MITIGATION OF FREQUENCY DEVIATION BY FUZZY CONTROLLER FOR MICROGRID WITH RENEWABLE ENERGY SOURCES

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Abstract : In general, presence of load fluctuations and variable energy sources like renewable sources in the system causes frequency to deviate from the standard frequency because of their variable nature. To reduce the frequency fluctuations and to maintain the frequency at desirable ranges, some controllers are required. In this work, a micro grid is considered to supply power to load. The Microgrid consists of renewable sources and fossil fuel based sources along with fast acting and reasonably sized battery energy storage system. This renewable energy sources and sudden load changes are responsible for the occurrence of frequency deviation in this system. Those deviations can be mitigated by using fuzzy based controller. The fuzzy logic controller is more advantageous than the other controllers and it is easy to implement in the practical systems. The results of the frequency deviation reduction with fuzzy logic controller are going to be compared with that of using mu-synthesis and also with conventional PID controller. The comparative results will show that the fuzzy logic controller can effectively reduce the frequency oscillations than other controllers. The proposed work is conducted using the Matlab and Simulink environment.

IndexTerms – Load frequency control, Wind turbine generator, Uncertainties and robust control, Fuzzy logic control

I.INTRODUCTION:

Electrical energy is a necessary ingredient for the economical and every one spherical development of any country. It is a desirable sort of energy, as a result of it will be generated centrally in bulk and transmitted economically over long distances. Further, it can be adapted easily and efficiently to domestic and industrial appliances, practically for lighting purposes and mechanical works. The conventional energy is obtained by conversion of fossil fuels (coal, Oil, natural gas), nuclear and hydro sources. Heat energy released by the fossil fuels is converted into the mechanical energy and then converting the mechanical energy through the generators to the electrical form [1].

The demand for electrical energy is increasing exponentially during the last few years due to the population and industrial growth. But the gradual depletion of fossil fuels and hike in fuel cost, the required power demand may not be fulfilled by the conventional power generations. And also they are harming the environment. To protect the environment considerable effort into the development of alternative, nonconventional, renewable and clean energy should be implemented with Solar, Photovoltaic, Wind, Wave and Ocean thermal sources.[2]

According to statistics created in recent years, it is found that almost 33% of the world's populations do not have access to electricity. Most of the non-electrified regions are found in developing countries. These regions will be electrified either by extending the grids of the prevailing power systems or by constructing isolated new power systems, which are alternative energy sources. In general, it is preferred to go for the extension of the existing grids but they are not always affordable the fact that most of the non- electrified regions in developing countries are located in remote and difficult areas, like hilly regions, forests, deserts and islands, which demand huge investment for grid extension. The very good solution for this problem is Microgrids. Microgrids consist of wind generations, solar generation, conventional generations, and different types of loads. This wind power generation is directly proportional to the cube of wind speed, but the wind speed varies.[3] it significantly impacts system stability and can cause large frequency and voltage deviations in Microgrids. The Microgrid conception assumes a cluster of loads and small sources (<100 kW) operating as a single controllable system that provides both power and heat to its local area.[4]

In the power system both active and reactive powers demands are never steady and they continually change with rising or falling trends. The mismatch between power demands to the generation will cause the variation in the frequency. That variation is very high when the system load and speed of wind speed is unknown. In such situations the conventional control approaches are no longer sufficient to constrain these deviations within a small range, and at the same time limit the battery size. Proportional-Integral-Derivative (PID) control has been well studied by a number of researchers [5, 6]. PID control methods are well understood, but have limited ability to trade off overshoot, rise time and damping oscillations. This can be overcome by the robust control techniques mu-synthesis controller and fuzzy logic controller.[7-9]

The main objective of this thesis discusses the modelling of the Microgrid, controlling and regulating the frequency deviations in the system with more sophisticated robust mu-synthesis control to achieve better performance despite unexpected disturbances and model uncertainties. Fuzzy logic control method without disturbances and model uncertainties has been proposed. The system frequency deviation is controlled under multi-controlling conditions such as PID, Robust mu-synthesis control and Fuzzy logic control using MATLAB/ SIMULINK environment. A comparison analysis is presented among PID, Robust mu-synthesis control and Fuzzy logic controller.

Following the introduction in Section I, the reminder of the paper is organized as follows. In Section II, the system modelling and configuration is presented. Some theoretical background of uncertainties and robust control are briefly presented in Section III. In Section IV, the design of the mu-synthesis controller and fuzzy logic controller are presented. Simulations are conducted in the Simulink™ and Matlab™ environment, and the results of simulation are presented and discussed in Section V. Finally in Section VI, conclusion and future scope of this paper are presented.

II.SYSTEM SETUP AND MODELLING

The typical setup of Microgrid contains the conventional and renewable energy sources and battery system and variable loads on the single bus bar. In this Microgrid the conventional system and storage systems can be controlled for required performance. The usage of renewable energy sources is to reduce the capital investment, carbon footprint and while at the same time limiting the frequency deviations, despite the presences of significant transients. Battery systems are used to suppress the high-frequency load transients. And for low-frequency load transients conventional generation system is used. In order to maintain the system frequency more advanced controllers are needed.

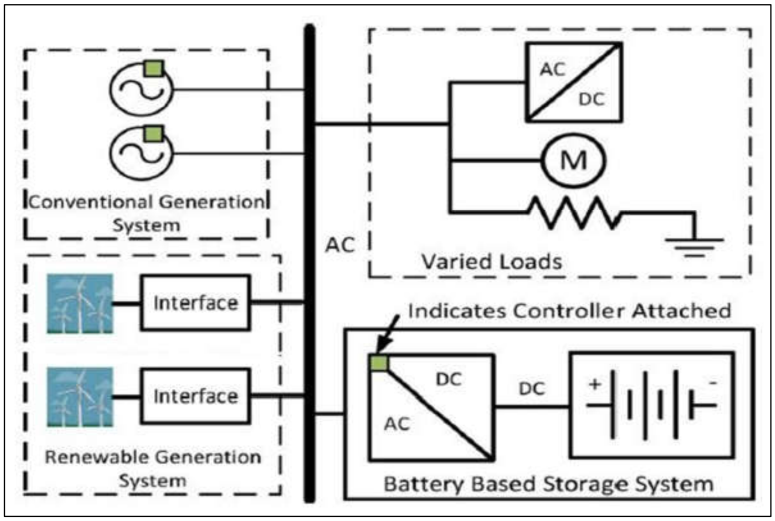

Fig.1 Structure of Microgrid with attached storage system

To analyze the frequency deviations in the Microgrid system mathematical model is used. This mathematical model used for the controller design. Microgrid modelled in 3 parts i.e. Conventional Generator System (CGS), Wind Turbine Generator System (WTG) and battery energy storage system.(BESS). [2,10,11]

In order to reduce the complexity of modelling the above convention generator system, wind turbine generator system and storage system simple transfer function models are used in Simulink. But still they capture the same intrinsic characteristics. It is clear that this model will has errors because is not the same as the original model, and because of that arises the question of if the controller that you get with the simple model is correct or not.

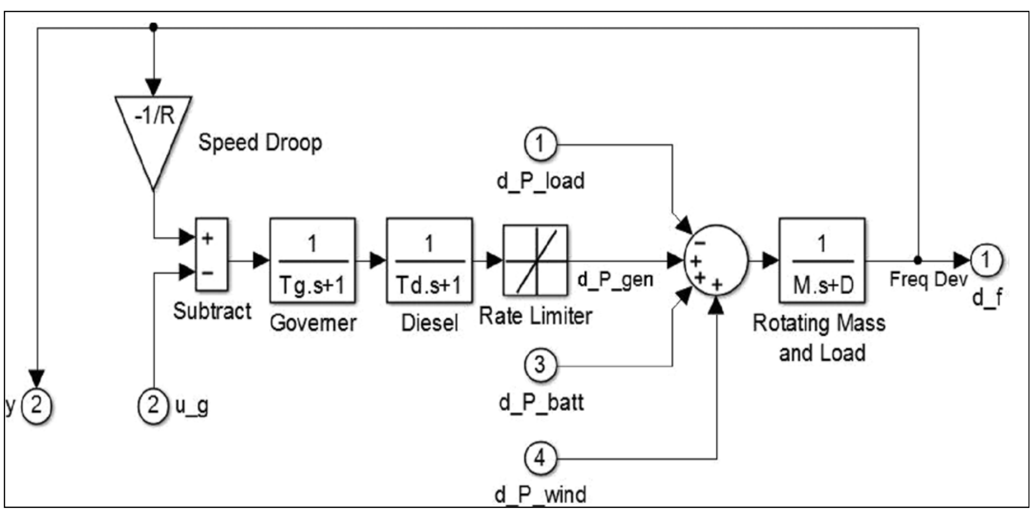

Fig.2 Conventional generator model[10,11]

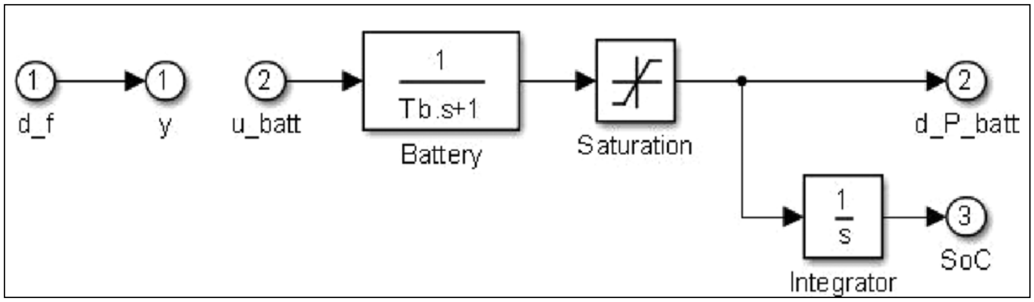

Fig.3 Battery model[2]

df is considered as the frequency error, it is caused by imbalance between the load demand and power generated. This signal is normalised to zero, and then shifted to deviations around the '0'. The load variation, the SS output variation and WTG output variation are denoted as dP_{Load}, dP_{batt} and dP_{wind} respectively. These three signals are summed at the summing block in the CG model along with the CG output variation dP_{gen}. Note that, during the charging or discharging periods, a battery based storage system acts as load or generation correspondingly.

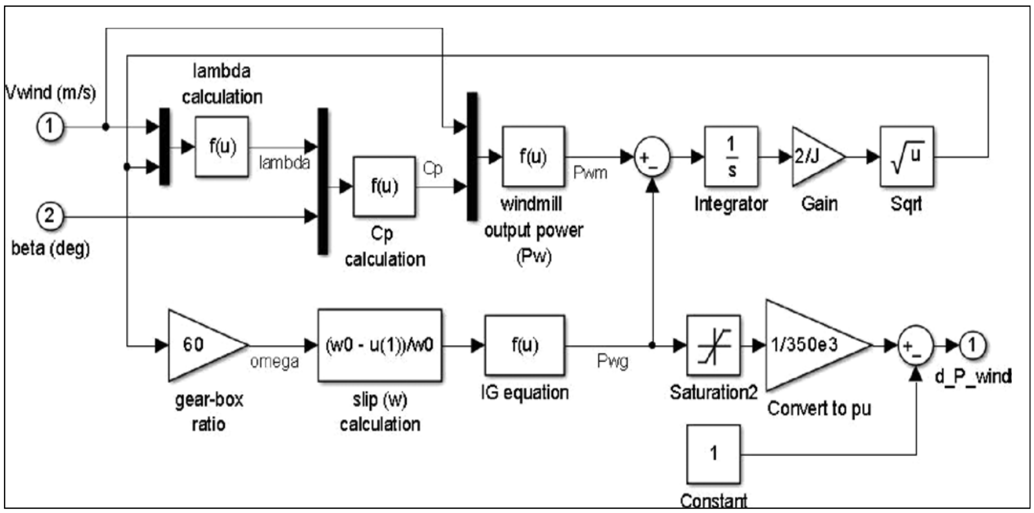

Fig.4 Wind Turbine Generator model[3]

dP_{batt}, dP_{gen} are the controlled outputs by controlling signals u_{batt}, $u_{gen.}$and dP_{load}, dP_{wind} are considered as perturbations of the system, and no control on this signals. The controlled outputs are used to minimise the system frequency deviation.

And wind turbine generator is designed with squirrel cage induction generator and its actual output denoted as $P_{wind,}$ but normalized to zero. WTG provides power according to the wind speed. The pitch angle is taken as 10º for this system. [3]

Wind power

$$P_{wind} = C_p \frac{1}{2} \rho A v^3 = \frac{1}{2} C_p \rho A v^3 \quad (2.1)$$

$$\text{Tip speed ratio(TSR)} = \lambda = \frac{speed\ of\ rotor\ tip}{wind\ speed} = \frac{\vartheta}{v} = \frac{\omega r}{v} \quad (2.2)$$

Wind power coefficient –

$$Cp(\lambda, \beta) = c1(\beta)\lambda^2 + c2(\beta)\lambda^3 + c3(\beta)\lambda^4 \quad (2.3)$$

$$c1(\beta) = c10 + c11\beta + c12\beta^2 + c13\beta^3 + c14\beta^4 \quad (2.4)$$

$$c2(\beta) = c20 + c21\beta + c22\beta^2 + c23\beta^3 + c24\beta^4 \quad (2.5)$$

$$c3(\beta) = c30 + c31\beta + c32\beta^2 + c33\beta^3 + c34\beta^4 \quad (2.6)$$

Constants

c10=1.5149e-2; c11=4.63367e-3; c12=-4.08951e-4; c13=1.3295e-5; c14=-1.0172e-7;
c20=-8.3119e-3; c21=1.14797e-3; c22=-1.29901e-4; c23=6.5878e-6; c24=-1.4048e-7;
c30=2.5134e-3; c31=-6.42182e-4; c32=6.378e-5; c33=-2.76762e-6; c34=4.53853e-8;

$$\text{Electrical power output } P_{GEN} = -3 \frac{{V_1}^2(1+s)S}{(R_1 - SR_2)^2 + (X_1 + X_2)^2} R_2 \quad (2.7)$$

$$\text{Slip} = S = \frac{\omega_0 - \omega}{\omega_0} \quad (2.8)$$

The angular velocity can be defined as below

$$\omega = \sqrt{\int \frac{2}{J}(P_w - P_g)dt} \quad (2.9)$$

By using above equations the WTG output power will be calculated.
All modelling parameters listed below table [12]

Table 1 Model parameters

Conventional generator parameters	
Governor time constant T_g	0.1s
Diesel engine time constant T_d	5.0s
Inertia constant M	0.15 pu MWs/Hz
Damping constant D	0.008pu MW/Hz
Speed droop R	3.0 Hz/pu
Storage system parameters	
Battery time constant T_b	0.1s
Wind turbine generator parameters	
Blade radius R_w	14m
Inertia coefficient J	62.993 kg/m3
Air density	1.225kg/m3
Rated output P_{wg}	350kW
Phase voltage	692.82 V
Stator resistance R_1	0.00397
Stator reactance X_1	0.0376
Rotor resistance R_2	0.00443
Rotor reactance X_2	0.0534
Control system parameters	
Number of measurements	3
Number of controls	2

III. UNCERTAINTIES AND ROBUST CONTROL

The first step that it has to be done when a Control Engineering design is going to be done, is to create the mathematical model of a physic plant. In most of the cases, this model will be nonlinear and it will have high order. A model with a very high order is not so useful in the point of view of the dynamics, because the process of the design is complicated and then, results of the controllers that are got will have very high level. Due to those reasons, is tried to get the simplest model but it has to be similar to the original model with same intrinsic characteristics and as complete as possible. It is clear that this model will has errors because is not the same as the original model, and because of that arises the question of if the controller that you get with the simple model is correct or not. This is reason because it was developed the theory of Robust Control.

The difference between the actual system and it's mathematical model is called as model uncertainty. two types of uncertainties are taken in to consideration while designing the robust control.

Modelling errors:

These arise due to inaccurate dynamics in the model of the plant. Here the structure of the model (including the order) is understood, however a number of the parameters are uncertain.[13]

Unmodelled Dynamics:

These arise due to neglected or unknown dynamics of the plant model. Here the model is in error attribute to missing dynamics, usually at high frequencies, either through deliberate neglect or because of a lack of understanding of the physical process. Any model of a true system can contain this source of uncertainty.

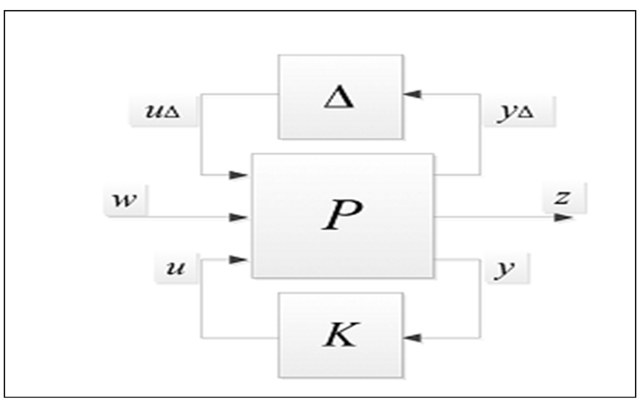

Fig.5 Control configuration for mu synthesis.

These perturbations are lumped together in the structured uncertainty description Δ. Given this setup the system robustness can be quantified via the smallest structured which makes the matrix singular at any given frequency. Computing this amount over all frequency allows one to seek out the smallest destabilizing perturbation. This metric is termed the structured singular value μ which stated mathematically is defined for a matrix M as [13]

$$\mu(M) = \frac{1}{\min\{\sigma(\Delta)\ |\det(I - M\Delta) = 0\}} \qquad (3.1)$$

H2, Hinf and Mu synthesis controllers are designed based on the robust control theory. Amongst, single mu–synthesis control can specifically design to manage with system uncertainties. Make a note of that, this robust control approach yields a influential tool for synthesizing multivariable controllers with good robustness to uncertainty and performance which includes tracking, disturbance and noise rejection [14]. The uncertainties in this robust control approach will describe via norms boundaries [15], but the mathematical descriptions will be associated back to traditional measures i.e. gain, phase margins etc.[13,19] Note that mu–synthesis controllers ware designed as to deliver both robust stability and robust performance. In that way mu-synthesis sacrifices a few nominal performances when compared to optimal control methods but provides robustness to model uncertainties. To get those nominal performances Fuzzy Logic controller is used. And for analysing the mu synthesis robust control theory has been studied, for implementing the fuzzy logic controller the fuzzy tool box from Matlab is used in this paper for design, analysis and simulation purposes. Conventional PID control and mu synthesis are used for comparison purposes.

IV. CONTROLLER DESIGN

4.1 Design of mu-synthesis:

In this paper, mu-synthesis controller was designed by using D-K iteration approach. This aims to bring a closed-loop system with optimized performance in the attendance of disturbance signals while state the same time retaining robustness to system model uncertainties. In order to precisely specify the robustness and performance criteria, the first step is to decide upon the design system interconnection.[17]

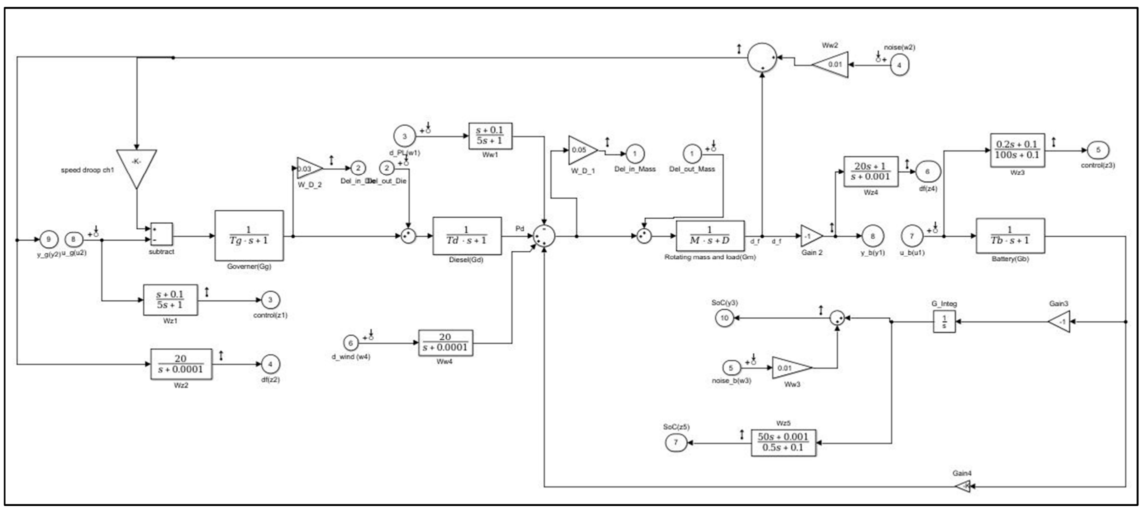

Fig.6 plant with model uncertainties for mu-synthesis controller

A . Uncertainty in the System

Nominal models of the small power system and battery are shown in Figs. 2 and 3. Multiplicative model uncertainties of 5%and 3% are added to model blocks 'Diesel' and 'Rotating Mass and Load' to represent modelling errors as shown in Fig. 6. Un modelled high frequency dynamics can also be included as additional perturbations, but we do not do so here. Measurement noise is added to the frequency deviation and So C signals.

B . Disturbance Signals on the system

Load and Wind turbine generation (renewable source) variations are the two major disturbances in the system. We know that wind turbine generator (WTG) injects power into the Microgrid but load draws power from the Microgrid. However, as we don't assume the WTG output to be under our control, we just combine the two into a single "disturbance" at the same summing junction for controller design purposes. Along with, there is for all time sensor noise in all measurements, and these are also included as disturbance signals. speed sensor and So C sensor noises are considered in our system.

C . Penalty Signals

The signals are chosen to penalize in the design interconnection. The performance criteria for the controller design optimization process effectively specified by penalty signals. In order to reduce the system frequency deviation, first the output signal is penalized. its SoC signal is penalized as well in order to mitigate the excessive usage of the battery. To limit the control authority a penalty is always applied on all control signals additionally. At this time, the control signals acting on the battery storage system and the diesel engine systems are penalized.

D . Performance weights Selection

The performance weights selection is more difficult which is used in the controller. As we said the net load in above Section B, which desires to be satisfied by some mixture of the battery and generator, is because of both the load and the WTG output. The net load exhibits both low and high frequency fluctuations. The diesel generators have taken care by low frequency load variations. The battery storage systems have the capability to absorb/deliver power from/to the system more quickly (via discharge/charge), and so this battery storage system is used to damp the high frequency fluctuations. therefore our controller profile needs to utilize primarily the battery (discharge/charge) at high frequency, primarily the diesel engine at low frequency, but it also supervise the battery SoC(frequency signal) and avoid overcharging/draining it. Fourier Transform analysis is applied to the wind turbine generator and load output and then the frequency spectrum analysis has done. It shows that the notable amplitudes of Microgrid load are below 6 rad/s. The wind turbine generator output spectrum analyses that amplitude is widely spread between 6 rad/s to 60 rad/s. The weights are chosen in such a way as to replicate the above frequency content of the (desired) signals, with weighting functions active in the desired frequency ranges.. Hence, the weights on the control error signals for battery, SoC and generator are selected as:

$$W_g{}^e = \frac{20}{s+0.0001} \quad (4.1)$$

$$W_b{}^e = \frac{20s+1}{s+0.001} \quad (4.2)$$

$$W_{Soc}{}^e = \frac{50s+0.001}{0.5s+0.01} \quad (4.3)$$

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:

$$W_g{}^c = \frac{s+0.1}{5s+1} \quad (4.4)$$

$$W_g{}^e = \frac{0.2s+0.1}{100s+0.1} \quad (4.5)$$

During the high frequency range the generator control signal is penalized, because we don't want the generator control signal to be implying, but rather let the battery deal with small fast transients. On the other hand, the battery control signal weight amplitude is heavily penalized in the low frequency range, since we do not wish the battery to try to handle large slow transients that are better handled by the generator.

E. Design of -synthesis Controller

Using the system uncertainties presented above, the state-space model will be built using the Robust Control Toolbox. The perturbed plant model is specified by uncertainty description, there are 12 first order transfer functions, this shows 12 states in the system. Already it contains dynamic uncertainties due weighting functions , it gives robustness to the system. 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™, then the system obtains an uncertain linear time-invariant system. 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 iterative algorithm combines mu-analysis and mu-synthesis to convey both robustness to optimized performance and uncertainties.

Even though the system removes some frequency deviations but it is not adequate to suppress the Microgrids frequency deviations. So decrees the frequency deviations more sophisticated controller is to be implemented so in this paper we chose the fuzzy logic controller is used.

4.2 Design of Fuzzy logic Control

Fuzzy logic controller consists of three stages i.e. fuzzification, interface mechanism and defuzzification. In the control system there will be input values that input values are fuzzified then processed and then after defuzzified.[7] In the fuzzification process the input values are taken and then membership functions are specified. In the input there will be error and change in error are taken normally. 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 modelling of the system is not required in FC.[8,9]

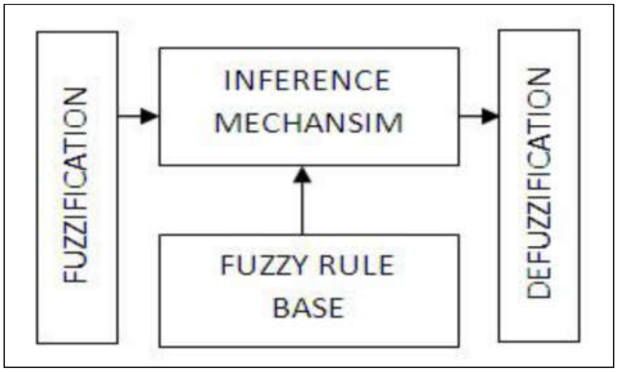

Fig.7 structure of Fuzzy controller.

Membership functions for the input variables are defined in such a way that it implies the input signals. That input 1 signal is named as dFD and five membership factions are taken for this input 1 and they are defines as VS(very small), S(small), M(medium), B(big) and VB(very big) .

First and last membership functions are taken as trapezoidal membership functions, and other as triangular membership factions. And the ranges and the values are edited in the Fig.8

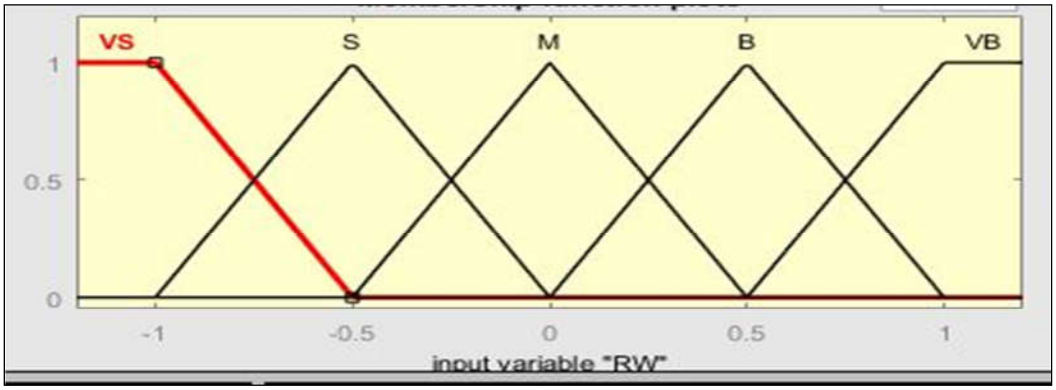

Fig.8 Membership functions for input variables1

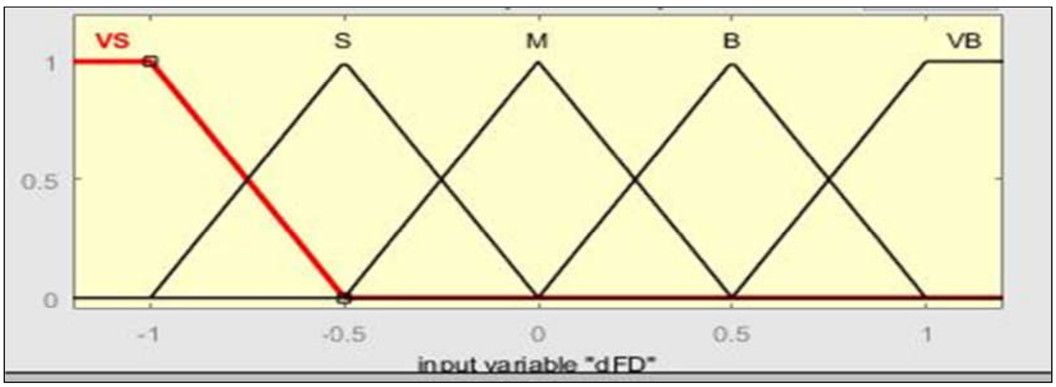

Fig.9 membership functions for input variables 2

And input variable 2 name is edited as RW and Five membership functions are taken i.e same as input 1. The range for the input variable 2 is taken from -1.2 to 1.2. Shown in Fig 9

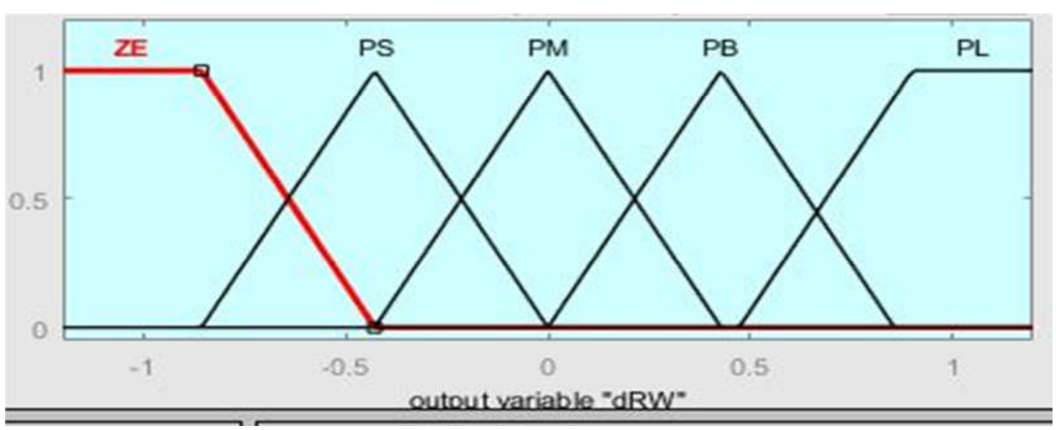

Fig.10 membership functions for output variables1

This output variable has five membership functions i.e ZE, PS, PM, PB and PL and these are ranged between the -1.2 to 1.2. Here ZE and PL membership function is taken as trap mf. And other taken as tran mf.

The fuzzy rules, a knowledge representation scheme for describing a function. For mapping or logical formula that generalizes an implication of two valued logic. The above Fig.10 represents the fuzzy rules which are implemented to control the system. “if” “and” “then” are used to write the fuzzy rules. Here the fuzzy rules ate obtained from the 2 input variables and 1 output variables. And input variables have 5x5 input membership functions so 25 fuzzy rules has developed in this project work.

V.SIMULATION AND DISCUSSION

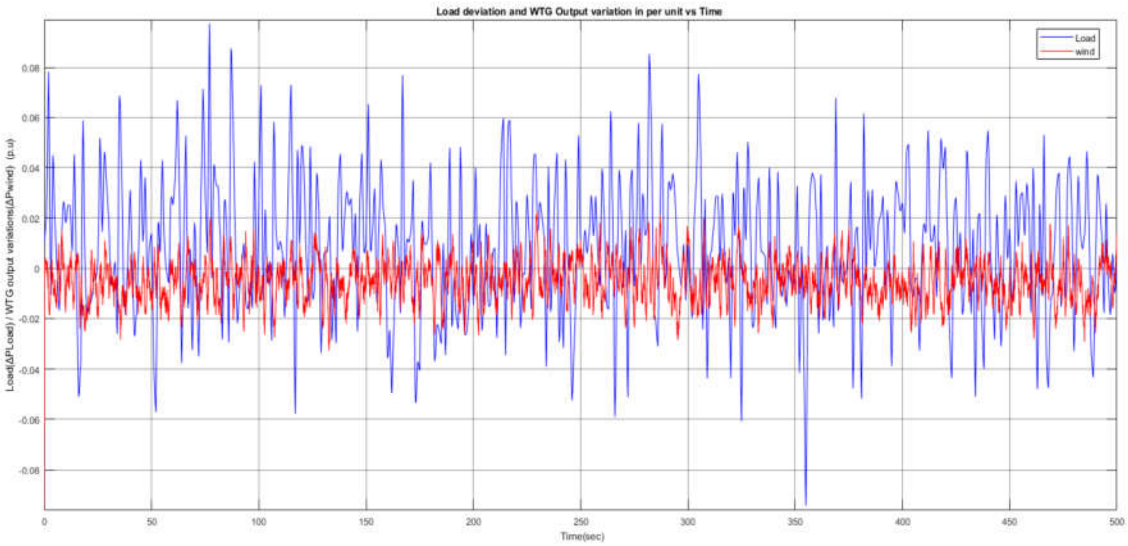

Fig.11 load deviations and WTG output variations power

The comparative output of the load and WTG are shown in the above Fig.11. And from Figure can be analyse that load which is in red shows that it is in between the 0.07 and -0.06. so the load is more amplitude than the WTG output.

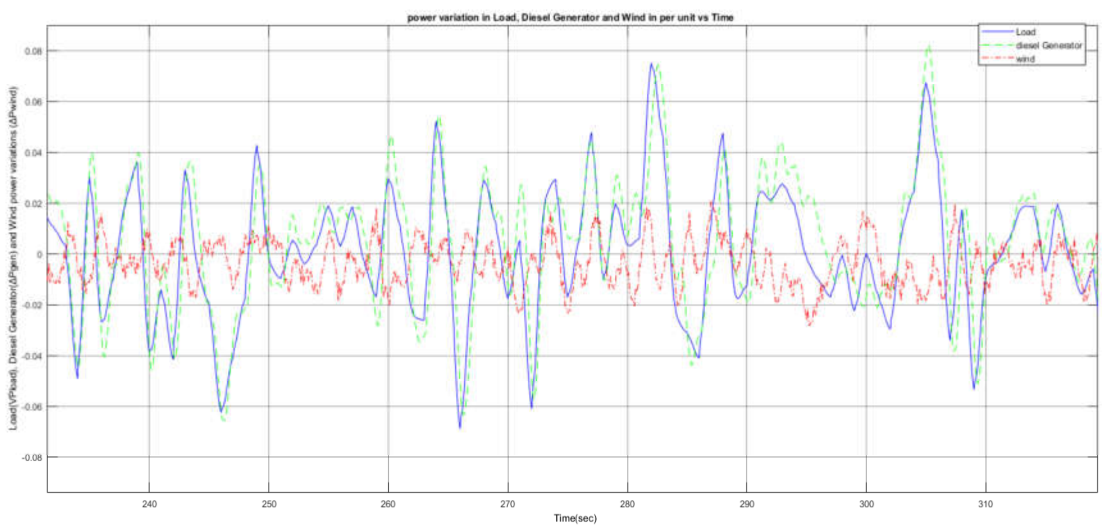

Fig.12 load deviations, WTG output variations and conventional generation power (240-310)

From the time interval from 240 to 310s, The load and WTG output variations have steep transients in this time interval, and the load and output power of each power source are compared in the Fig.12, which shows individual generation/ load power deviations from nominal value. For instance, as shown in Fig.12, at 260s the generator increases its output power by 7% to match the 5% increase in load and 2% decrease in the wind generation. The generator output follows the net load (combined load and WTG) variations and provides the major portion of the power.

5.1 Case 1: frequency deviation reduction using PID

The PID controller is tuned without specific considerations of uncertainties (un-modelled dynamics and disturbance signals). Hence when the PID controller is used for controlling the plant with uncertain load and WTG variation, bigger frequency variations takes place. As shown in the Fig.13 the variations in the frequency is more and it is between the 0.005 and -0.005. it can be seen that PID can no longer maintain the acceptable system performance. Due to uncertainty disturbances in the systems PID can't be suitable for this Microgrid so the mu- synthesis controller is applied to the Microgrid to minimise the frequency deviations.

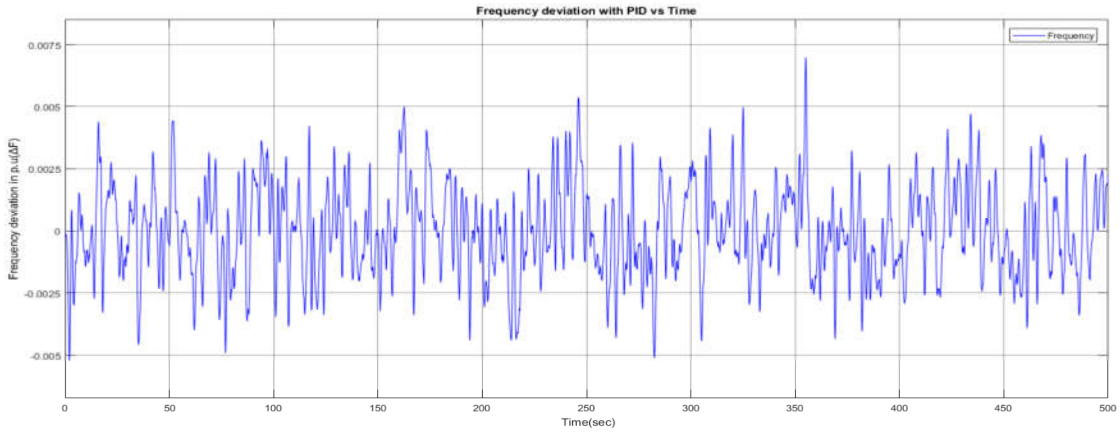

Fig.13 frequency deviations by using PID controller

5.2 Case 2: frequency deviation reduction using Robust mu-synthesis

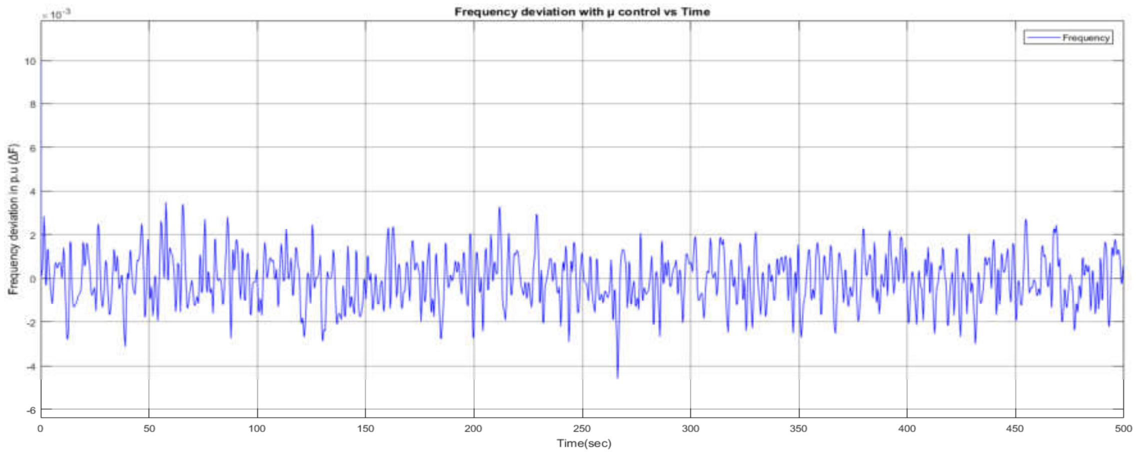

Fig.14 frequency deviations by using mu-synthesis controller

The above Fig.14 shows the frequency deviations when mu-synthesis controller is implemented. When the mu synthesis control is implemented to the plant the uncertainties in the system are addressed so the mathematical model will be mostly accurate to the actual system. And it controls the system frequency deviations. And it decreases the frequency deviations to more less values. When high frequency variations in the system it was controlled by battery and when the low frequency variations are in the system that was controlled by conventional generator. The frequency deviation is limited between the $2x10^{-3}$ to $-2x10^{-3}$ and it is very less compared to the PID.

5.2 Case 2: frequency deviation reduction using Fuzzy logic controller

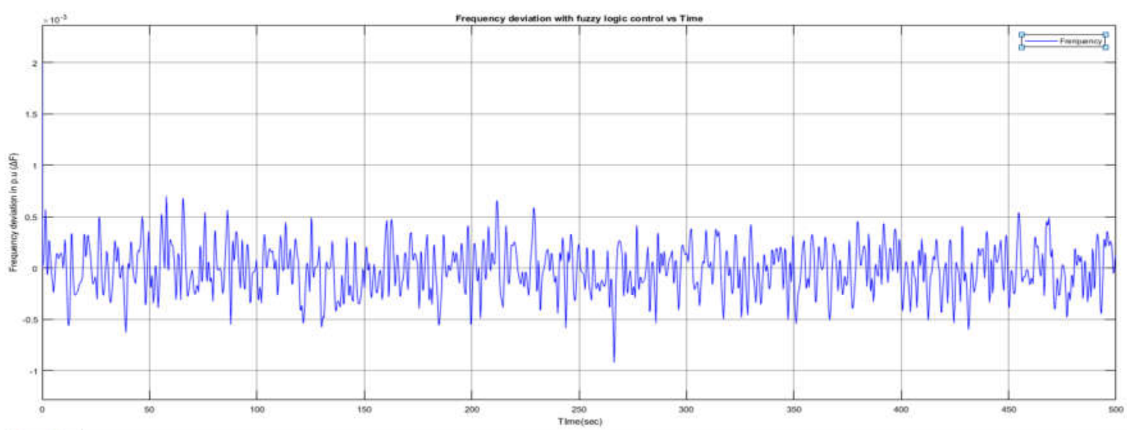

Fig.15 frequency deviations by using Fuzzy logic controller

The fuzzy logic controller is used along with uncertain are simulated. And fuzzy based logic rules are used to determine the good results. The above plot represents the frequency deviation in the Microgrid. This Fig.15 has frequency deviation between the $0.5x10^{-3}$ to $-0.5x10^{-3}$ this is indicating that the frequency deviations are dramatically decreased with the fuzzy logic controller.

5.3 Comparative analysis

The frequency deviation of the microgrid was simulated with different controllers like PID controller, mu–synthesis controller and fuzzy logic controller.

When comparing the results of mu-synthesis with PID, mu-synthesis has reduced the frequency deviations magnitude more than the PID.i.e while using PID normalised frequency range is -0.05 to 0.05. but while using mu-synthesis normalised Frequency range is $-2x10^{-3}$ to $2x10^{-3}$.

When comparing the Fuzzy logic controller with PID and mu-synthesis, Fuzzy logic is assuring the more performance than others. i.e $-0.5x\ 10^{-3}$ to $0.5\ x10^{-3}$.

Table 2 Comparative analysis table

	Normalised frequency deviation Range
By using PID	-0.05 to 0.05
By using mu-synthesis	$-2x10^{-3}$ to $2x10^{-3}$
By using fuzzy	$-0.5x\ 10^{-3}$ to $0.5\ x10^{-3}$

CONCLUSION

The modelling, controlling and regulating of the Microgrid for the frequency deviations in the system has done with more sophisticated robust mu-synthesis control to achieve better performance despite unexpected disturbances and model uncertainties in MATLAB/SIMULINK environment. Further a fuzzy logic control method was proposed to reduce the frequency deviations in the system. The system frequency deviation was controlled under multi-controlling conditions such as PID, Robust mu-synthesis control and Fuzzy logic control using MATLAB/ SIMULINK environment. A comparative analysis was presented among PID, Robust mu-synthesis control and Fuzzy logic controller. The comparative analysis shows that the proposed fuzzy logic controller reduces the frequency deviations in the system effectively when compared with PID and mu-synthesis control approaches.

This work mainly shows the preliminary form of the frequency deviation reduction using fuzzy logic controller. And it focuses on the control of the real power and frequency. In future work the application of these tolls and control techniques to control the reactive power and voltage in Microgrid. And further this can be extended to apply the advanced control techniques like ANN.

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