# Fuzzy Logic Approach Based Novel Frequency Control Strategy by Wind Turbine Generator in a Wind-Diesel Autonomous Microgrid

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***Abstract*—Intermittency in the wind turbine generator (WTG) output power is affecting the microgrid parameters significantly, principally on the frequency of the microgrid (MG). As a result, MG experiences large frequency excursions and becomes unstable.Considering this as problem, this paper introduces a novel control strategy for WTG output power to mitigate the frequency excursions in the wind-diesel autonomous MG.In the proposed method, a conventional fixed wind power command is replaced by an optimum adaptive wind power command based on power system condition.To perform this task, fuzzy logic approach is employed by considering frequency deviation and wind velocity as inputs and change in power as output. A real time wind-diesel hybrid model is considered as test system to examine the proposed strategy.The dynamic model is developed in MATLAB and, the superiority of proposed approach in mitigating the frequency deviation is alleviated by comparing with constant wind power command based WTG.**

***Keywords*—frequency control, fuzzy logic approach, adaptive wind power command, microgrid, frequency excursions.**

## I. Introduction

Diesel engine generators (DEGs) are main power sources for isolated islands and remote locations. These DEGs require heavy oil which is very costly (fuel cost + storage cost + transport cost) and hazardous to the environment. With concerns to environment pollution & cost issues, renewable energy sources (REs) are an attractive solution. Among REs, wind power is most promising one because of present technologies allows for large-scale power generation. Substantial growth in wind power installation whole over the world, introducing new challenges and technical issues inthe secure operation of power system, especially in microgrids(MGs)[1-2].Active power control of WTG side and frequency control of MG are key issues concern to MG stability[3].

WTG output power is highly intermittent in nature, due to its output which is proportional to the cube of wind speed. When this fluctuating power is fed to MG, it may cause large frequency deviations [4-6]. Several authors proposed energy storage system (ESS) based approaches [7-9] for smoothing the wind power before feeding to the grid for frequency control. But, ESS approach is costly and frequent charging and discharging reduces the battery life cycle. This paper focuses on frequency control of MG through output power control of WTG, without using ESS with using the frequency deviations of MG and wind speed deviations. For frequency control in MG, three control levels are employed. Two control levels from WTG side and one is from diesel engine generator side. Out of these two controllers in WTG, one is central controller, which is used to determine the WTG power command by considering wind speed &frequency deviation of MG.To mitigate the frequency deviations in MGthrough optimized wind power command, few authors proposed different strategies [10-12].In [4 & 10-12] authors' proposed novel fuzzy logic approach (FLA) based power command signal for WTG /PV in a MG for leveling output power by accounting power system conditions. But, it uses two fuzzy logic controllers for generating power command signal and it increases the complexity in the calculation. In this work, a new approach is proposed with only one fuzzy controllerto generate the WTG power command.

Second controller in WTG is local controller i.e. pitch angle controller. Which is required to follow the WTG power command. In general, the function of this controller is to keep WTG output power to its rated value, when its speed is above the rated wind speed. In [13-15] authors proposed conventional PI/PID controllers for pitch angle control of a WTG. The drawback of this method is, it operates in predetermined operating conditions. For sudden change in operating condition, conventional PI controllers may not provide optimal performance.

In [16-17] authors proposed tuning of PI/PID controllers with different meta-heuristic techniques. Problem with these meta-heuristic techniques is, their performance highly depends on algorithmic specified parameters; improper selection of these parameters may not get optimal performance. In [6&18] few authors proposed variety of predictive control approaches for pitch angle control in WTG. In [19-20] authors proposed FLC based pitch angle controller. From the literature it can be found that fuzzy approach is providing better performance compared to conventional and Meta heuristic based controllers. This paper proposes frequency control of an autonomous MG through WTG output power control. In order to control the WTG output power according to power command signal, it requires an intelligent and efficient controller. Proposed FLC basedpitch angle controller is found to be suitable.

Third controller is in the diesel engine generator (DEG) side. Even though energy storage systems employed in the MG in different studies, several authors demonstrated the inability of fixed gain PI/PID controllers

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in frequency control from the DEG side [5,21]. In this work, to demonstrate the effectiveness of proposed strategy in controlling frequency from WTG side, a simple integral controller is considered in DEG side.The key contribution of this paper are; In this work based on MG operating condition (frequency deviation) and change in wind velocity an optimum power command signal is generated as input to WTG instead of fixed wind command. To follow this wind command signal, a fuzzy logic based pitch angle controller is employed.

## II. SYSTEM MODELLING

Fig.1 depicts the wind-diesel autonomous MG model [4]. Total capacity of MG is 687.5 KW (rating of DEG: 500 KVA; rating of WTG: 275 KW).DEG is responsible for load-generation imbalance in the MG, by supplying deficientamount to the load based on wind power availabilityThe detailed modelling of each component is explained below.

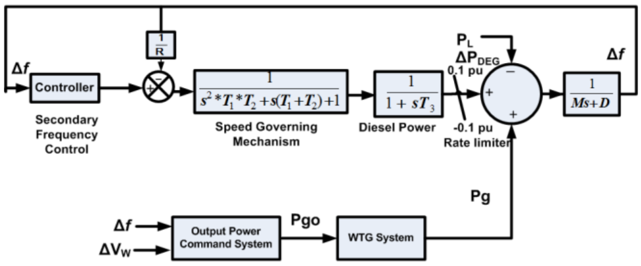



Fig.1 Frequency response model of Wind-Diesel autonomous MG 2.1 WTG model

Fig2 depicts the standard model of WTG system [22].Where Pg, $P_{go}^*$, 'e' in Fig.2 indicates the WTG output power, power command signal generated by fuzzy logic controller, error in output power. The function of hydraulic servo system is to smooth the WTG output power. In this work SQIG is used as wind generator.

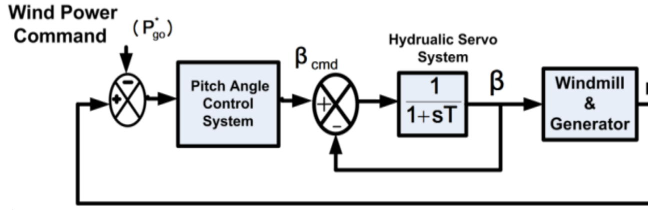



Fig. 2 WTG system

Fig.3 shows the windmill and generator model [22]. The mechanical output power of windmill can be expressed as:

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

Where 'ρ' is air density, 'A' is swept the area, '$V_w$' is the wind velocity, '$C_p$' is power coefficient which can beexpressed as:

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

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

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

The WTG output power ($P_g$) can be 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 which is defined as:

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

The angular speed (ω)can be expressed as:

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

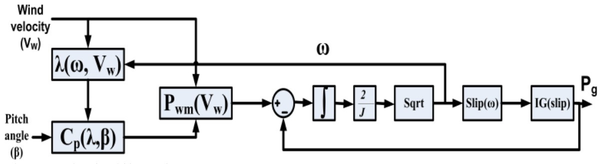



Fig.3 Windmill and generator

Conventional control strategy, WTG output power command kept constant at its rated value$P_{go}^* = 0.4$ (0.4 is per unit value). In conventional strategy, pitch angle control is activated only when wind speed is in between rated and cut-out region. When wind speed is in between cut in & rated speed, β is kept constant at $2^O$. But, in this region wind power is highly fluctuating (according to Eq. 1), this fluctuating power causes large frequency deviations in MG. Therefore, to mitigate these frequency oscillations in MG within tolerable limits, The WTG Output power control is to be extended for all operating regions (i.e. pitch control law to be extended for region where winds speed in between cut-in&rated). It's presumable that proposedmethod able to perform this task by coordinating with pitch angle controller.In this paper cut-in, rated and cut out wind velocities are 6,12,27 m/s.

## III. WTG POWER COMMAND & PITCH ANGLE CONTROL SYSTEM

With concern to MG stability, WTG constant power command signal is replaced with variable power command by using fuzzy logic approach (FLA). To follow this output power command, pitch control has to be extended for two operating regions. For this task,fuzzy logic control (FLC) based pitch angle control is employed. Section 3.1 describes generation of WTG power command signal using FLA. Section 3.2 describes fuzzy logic based pitch angle control system.

### 3.1 FLA based WTG power command signal

It has been proved the ability of fuzzy logic approach from the decades in the renewable energy fields [21,23-24]. The primary motive of present work is to establish an effective frequency regulation of MGwith the help of the WTG. Therefore, no new fuzzy is developed here; instead of that novel strategy with fuzzy approach for WTG power control according to wind velocity and frequency deviations is developed.

Fig.4 depicts the WTG output power command signal generation ($P_{go}^*$) by using FLA. Fuzzy approach is best choice when it is difficult to derive the mathematical expressions and high uncertainty present in the system [6,11,21] and it sinks for present scenario.

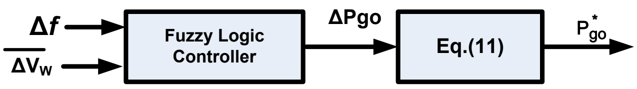



Fig. 4 Generation of WTG power command signal

As shown in Fig.4, proposed approach has two inputs; frequency deviation (Δf) and change in wind speed $(\overline{\Delta V_w})$ which can be defined as:

$$\Delta V_w = \int_{t-T}^{t} V_w dt - V_w \quad (6)$$

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

Where, 'T' is integral time interval which is 20seconds. 't' is present time and $V_W$ is instantaneous wind velocity. Fuzzy membership functions (MFs) and rule base of proposed approaches is show in Fig.5 and Table.1

Here, $\Delta P_{go}$ is controlled according to MG condition by considering frequency deviation as one of the input ($\Delta f$). MFs & rule base are selected in such a manner, to stop the further rise in frequency deviation by using trail & error method. The sample fuzzy rule is described below:

Rule j: *if*$\Delta f$ is MN &$\Delta V_w$is MP *then*$\Delta P_{go}$ is Z

TABLEI: RULESFOROUTPUTPOWERCOMMANDSYSTEM

| $\Delta P_{go}$ | | $\Delta f$ | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | LN | MN | SN | Z | SP | MP | LP |
| $\overline{\Delta V_W}$ | 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 |

In rule j, *if*part is called antecedent ($\zeta_j$) and *then* part is called consequent ($Q_l$).Equivalent crisp value (defuzzified value) from fuzzy reasoning is calculated by using Eq. (8):

$$\Delta P_{go} = \frac{\sum_{j=1}^{49} \zeta_j Q_l}{\sum_{j=1}^{49} Q_l} \quad (8)$$

From the output of FLC $\Delta P_{go}$, The WTG power command can be defined as:

$$P_{go}^* = P_{rated} - \Delta P_{go} \quad (9)$$

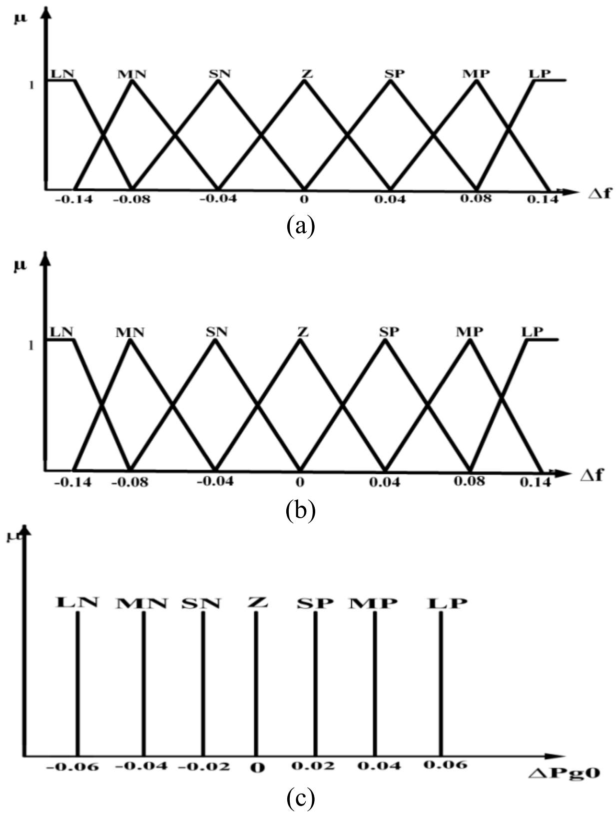


Fig.5a),b)MFs of inputs &c) output of FLC of power command system.

3.2 FLC based WTG pitch angle controller

Fig.6 depicts FLC based pitch angle controller system. FLC is employed because it can handle effectively with non-linear systems .Here; the WTG power output is highly non-linear and uncertain by nature. So, proposed controller able to follow output power command efficiently. In Fig.6 'e' is output power error, $\Delta e$ is change in error and $\beta_{cmd}$is pitch angle command.

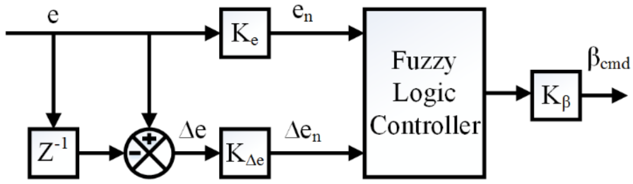


Fig.6 Structure of FLC based pitch angle controller

The FLC is formulated using MFs for the input parameters such as e &$\Delta e$, which are defined as:

$$e = P_{go}(k) - P_{go}^*(k) \quad (10)$$

$$\Delta e = e(k) - e(k-1) \quad (11)$$

The MFs for the inputs and output of FLC are shown in Fig. 7.

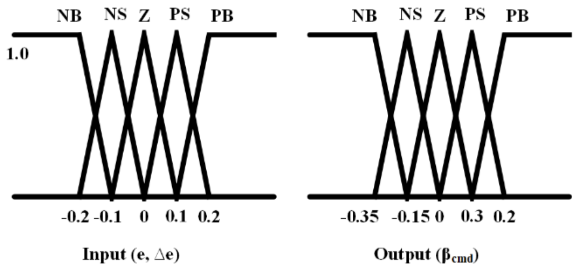


Fig.7 MFs for e, $\Delta e$ and $\beta_{cmd}$

Two inputs with five fuzzy sets ($5^2$), FLC is consists of 25 rules to resemble different operating Conditions as mentioned in Table 2. The sample control rule is described below.

If 'e' is NM and '$\Delta e$' is PS then $\beta_{cmd}$ is NS

Equivalent crisp value ($\beta_{cmd}$) from fuzzy reasoning is calculated by using Eq. (12):

$$.\ \beta_{cmd} = \frac{\sum_{i=1}^{25} \mu_i w_i}{\sum_{i=1}^{25} \mu_i} \quad 1□.$$

Table II: Rules for pitch control mechanism

| $\beta_{cmd}$ | | $\Delta e$ | | | | |
|---|---|---|---|---|---|---|
| | | NB | NS | Z | PS | PB |
| e | NB | NB | NB | NS | NS | Z |
| | NS | NB | NS | NS | Z | PS |
| | Z | NS | NS | Z | PS | PS |
| | PS | NS | Z | PS | PB | NB |
| | PB | Z | PS | PS | PB | NB |

## IV. Simulation Results

In order to demonstrate the performance of the proposed approach in minimizing the frequency deviations of MG, a real-time test system mentioned in [10] is considered for this study. Table 3 shows the various parameters of micro grid. In result analysis proposed approach is compared& contrasted with traditional approach. A 300 seconds sample data of wind speed and load are shown in Fig. 8 & 9 respectively. To demonstrate the compatibility of the proposed approach, in Fig. 9 from t=0 to 180 seconds, it is considered that wind speed is above the rated speed and for t=181 to 300 seconds it is below the rated wind speed.

4.1 Simulation results with traditional approach

Fig. 10 depicts the outcomes with traditional method. Fig. 10(a) shows the WTG output power $P_{go}$, Fig. 10(b) shows the constant power command signal $P_{go}^{*}$ and Fig. 10(c) shows the corresponding pitch angle. In conventional approach, wind power command $P_{go}$ is kept constant at 0.4pu and also pitch angle is in between $2^{o}$-$90^{o}$, as shown in (b) & (c). It is observed in [c], when wind speed is above the rated speed [i.e.12-28 m/sec] from t=0-180 s, pitch angle is efficiently operated by fuzzy logic based pitch angle controller. In this range i.e. from t=0-180 s frequency deviation in MG is almost near the acceptable limit (except at initial stage) as shown in [d]. From t = 180-280 s wind speed is in between cut in and the rated speed (6-12 m/s) and pitch angle is kept constant at $2^{o}$,resulting in large WTG output power fluctuations (according to Eq. (1)). This fluctuating power fed to MG, creating large frequency deviations as shown in [d].The diesel power fluctuations shown in [e], which are high in conventional approach.

TABLE III MG PARAMETERS

| | |
|---|---|
| WTG Parameters | |
| R(Radius of Blade) | 14m |
| V(Phase Voltage) | 400v |
| $R_s$ | 0.00397 Ω |
| $R_r$ | 0.00443 Ω |
| $X_s$ | 0.0376 Ω |
| $X_r$ | 0.0536 Ω |
| 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) | 0.1,0.25s |
| $T_3$(Time constant of Diesel generator) | 5s |
| D(Damping coefficient) | 0.012 puMW/Hz |
| M(Inertia Constant) | 0.1 puMW/Hz |

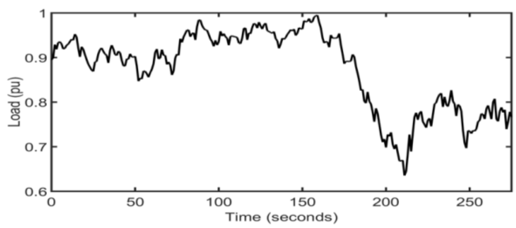



Fig. 8 Load pattern

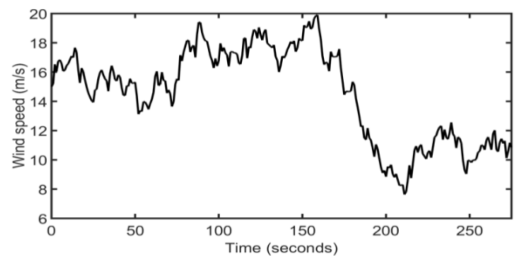



Fig. 9 Wind Speed

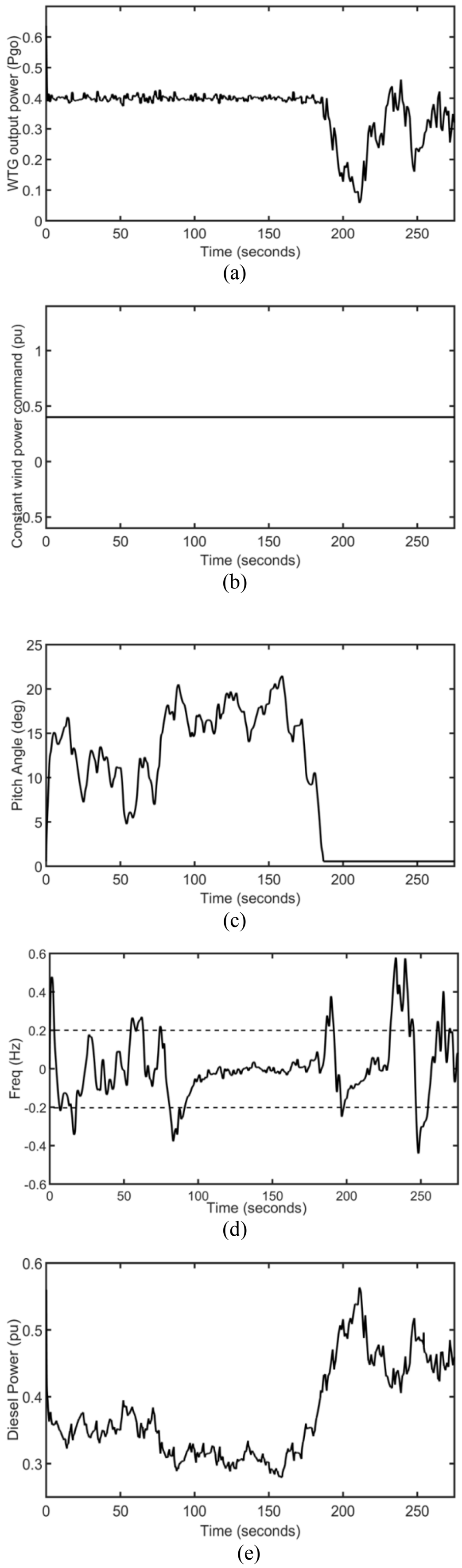
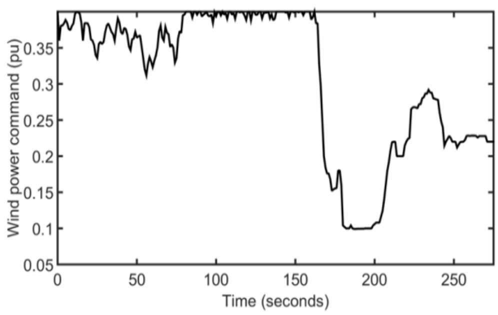


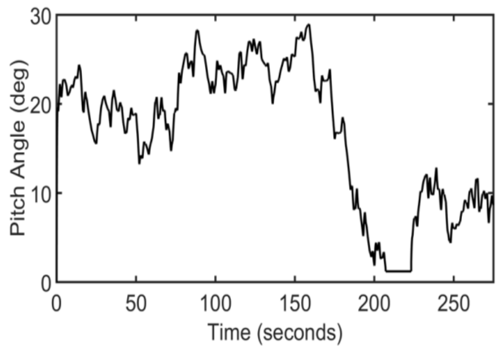

Fig.10 Simulation outcomes with traditional control strategy (a) WTG power ($P_g$) (b) WTG power command signal (c) Pitch angle (d) frequency deviation of MG & (e) DEG output power

4.2 Simulation results with the proposedapproach

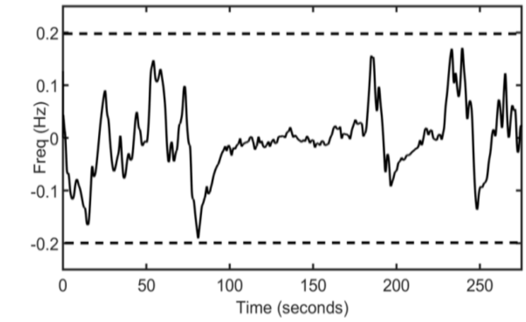
Fig.11 shows the outcomes with the proposed approach. Fig.11 [a] shows the WTG power command signal. This power command is generated based on MG condition and wind speed, prioritizing to stop large excursion in MG frequency deviation. In Fig. 10[d], it is observed that, for t=0-90 sec, there is considerable frequencydeviation due to WTG output andload fluctuations $P_L$. So, WTG power command signal ($P_{go}$) is reduced which can be observed in Fig. 11(a). From t=100-180 seconds, frequency deviation is significantly less as shown in Fig. 10 [d]. Hence, power command is increased to maximum extent i.e. $P_{go}$=0.4pu (note that t=0-180 s wind speed is above the rated speed so that rated power available is maximum i.e. 0.4pu) so that, the full output power of WTG can be used. From t=180-280 s wind speed is in between cut-in and rated speed which is creating huge power fluctuations and at that time load variations also high. These two situations creating huge frequency deviations as shown in Fig. 10 [d], so to stop the further rise in frequency deviation, WTG power command is decreased as shown in Fig.11 [a].Fig. 11 [b] shows the pitch angle (β) of WTG, it is observed that in the proposed method of pitch angle control is extended to two operating regions (i.e. proposed method operates in cut in-rated & rated- cut out range, earlier in conventional method pitch angle control operates only when wind speed is in between rated and cut out range) for frequency control in MG. Fig.11[c] shows the frequency deviation of MG, which is within the range of $\pm$0.2 Hz. Fig.11 [d]shows DEG output power($\Delta P_d$) &DEG output power is controlled according to load variations $P_L$. It is observed that,DEG fluctuations are reduced significantly compared with the conventional method as shown in Fig. 11[e]. This is achieved through output power control of WTG.



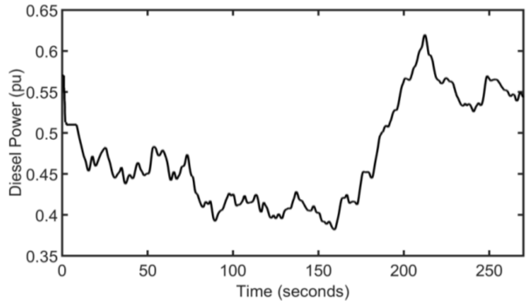
(a)



(b)



(c)



(d)

Fig.11 Simulation outcomes with proposed approach (a) WTG power command signal (c) Pitch angle (d) frequency deviation of MG & (e) DEG output power

## V. CONCLUSION

In this work, FLA based novel frequency regulation method is proposed for an autonomous wind-diesel MG, by considering wind speed and MG frequency deviations. Fuzzy sets (MFs parameters) and rules are designed and tuned heuristically till the further rise in frequency deviations are minimized. Simulation results are demonstrating that the proposed approach is fruitful in minimizing the frequency excursions remarkably in comparison with the traditional method. In general, the usual practice to minimize the frequency excursions is done by smoothing the WTG output power with ESS.In this work, a novel frequency regulation approach without using ESS is proposed. 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. Moreover, when this MG is connected to main grid proposed approach can share the frequency control duties by considering the wind-diesel system as a distributed source.

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