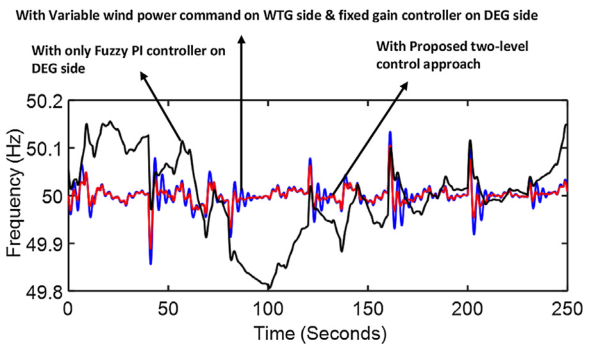

FIGURE 12

Response of frequency deviation for Scenario 4.

performance of MG is studied with fixed gain PI, GA-PI, fuzzy gain scheduling method and proposed robust fuzzy tuned PI controller. The frequency deviation response of various controllers is shown in Figure 11, and the quantitative analysis of Figure 11 presented in Table 4. From Table 4 all the controllers make frequency deviation near to zero but the proposed fuzzy tuned PI controller has quick response and little chattering which is more effective than all other controllers in literature. From this scenario, the proposed fuzzy tuned PI controller can be used in DEG side instead of a simple integral controller in scenario 2, which is the proposed two-level control mechanism. The superiority of proposed two-level controller in mitigating frequency deviations over scenario 1 &2 is explained in scenario 4.

Scenario 4

Objective: This scenario aims to propose a two-level control mechanism for further reduction in frequency deviation of MG.

In this case, From the Scenario 2, a variable wind power command of WTG is generated by FLC approach (first level controller) in WTG side and a simple integral controller is replaced by the fuzzy tuned PI controller on DEG side (Second level controller) to propose a two-level control mechanism for the reduction in MG frequency oscillations. The test condition is similar to Scenario 2 but in addition to that 50% reduction in load damping coefficient (D) and system inertia (H), and 20% increase in governor time constant (T_G) are considered as parametric uncertainties. The frequency deviation response of MG for Scenario 4 is shown in Figure 12. From Figure 12 it is observed that the proposed two-level control mechanism effectively reduces the MG frequency deviations compared to other Scenarios.

Conclusion

In this work, a novel two-level control mechanism has been presented to mitigate frequency fluctuations in an autonomous wind-diesel microgrid. The first level control technique is proposed to generate the WTG power command signal based on MG condition. In the second level, a robust fuzzy tuned PI controller is proposed on the DEG side for further reduction in frequency fluctuations for all operating conditions. The frequency regulation with the proposed method has been shown acceptably with reliable response during normal as well as critical operating scenarios. Encountering parametric uncertainties in the test system, it was observed that the proposed approach demonstrates a superior response than the other methods stated in the literature, more specifically in terms of restrained undershoots and fast settling of frequency deviations. The simulation results are witnessed that the proposed approach is well suited in minimizing the microgrid frequency deviations. The technical merit of this paper is, the frequency can be controlled to within the acceptable range in wind-rich MG without any energy storage systems.

Conflict of interest

The authors have declared no conflict of interest

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