MICROGRID FREQUENCY REGULATION WITH ATTACHED STORAGE SYSTEM USING FUZZY ROBUST CONTROL

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ABSTRACT: In this paper, we propose a robust control procedure with fuzzy intelligence for decreasing system frequency deviation, caused by load change and renewable sources, in a smart microgrid system with appended storage. Frequency deviations are related with renewable energy sources due to their innate fluctuation. In this work, we consider a microgrid where petroleum product generators and renewable energy sources are joined with a sensibly sized, quick acting battery-based storage system. We create robust control methodologies for frequency deviation decrease, regardless of the nearness of huge (demonstrate) uncertainties utilizing Fuzzy Logic Controller. The upsides of our approach are outlined by looking at system frequency deviation between the proposed system and the reference system which utilizes governors to adapt to load and renewable energy source transients. All the simulations are conducted in the Matlab™ and Simulink environment.

Index terms: **Microgrid, energy storage system, power system, Fuzzy control**

I. INTRODUCTION

Microgrid plays a vital role in small-scale power distribution systems .They facilitate numerous benefits due to wide penetration of renewable energy sources (RESs) and energy storage devices into power systems such as reduce systems losses, enhancing system reliability ,reducing greenhouse gas emissions and increase the reliability of electricity supply to the customers. Wind energy is a fluctuating resource which can diverge quickly and causes the frequency deviation. To overcome this problem, a frequency control scheme for a small power system by a coordinated control strategy of a wind turbine generator (WTG) and a battery energy storage system (BESS) is proposed in [1]. A minimal order observer is utilized as a disturbance observer to estimate the load of the power system. The load deviations are considered in a frequency domain. The low frequency component is reduced by the pitch angle control system of the WTG, while the high frequency component is reduced by the charge/discharge of the BESS, respectively in a microgrid [1].

The main objective of Load Frequency Control(LFC) is to regulate the power output of the electric generator within an area in response to changes in system frequency and tie-line loading .Proportional Integral Derivative (PID) control has been well studied by a number of researchers [2], [3]. PID control methods are well understood, but have limited ability to tradeoff overshoot, rise time and damping oscillations. In [4] a study on isolated hybrid distributed generation (DG) system for improving the frequency deviation profile. The frequency control problem is addressed for DG system connected with superconducting magnetic energy storage (SMES) or ultra-capacitor (UC). The particle swarm optimization (PSO) based loop shaping of H-infinity controller is used and compared with those obtained by genetic algorithm (GA) to minimize the frequency deviation. The autonomous decentralized frequency control system of parallel operated decentralized generators based on droop characteristic is presented in [4].

In order to reduce output power fluctuation of wind farm, [5] presents a output power leveling control strategy of wind farm based on both average wind farm output power and standard deviation of wind farm output power, coordinated control strategy for WTGs, and pitch angle control using a generalized predictive controller (GPC) in all operating regions for WTG. In [6], two robust decentralized control design methodologies for load frequency control (LFC) are proposed. The first one is based on H_∞ control design using linear matrix inequalities (LMI) technique in order to obtain robustness against uncertainties. The second controller has a simpler structure, which is more appealing from an implementation point of view, and it is tuned by a proposed novel robust control design algorithm to achieve the same robust performance as the first one.

An approach based on μ-synthesis tools is proposed for the design of robust load frequency controller for electric power system in deregulated environment [7]. Note that μ-synthesis controllers are designed so as to deliver both robust stability and robust performance. In [8] [9] analyses fuzzy logic control application for load frequency control in power system.

This work develops robust control strategies with fuzzy intelligent for both battery and conventional generation systems, with controllers designed to minimize battery size while simultaneously reducing frequency variation, despite variable loads in the microgrid, and the incorporation of a WTG source. Fuzzy-PC controllers are designed to cope with load transients, WTG output fluctuations, model uncertainties and measurement noise/errors.

Following the introduction in Section I, the rest of the paper is organized as follows. In Section II, the system configuration is presented. Some theoretical background of μ-synthesis is briefly presented in Section III. In Section IV, the μ-synthesis controller is designed and brief analysis about Fuzzy logic control is presented. Simulations are conducted in the Matlab™ and Simulink™ environment, and the simulation results are presented and discussed in Section VI. Finally, some concluding remarks are presented in Section VII.

II. SYSTEM SETUP AND MODELING

A Typical mill setup of a micro grid with storage system is appeared in Fig. 1. The energy sources incorporate both conventional and renewable generation systems. On the normal bus-bar are energy sources, variable loads, and furthermore a battery-based storage system. The green blocks show that specific component is under control for wanted execution. The fundamental thought is to expand the usage of renewable energy, thus decrease the non-renewable energy source utilization, while in the meantime maintaining system stable. Here system solidness is reflected by acquiring just restricted system frequency deviations, regardless of the nearness of critical transients. Low frequency load transients are dealt with by conventional generators (using diesel or flammable gas engines as their prime mover).

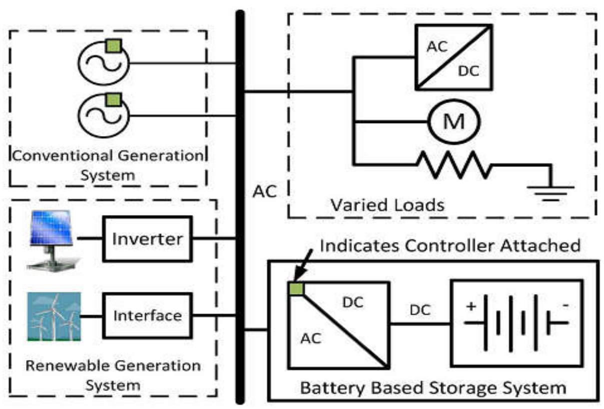


Fig. 1. Structure of microgrid with attached storage system.

The connected storage system can respond substantially more rapidly to load transients, thus it is fundamentally utilized for stifling the high frequency load transients caused by renewable energy sources. Keeping in mind the end goal to limit the frequency deviation, a mathematical model is utilized for system examination and controller outline. This model comprises of three sections: conventional generator (CG), storage system (SS) and Wind Turbine Generator (WTG).The relating Simulink models are appeared in Figs. 2 – 4.Note that keeping in mind the end goal to restrict the model intricacy, basic exchange functions models are utilized for every one of these blocks in the controller configuration process.

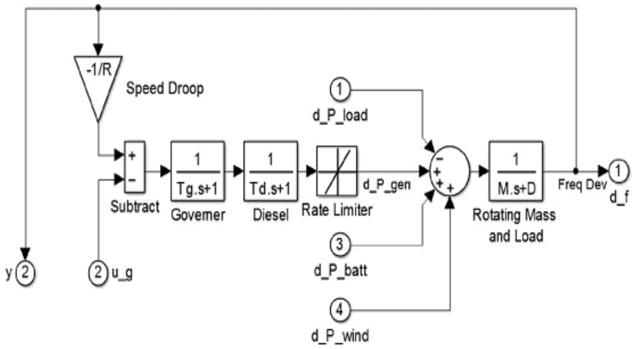


Fig.2.Conventional generator (Small Power System) model

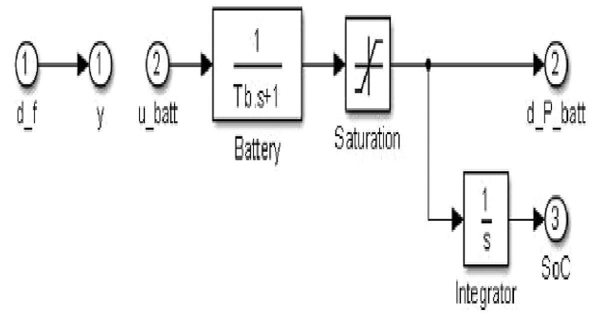


Fig. 3. Battery model

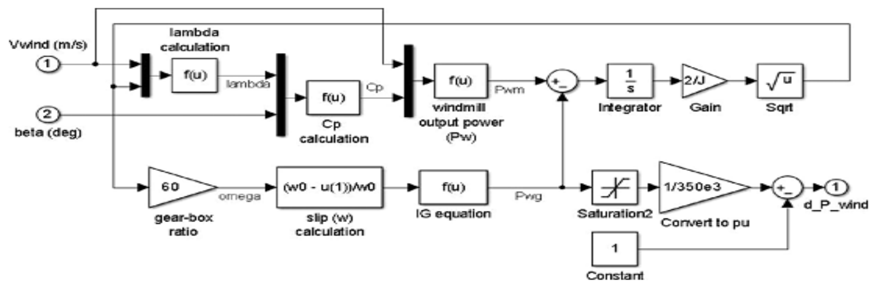


Fig. 4. Wind turbine generator model

Anyway these models still catch the fundamental power/frequency tradeoffs in such systems. Since change in frequency is caused by the irregularity between the power created and the power devoured by the load, signals in the model are first standardized to per-unit (pu), and after that moved to deviations around'0' (comparing physically to deviations from ostensible 60 Hz). Consequently, the load variety, the SS output variety and WTG output variety are signified and individually. These three signals are summed at the summing block in the CG display along side the CG output variety.

Note that, amid the charging or releasing periods, a battery based storage system goes about as load or generation correspondingly. In our modelΔP_B, and $\Delta P_G$are controlled power deviations, as appeared in Figs. 2 and 3; the control signals u_g, u_b . Δf is considered as the blunder signal. The controller gets estimations and outputs incitation/control signals. Despite the fact that $\Delta P_B$is a controlled output, the output is restricted by a saturation block in order to forestall quick charge and release. Furthermore, the State of Charge (SoC) variety of the SS is displayed by coordinating its output power deviation. It is controlled indirectly by strikingΔP_B.

Meanwhile, $\Delta P_{load}$and ΔP_{wind} are considered as perturbations to the system in the robust controller union technique. There is no control over these two signals. But Δf is minimized using Controlled output without considering their variations. Controlled output without considering their variations. A genuine wind profile is utilized here with an example time of 50 ms recreated for 500 s. The WTG genuine output power is standardized by its evaluated output and again moved to deviations around "0" (in the linear model). is "0" unless the precise speed of the rigging box output is higher than the synchronous rakish speed. A settled pitch point of 10 is utilized. Our controller does not order the WTG, rather the WTG produces power as per the given wind speed profile (it is considered as external disturbance). Tip speed ratio, windmill output, Slip and WTG output power as appeared in Fig. 4, and are given as: $\lambda = \frac{R_\omega . \omega}{V_{wind}}$; $P_{wm} = C_p(\lambda, \beta) V_w{}^3 \rho A/2$; $S_s = (\omega_o - \omega)/\omega_o$;

$P_{wg} = -3V^2 S_s(1 + S_s)/((R_2 - S_s R_1)^2 + S_s{}^2 (X_1 + X_2)^2)$;

Where, V_{wind} is the wind speed, A is windmill rotor cross section area, ω_o is synchronous angular speed, and ω is angular rotor speed for a windmill. All the modeling parameters are listed in Table I.

TABLE- I MODEL PARAMETERS

Conventional generator parameters:		Wind turbine generator parameters:	
Governor time constant T_g	0.1s	Blade radius R_w	14 m
Diesel engine time constant T_d	5.0s	Inertia coefficient J	62.99kgm^2
Inertia constant M	0.15puMWs/Hz	Air density p	
Damping constant D	0.008puMWs/Hz	1.225kg/m^3	
Speed droop R	3.0 Hz/ pu	Rated output P_{wg}	350KW
Storage system parameters:		Phase voltage V	670 v
Battery time constant T_d	0.1s	Stator resistance R_1	0.00397Ω
		Stator reactance X_1	0.0376Ω
		Rotor resistance R	0.00443Ω
		Rotor reactance X_2	0.0534Ω

III. UNCERTAINTIES AND ROBUST CONTROL

No mathematical model can describe exactly a physical system. This modeling error can adequately affect the performance of a control system. The difference between the actual system and its mathematical model (used to develop controller designs) is known as model uncertainty. The two types of uncertainty which are taken into consideration while designing a robust controller are:

1) Modeling Errors: These arise due to inaccurate dynamics in the model of the plant (particularly at high frequencies).

2) Un-modeled Dynamics: These arise due to neglected or unknown dynamics of the plant.

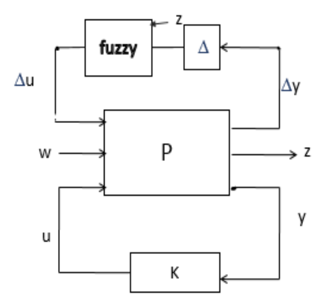


Fig 5. Control configuration for μ –synthesis with Fuzzy pc

These perturbations are usually lumped together in a structured uncertainty description , where is block diagonal (see Fig. 5).Given this setup the system robustness can be quantified via the smallest structured which makes the matrix singular at any given frequency. Computing this quantity over all robustness, this metric is termed the structured singular value (denoted), which stated mathematically is defined for a matrix

$$\mu(M) = \frac{1}{\min_{\Delta}\{\sigma(\Delta)|\det(I - M\Delta) = 0\}} \quad (1)$$

Where M the lower linear fractional transformation (LFT) and Δ is block diagonal, and synthesis controllers are all designed based on Optimal/robust control theory.. Robust control theory has been studied extensively in the literature, and we refer interested readers to [10] and [11] for detailed information. The Robust Control Toolbox from Matlab is used in this paper for design, analysis and simulation purposes with Fuzzy Control. Finally, note that we utilize conventional PID control for comparison purposes.

IV. CONTROLLER DESIGN

We utilize the D-K iteration approach for - amalgamation controller outline. This intends to convey a shut circle system with advanced execution within the sight of unsettling influence signals while state a similar time holding robustness to system demonstrate uncertainties. Keeping in mind the end goal to unequivocally indicate the robustness and execution criteria, the initial step is to settle on the outline system interconnection.

A. Uncertainty in the System

In Figs. 2 and 3 we can see the nominal models of power system and battery. Multiplicative model uncertainties of 5%and 3% are added to model blocks 'Diesel' and 'Rotating Mass and Load' to represent modeling errors as shown in Fig. 6.Un- modeled high frequency dynamics can also be included as additional perturbations, but we do not do so here. . In order to minimize the system frequency deviation, signals are penalized at input and output along with SoC to regulate battery usage .control signals are also penalized to limit the control authority.

B. Disturbance Signals on the system

Two major disturbances in the system are due to variations in load and renewable source (WTG) generation. Note that load draws power from the system, but WTG injects power into the system. However, since we do not assume the WTG output to be under our control, for controller design purposes we combine the two into a single "disturbance" at the same summing junction. In our system, SoC sensor and speed sensor noises are considered as additional disturbances.

C. Performance weights Selection

The choice of performance weights to be used in the controller is more difficult. The net load mentioned in Section IV-B, which needs to be fulfilled by some combination of the generator and battery, is due to both the physical load and the WTG output .The low frequency load variations are taken care of by the diesel generator. The battery has the ability to deliver/absorb power to/from the system more quickly (via discharge /charge), and so it is used to damp the high frequency variations. Fourier Transform analysis is applied to the load and WTG output. The weights are selected in such a way as to reflect the spectrum analysis of load and WTG frequency content of the (desired) signals, with weighting functions active in the desired frequency ranges.

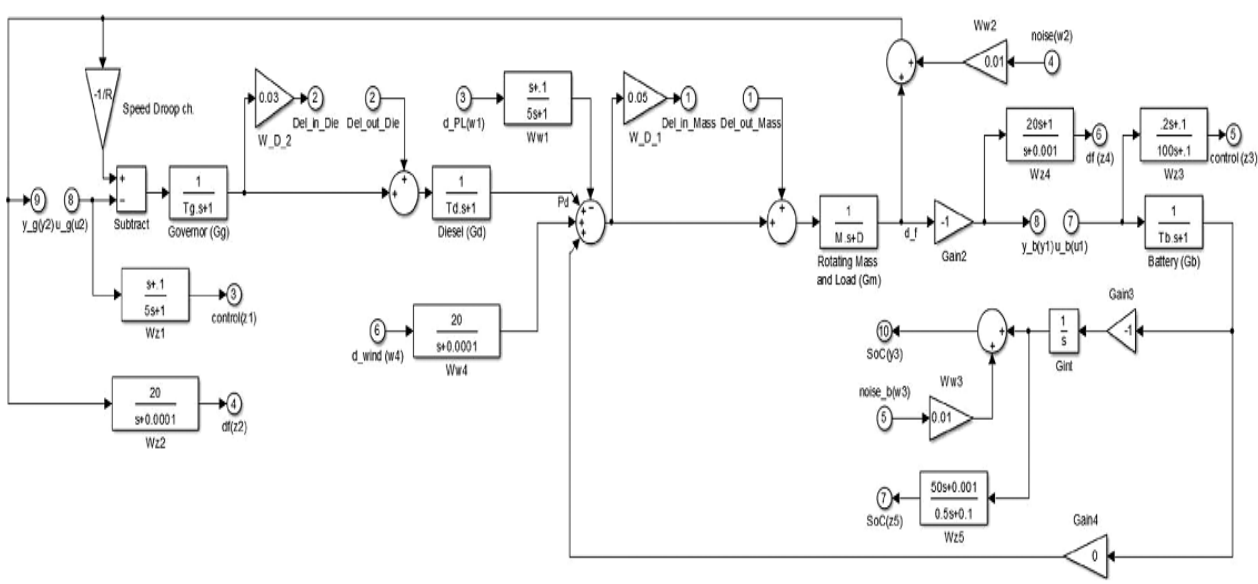


Fig. 6. Plant with model uncertainties

If the constraint is to be imposed across all frequency, then a constant gain is used. Hence, the weights on the control error signals for generator, battery and SoC are selected as:

$$W_g^e = \frac{20}{S+0.0001} \qquad (2)$$

$$W_b^e = \frac{20S+1}{S+0.001} \qquad (3)$$

$$W_{SOC}^e = \frac{50S+0.001}{0.5S+0.1} \qquad (4)$$

The weights on the control input are selected in the same way. The control weight for controlling the diesel engine and battery are given as:

$$W_g^c = \frac{S+0.1}{5S+1} \qquad (5)$$

$$W_b^c = \frac{0.2S+0.1}{100S+0.1} \qquad (6)$$

This MIMO controller design approach will yield a closed-loop design where each component primarily handles the (frequency) region it is best suited for, with an appropriate combination of resources dealing with the transition (frequency) region. Weights on load and WTG outputs are also applied. The selected weights with model uncertainties are shown in Fig. 6 along with the interconnection structure.

Using the system uncertainties presented in Section IV-A, and weights we have developed in Section IV-C, the interconnection state-space model can be built using the Robust Control Toolbox. The structured uncertainty description specifies the perturbed plant model, and it is normalized so that. The given Simulink model in Fig. 6 is first linearized with an operating point of 0. As shown in Fig. 6, there are 12 first order transfer functions, which indicates that the system has 12 states. It is to be noted that the system already contains dynamic uncertainties via weighting functions, which set the robustness specification. The state-space representation (matrices A, B, C, D)of the linearized open-loop plant model (P in Fig. 5) is obtained using the MATLAB™ command 'linmod' (applied to Fig. 6),resulting in a system of order 12.The block-diagonal uncertainty structure , as shown in Fig. 5, is then obtained as an uncertain linear time-invariant object.

The Linear Fractional Transformation (LFT) of the linearized uncertain plant (P) and the block diagonal uncertainty structure is taken to obtain the weighted, uncertain control design interconnection model. The designed robust controller is seen to be of order 12 (same as the design interconnect). hardware**.**

D.FUZZY LOGIC CONTROLLER

In FLC, basic control action is determined by a set of linguistic rules. These rules are determined by the system. Since the numerical variables are converted into linguistic variables, mathematical modeling of the system is not required in FC.

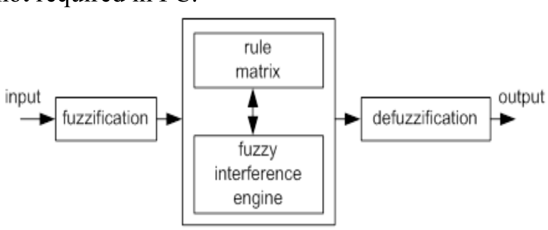


Fig.9.Fuzzy logic controller

Change in error	Error						
	NB	NM	NS	Z	PS	PM	PB
NB	PB	PB	PB	PM	PM	PS	Z
NM	PB	PB	PM	PM	PS	Z	Z
NS	PB	PM	PS	PS	Z	NM	NB
Z	PB	PM	PS	Z	NS	NM	NB
PS	PM	PS	Z	NS	NM	NB	NB
PM	PS	Z	NS	NM	NM	NB	NB
PB	Z	NS	NM	NM	NB	NB	NB

TABLE III Fuzzy Rules s

The FLC comprises of three parts: fuzzification, interference engine and defuzzification. The FC is characterized as i. seven fuzzy sets for each input and output. ii. Triangular membership functions for simplicity. iii. Fuzzification using continuous universe of discourse. iv. Implication using Mamdani's, 'min' operator. v. Defuzzification using the height method.

Fuzzification: Membership function values are assigned to the linguistic variables, using seven fuzzy subsets: NB (Negative Big), NM (Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive Small), PM (Positive Medium), and PB (Positive Big). The Partition of fuzzy subsets and the shape of membership *CE(k), E(k)* function adapt the shape up to appropriate system. The value of input error and change in error are normalized by an input scaling factor.

In this system the input scaling factor has been designed such that input values are between -1 and +1. The triangular shape of the membership function of this arrangement presumes that for any particular *E(k)* input there is only one dominant fuzzy subset. The input error for the FLC is given as

$$E(k) = \frac{P_{ph(k)} - P_{ph(k-1)}}{V_{ph(k)} - V_{ph(k-1)}} \quad (7)$$

$$CE(k) = E(k) - E(k-1) \quad (8)$$

Inference Method: Several composition methods such as Max–Min and Max-Dot have been proposed in the literature. In this paper Min method is used. The output membership function of each rule is given by the minimum operator and maximum operator. Table 1 shows rule base of the FLC.

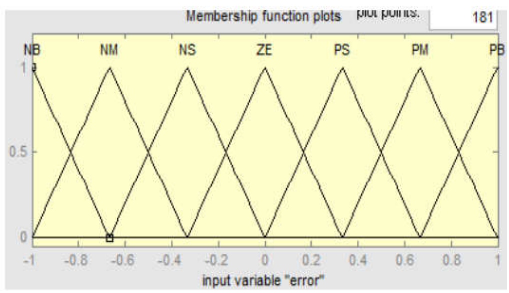


Fig.10.Membership functions

Defuzzification: As a plant usually requires a non-fuzzy value of control, a defuzzification stage is needed. To compute the output of the FLC, „height" method is used and the FLC output modifies the control output. Further, the output of FLC controls the switch in the inverter. In UPQC, the active power, reactive power, terminal voltage of the line and capacitor voltage are required to be maintained. In order to control these parameters, they are sensed and compared with the reference values. To achieve this, the membership functions of FC are: error, change in error and output

The set of FC rules are derived from

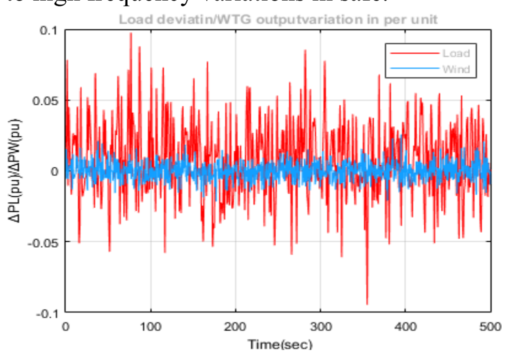
$$u = -[\alpha E + (1-\alpha)*C] \quad (9)$$

Where α is self-adjustable factor which can regulate the whole operation. E is the error of the system, C is the change in error and u is the control variable. A large value of error E indicates that given system is not in the balanced state. If the system is unbalanced, the controller should enlarge its control variables to balance the system as early as possible. One the other hand, small value of the error E indicates that the system is near to balanced state. We utilize the Ziegler-Nichols method for PID tuning, and the PID comparison case is implemented with 100% battery attached and μ-synthesis also compared with fuzzy controller.

VI. SIMULATION AND DISCUSSION

In this section a series of simulation results for fuzzy controller, the μ-synthesis and PID controllers are shown. The load and WTG output deviation in pu are shown in Fig. 11. ΔP_{wind} is about 40% ofΔP_{load} .Fig. 12 shows the frequency deviation under fuzzy control for 500s. In this simulation, no incarceration were added to the battery, which can deliver its maximum rated power. It can be seen that the peak is about, occurring at 280 s. From Fig. 11, we can see that from 240 s to 300 s, the load decreases and WTG output increases, which implies there is excess of power in the system. This causes the system frequency to increase and so change in frequency decrease.

The load and WTG output variations have sheer transients in this time interval, and the load and output power of each power source are compared in Fig. 13, which shows individual generation/load power deviations from the nominal value. For instance, as shown in Fig. 13, at 248 s the generator increases its output power by 6% to match the 5.5% increase in load and 0.5% decrease in wind generation. In the major portion of power variation the generator output follows the net load (combined load and WTG). By keeping SoC at desired point, battery can efficiently reacts to high frequency variations in safe.



11. Load and WTG output variations

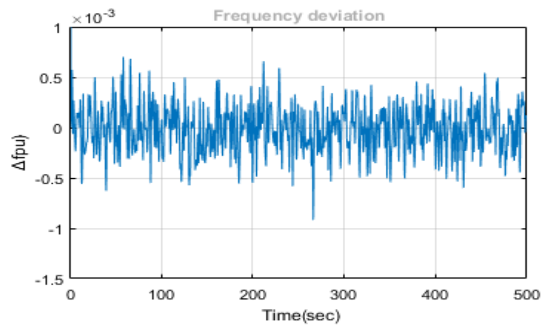


Fig. 12. Frequency deviation with control and maximum battery power

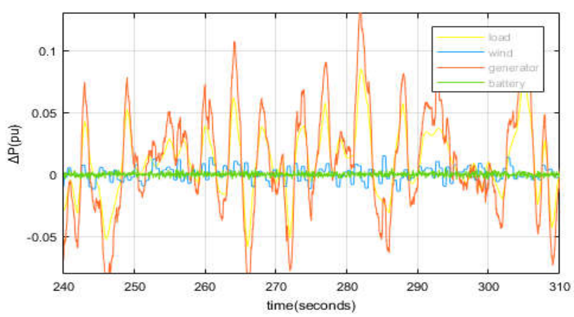


Fig. 13. Power variations with maximum battery power

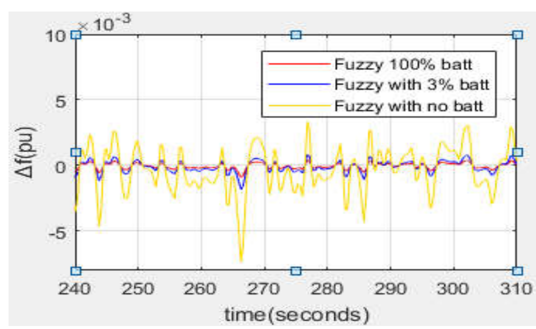


Fig.14.Frequency deviation comparison with fully battery

The biggest load transient occurs when load increases and wind power decreases as shown in Fig. 14, which shows the frequency variation under control for a variety of different battery scenarios and also explains how the system is stable as frequency variation is always almost 1% without battery(zero battery) and other case less than 1% which we needed to maintain system without tripping the circuit breakers and relays Fig. 15 shows how the power varies for load, generator and wind with no battery system attached. By comparing Figs.13 and 15, one can see that the latter has more high frequency harmonics on the generator power variation. The reason is that, in this case, there is no battery, and so the generator is forced to compensate the high frequency load/wind power variations. As shown in Fig. 16, when full battery is attached for different cases, the Fuzzy controller has much better performance than the μ-syntheses and PID method, and it significantly reduces the peak frequency deviations. In order to specifically examine system robustness, Fig. 17 shows the system frequency deviation when 10% model uncertainty is added to the diesel engine and rotating mass models, and 10% noise is added to all measurements Of course disturbances arising from the load and WTG variation are also present as before. However, the fuzzy controller can still provide satisfactory performances despite these significant uncertainties.

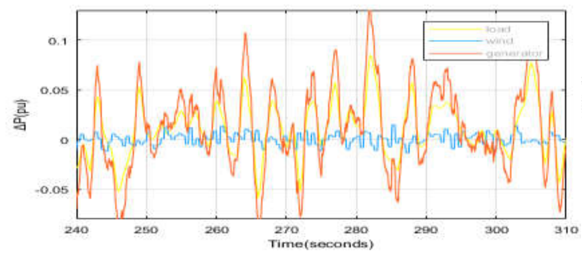


Fig. 15. Power variation without attached battery

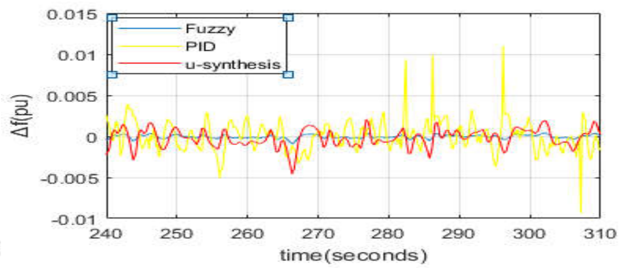


Fig. 16. Frequency deviations comparison between μ-syntheses, Fuzzy with full battery attached.

Our controller design was the result of a careful weight selection process, to achieve the desired robust performance. To summarize, these simulations show us several things. First of all, comparing Figs. 13 and 15, one can see that the battery is affecting the high frequency harmonics of generate or power, which is necessary to cope with the high variability of the net load (which includes the WTG). However the battery is having negligible effect on the overall amount of power the generator supplies. This is crucial since we can only consider relatively small batteries for practical microgrids, where the generator power is always supplying the vast bulk of the net load. However from Figs. 14 one can see that small amounts of battery storage, coupled with an advanced MIMO control algorithm, can still deliver adequate performance and maintain frequency stability. Finally, it is apparent from Fig. 17 that Fuzzy control can deliver that same level of performance for the same size battery, despite our best efforts to tune it correctly. One can see from the figure that, although it delivers decent performance for much of the time, there are still occasional large frequency deviations for the PID control which are unacceptable, and are avoided by the more sophisticated MIMO controller design.

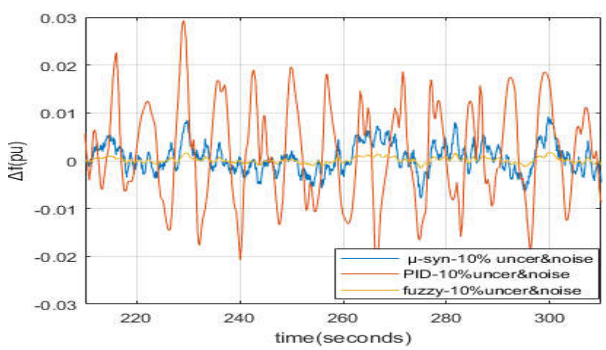


Fig. 18. Frequency deviations comparison between μ-syntheses, fuzzy, PID with10% model uncertainty and measurement noise

VI. CONCLUSION

In this paper, we have demonstrated that by consolidating a little battery with a refined robust control calculation, one can fundamentally diminish system frequency deviation in a microgrid. At the end of the day, indicating a specific reasonable frequency deviation, the robust control approach enables us to convey that execution level while using a littler battery. Since battery-based storage systems are extremely costly, this is a critical favorable position. This new approach is substantially more robust, and has better execution, when contrasted with μ-syntheses control. Our approach uses - union for the controller outline, and watchful weight determination is critical, to implement great tradeoffs in the controller. Amid the controller configuration process, since the model uncertainties and system exhibitions are considered in the meantime, system robustness and execution is very much adjusted.

The battery based storage system is constantly charged or released to manage quick transients. In the meantime it is important to keep the So C around half, which the MIMO controller does. Conventional generators are slower, and convey the main part of the power while adapting to vast load varieties. The subsequent shut circle microgrid system does not control these devices (battery and generator) freely, yet rather at the same time utilizes the generator to deal with extensive moderate load transients, while using the battery to smooth out quick transients. Along these lines the general system execution of the Microgrid is improved with sophisticated Fuzzy control .

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