Performance analysis of Controllers for Load Frequency Control in Wind Integrated Power System

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ABSTRACT
This paper presents the performance of controllers in automatic generation control of a power system containing wind units along with conventional units. The two area system has been simulated with Proportional Integral (PI) and Fuzzy Logic Controller (FLC) and system performance has been analyzed and compared in terms of frequency response, Area Control Error (ACE) and response of wind units following a disturbance. A perturbation of 2 percent has been used to study the response of the system. It has been observed that wind units respond instantly to the disturbance and help the conventional units to take up the load change which are slightly slow in their response. The performance of fuzzy controller has been found superior to PI controller in frequency regulation which may be due to its better ability to manage the variability of the system under investigation.

Keywords
Fuzzy logic controller, Wind unit, Load frequency control, inertial control

1. INTRODUCTION
Now a days, the practical power system is an integration of different renewable and non-renewable sources of generation like thermal, hydro, wind, solar etc. Because the researchers focus have shifted towards the inclusion of non-polluted resources of energy, and among them, the wind power has the potential to displace the conventional generation to certain extent. However, due to large penetration of the wind power, the power system frequency will be more prone to the system variation, as the wind units do not join in the frequency regulation normally. Due to this the major task of Automatic Generation Control (AGC) is to keep area frequency stable and to exchange of power over inter-area tie-lines on their respective scheduled values by managing bus voltage in the whole system. It has been a topic of major concern because the variable nature of different interconnected load effect power system frequency and bus voltages. Hence to control the power system real power output, frequency, and tie lie power interchange within specified limits of each generating units is known as Load Frequency Control (LFC). LFC is generally considered as a part of automatic generation control, which plays an important role in the performance of power system [1]. Due to more energy demand the size of modern power system has also become wider and complex day by day. The inadequate control of this complex power system may affect the system frequency and oscillation might propagate into wide area resulting in a system blackout.

Therefore, a lot of work has been carried out from the beginning as reported in the literature. Elgerd and Fosha [1] have carried out the analysis of AGC problem of a two-area non-reheat thermal system by optimizing controller gain by using Integral Squared Error (ISE) technique. They have analyzed the effect of variation of the system frequency dynamic performance of power system. Technique based on adding coordinated in advertent interchange to control and time-error correction factors to area control errors on a system wide basis is presented by Cohn [2].The response of reheat and governor dead band nonlinearity on LFC is considered in [3]. Karna vasand Papadopoulos [4] carried out a work to maintain the system power output and frequency in the prescribed limits by controlling the speed of the generator with the help of fuel rate position control. Green [5] has proposed a transformed AGC. Transformed AGC eliminates the need for bias settings, directly controlling the nominal frequency set point of each unit. Reformatetal.[6] have proposed a new method of designing control systems in the area of power systems which relies on a combination of advanced system simulations and genetic computations. LFC of two area thermal-thermal power system with time delay is considered [7]. To get rid of overshoot of the conventional proportional integral control, an extended integral control scheme by including generation rate constraints is presented by Moon etal. [8]. Regulation error in load frequency control of at two area non-reheat system is disused by Boseand Atiyyah [9]Previous research revealed that inertial support from the wind units can reduce the adverse effects of load perturbation and contingency on the system [10] [11]. The control capabilities of the variable speed wind turbine have improved with the advancements in technology. The Doubly Fed Induction generator (DFIG) based wind turbine can now be used efficiently for frequency control services. The wind units contribute towards system frequency regulation through inertial control, pitch control, and the speed control [12]. The power (pitch+ speed) control scheme is applied on the DFIG to use it in the frequency regulation services. The DFIG operates according to a de-loaded optimum power extraction curve, such that the active power injected increases or decreases according to the variations in the system frequency [13]. The Dynamic participation of the DFIG in the frequency control is analyzed through modified inertial control which responds proportionally to the frequency deviation and uses the kinetic energy of the turbine blades to improve the frequency [14-17]Many types of controllers have been tested in conventional two-area LFC problem to regain the normal state of operation of the power system after any disturbance. These controllers for AGC are: Proportional and Integral (PI), Proportional-Integral-Derivative (PID), and the optimal controllers. In addition to these controllers, the fuzzy logic controller is also used quite often. The design steps for fuzzy logic controller as used for AGC problem have been elaborated in [12] [15]. It has been applied in number of control applications in the power system. The fuzzy controller is used to provide ancillary services in competitive market structure through price based mechanisms [13]. Many researchers have explored the techniques to design different types of AGC controllers but no efforts were made to diminish the oscillations in system frequency and tie-line power interchange by giving the inertial support of DFIG in the interconnected system including wind generation unit. In the analysis of an interconnected power system, some areas are considered as the channels of disturbances and in this situation, the conventional frequency control, that is, the governor may no longer be able to attenuate the oscillations in frequency and tie-power fluctuations because of its slow response [1][10]. Therefore it is important to minimize these oscillations [18][19] by other means and it should not dynamically interact with AGC response.In this paper, an effort has been made to apply PI and fuzzy controller for the automatic load frequency control for the two-area interconnected system with the DFIGs based wind turbine unit integrated to both the areas of thermal power system The simulations were carried out in presence of the wind penetration level of 10% and the frequency responses for load perturbation of 2% have been obtained with optimized parameters of the DFIG controller. In view of the above the aims of the paper are as follow:

(i) To examine the effect of proposed controllers on power system dynamic response under 2 % load perturbation.

(ii) To examine the response of the controller in power system frequency regulation, tie-line outages on transient performance.

iii) To examine the effect of DFIG in the interconnected system

(iv) To obtain the overall response by including proposed controller with DFIG unit and compare the effectiveness of the proposed controller.

The rest of the paper is structured as follows: in Section 2 contains the model of two-area system under investigation; then modeling of DFIG for frequency regulation through inertial control is discussed in section 3. The fuzzy rule design for controller has been discussed in section 4; section 5 deals with detailed discussion on results obtained and Section 6 carries the conclusions.

2. SYSTEM UNDER INVESTIGATION

The objective of the LFC is to fix the frequency to it's prescribes limits as soon as possible and to regulate the tie-line power flow fluctuations between neighboring control areas. The simulations have been conducted on two-area hybrid interconnected system shown in Fig.1. The DFIGs are connected to both the areas and they contribute towards frequency regulations by providing inertial support to the system. The fuzzy logic controller is used to generate proportional accurate signal for any incoming ACE as a result of any load change. Fig. 2 shows the block named as fuzzy logic controller. A load perturbation of 2 percent in area-1 at time t=1 sec is applied. To enhance the participation of the DFIG in frequency control in response to system disturbances, optimal values of the speed control parameters (K_{wp} and K_{wi}) of the DFIG-based wind turbine have been obtained. Integral Square Error technique is used for obtaining the optimum values of K_{wp} and $K_{wi}$to minimize the objective function defined as "*Performance Index J*":

$$J = \sum[\Delta f_1{}^2 + \Delta f_2{}^2 + \Delta P_{tie}{}^2]\Delta T \qquad (1)$$

Where ΔT is a given time interval for taking samples, Δfi is discrete value of incremental change in frequency for the ith area and ΔPtie is value of incremental change in tie-line power. The optimal values of the DFIG speed controller parameters are obtained by searching for the minimum value of J.

3. DFIG MODELLING

Double fed induction generator is widely used wind turbines in present times. It is the combination of an induction generator with a multiphase wound rotor and a multiphase slip ring assembly with brushes for access to the rotor windings. Traditionally, the wind units do not participate in load frequency control. But, now with latest techniques, DFIG based wind turbine generates power and the kinetic energy stored in the mechanical system of the wind turbines can be extracted to maintain the primary frequency regulation and to eliminate the power system dynamics oscillation with variable speed generators. Although, the steady-state active power delivered to the grid by a DFIG depends on the wind speed, the power can be dynamically controlled to a certain extent by utilizing the stored mechanical energy. An additional control signal is created to adapt the power set points ΔP*f as a function of deviation and rate of change of frequency in emulation control of the DFIG. The controllers try to keep the turbine at its optimal speed in order to produce the maximum power. A power set point ΔP*ω based on measured speed and measured electrical power is provided by the controller. The ΔPNC has two components; $\Delta P^*{}_f$ the additional based on optimum turbine speed as a function of wind speed and given as

$$\Delta P^*{}_\omega = -K_{wp}(\omega^* - \omega) + K_{wi}\int(\omega^* - \omega)dt \qquad (2)$$

$$\Delta P_{NC} = \Delta P^*{}_f + \Delta P^*{}_\omega \qquad (3)$$

Where K_{wp} and K_{wi} are constants of PI controller, which provides fast speed recovery and transient speed variation, which helps non-conventional generators to supply the required active power to reduce deviations. The contribution of the DFIG towards system inertia is given by:

$$\frac{2H}{f}\frac{d\Delta f}{dt} = \Delta P_f - D\Delta_f = \Delta P_g + \Delta P_{NC} - \Delta P_{12} - \Delta PD - D\Delta f \qquad (4)$$

The swing equation (11) gives an idea about contribution of DFIG towards system inertia. It has an additional reference power setting which is build based on the change in frequency using a washout filter with time constant T_w, that relies on a conventional primary regulation performance in a transient.

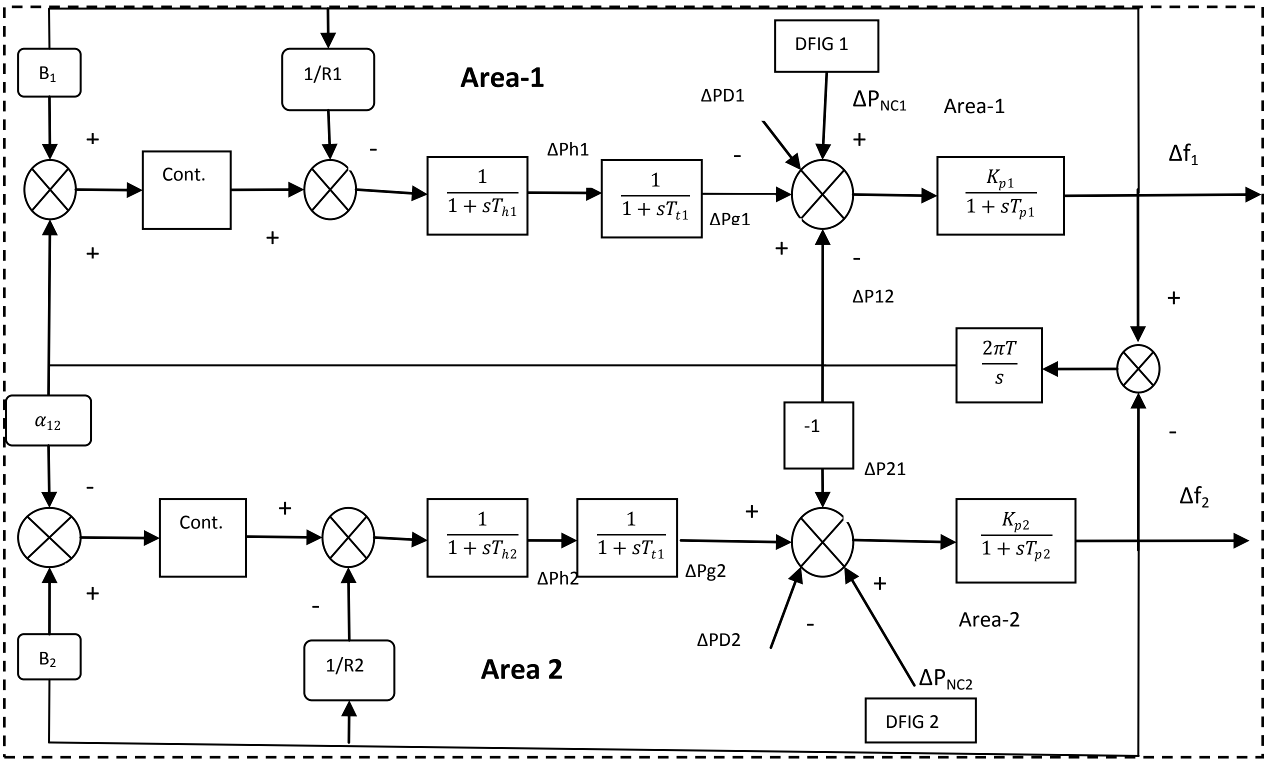

Fig.1. Linearized model of two-area interconnected power system

$$\Delta P_f^* = \frac{1}{R}\left(\Delta X_2\right) \tag{5}$$

Where, R is the droop constant as used conventionally and ΔX_2 is the frequency change measured where the wind turbine is connected to the network.

The DFIG responds to frequency deviations during transients by using their stored kinetic energy, and cannot act in a permanent system frequency deviation. For this reason, the frequency term $\left(\Delta X_2\right)$ used in (12) is the result of a washout filter, as shown in Fig.2. In this approach, the DFIG inertia contributes to that of the rest of system. The controller proposed makes use of the frequency deviations instead of the derivative of frequency as in the control law to provide fast active power injection control. The active power injected by the wind turbine is ΔPNC. The power injected is compared with ΔPNC ref so as to obtain the maximum power output, which is obtained by maintaining reference rotor speed where maximum power is obtained.

4. DESIGN OF FUZZY LOGIC CONTROLLER

Fuzzy logic becomes a powerful tool in many engineering applications, especially in control of power system dynamics performance. It needs less computation and also does not need exact mathematical model of the system the rule base and Inference mechanism is the heart of fuzzy logic controller [4]. Based on system operating condition FLC provides no Control action to full control action in extremely non-linear manner. Fuzzy logic contains four main parts: Fuzzication interface, knowledge base, decision making logic and defuzzification interface. Fuzzification interface is the process of mapping inputs to fuzzy sets in the various input universe of discourse the mapped data are converted to linguistic terms [10],[11].The knowledge base consists of a data base and linguistic controls rules. The data base provides the necessary definitions, which are used to define the linguistic control rules and fuzzy data manipulation in a FLC. The decision making logic has the ability of stimulating human decision making based on fuzzy concept [10], [11]. Defuzzification converts the range of values of output variable into non-fuzzy logic decision system. The design of the fuzzy logic controller involves three basic steps namely: input parameter allocation, framing of rules associated with inputs, and defuzzifying of the output in to a real value. The ACE is the main parameter in to the regulation component of LFC. The ACE and the rate of change of ACE (ΔACE) are considered as the inputs to the fuzzy logic controller and Δu is the output. The fuzzy controller has the essence of the conventional PI controller, which is given as

$$u = K_p + Ki\int edt \tag{6}$$

Where K_p and K_i are the proportional and integral gains respectively and e is the error signal. Taking derivative of the (6) w.r.t. time, u can be expressed as

$$u = K_p e + Kie \tag{7}$$

Both ACE and ΔACE are divided in to seven control areas based on magnitudes and sign. The areas are NL, NM, NS, Z, PS, PM and PL which stands for negative large, negative medium, negative small, zero, positive small, positive medium, and positive large respectively. The mathematical formula applied is the "Min/Max" rule for 'and' and 'or' respectively. This reduces calculation complexity and time. Symmetrical triangular membership function is considered for all the variables.

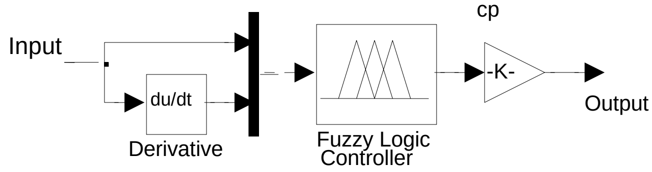

Fig.2 Fuzzy Logic Controller

Each fuzzy variable is quantized in to seven fuzzy sets; there are 49 rules that are required to generate a fuzzy output. The rules for the controller are decided based on the value of ACE, e and change in ACEΔe. If the value of e is positive and Δe is negative, the system will reduce the error itself, which means the output in that case should be zero. The most important step in controller design is defuzzification. The output of the inference system is a fuzzy value, and physical process cannot deal with fuzzy value, so it is essential to covert this fuzzy value in to a real value. The center of gravity method is used for defuzzification due to its simplicity. The detailed procedure on fuzzy controller formation is described in [9] [10].

5. SIMULATION AND RESULTS

The proposed controllers (PI and Fuzzy Logic Controller) have been applied to a DFIG unit based two area power system to investigate the response of system frequency control. The parameters of whole system are given in [13]. The Simulations have been conducted in SIMULINK MATLAB 7.10.1. It is to be noted that 2 % step load disturbance in each area is given to analyze the response of traditional plants including DFIG based wind turbine with PI and fuzzy logic controller for 10 % of wind penetration.

5.1 Comparison of PI controller with fuzzy logic controller

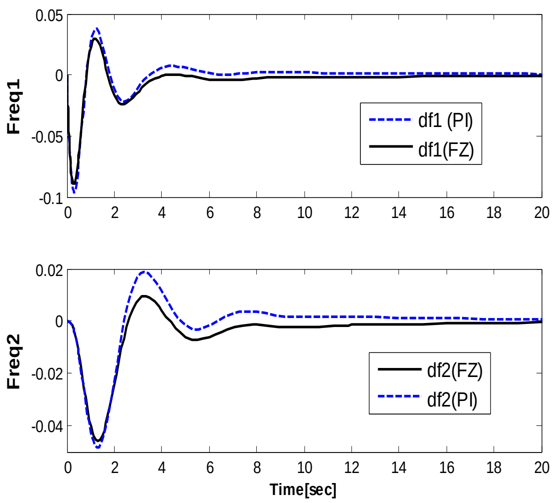

Fig.3. Frequency responses after including PI and Fuzzy Logic Controller (a) area-1 (b) area-2

Figure 3 shows the comparison between the performance of PI and fuzzy logic controller applied to both the areas. It can be observed from the figure that the system with FLC gives better performance as compare to the system with PI in terms of peak overshoot, peak time and settling time in both areas of the proposed power system. The frequency deviation response of FLC controller is much better than PI controller.

Figure 4 shows the power generation response of conventional unit having PI and FLC controller on the both areas. From the obtained waveform, it can be analysed that the generation response of conventional units with FLC controller is much better that the PI controller on both sides after a step disturbance of 2% .The FLC controller more rapidly damped the oscillation as compare to PI controller. The peak excursions are lower in the unit having FLC controller and the performance in term of peak overshoot and settling time is also good on both sides. Conventional generator having FLC controller generates more power during disturbance to damp out the oscillation.

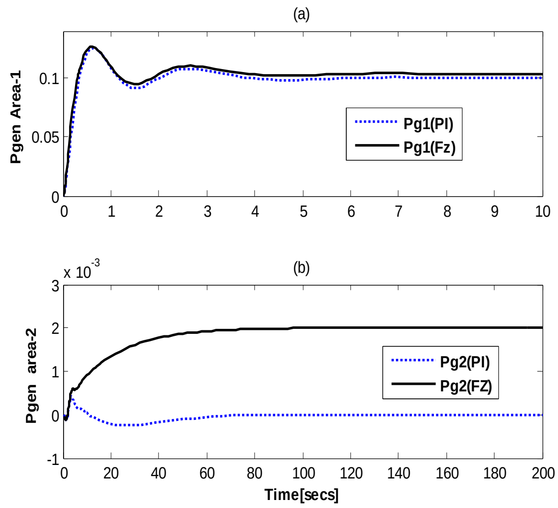

Fig.4. Generation response of conventional units having PI and Fuzzy Logic Controller (a) area-1 (b) area-2

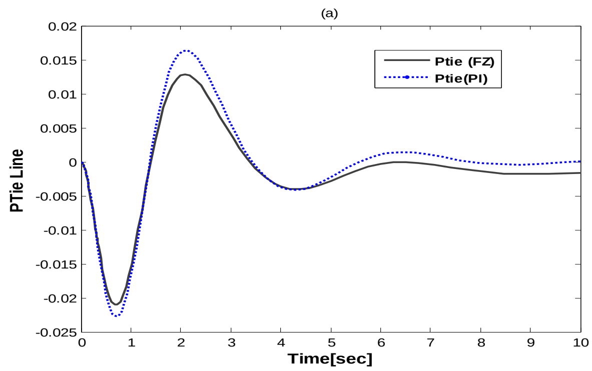

Fig.5 Tie-Line power Response after including PI and Fuzzy Logic Controller

Figure 5 shows the effect of proposed controllers in both the areas to control the tie-line oscillation in the presence of the controller in the system. It can be seen that the controllers help in reducing the tie-line oscillations between the two control areas. Further, the system having FLC controller damps the tie-line oscillations faster as compare to the system having PI controller. Area control errors (ACEs) for area-1 and 2 following a step load perturbation in area-1 are presented in Fig.6 (a) & (b) respectively. It is observed that the errors are much lesser in the case of FLC controller. Peak overshoots are smaller and settling times are smaller during the step disturbance of 2% and oscillations are damped more quickly by the FLC as compare to PI controller.

5.2 Effect after including DFIG unit in Both Areas

Figure 7 shows the generation response of the DFIGs unit having PI and fuzzy logic controller in area-1 and area-2 respectively for a load change of 2%. It can be observed that the DFIG having FLC increases its generation more as compared to the DFIG having PI in both the areas when there is any variation in the load. The DFIG provides system frequency support in initial intervals of disturbance only by providing active power support and final generation is taken over by the conventional units. Hence, it can be observed that the presence of the DFIG in the system helps in reducing the oscillations of both the areas.

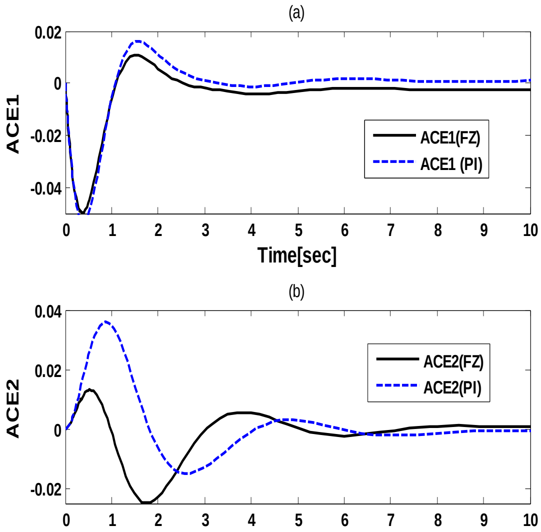

Fig. 6 Area control errors of two areas having PI and Fuzzy Logic Controller (a) area 1 (b) area 2

Figure 8 presents the DFIG based wind turbines speed variation responses following a load change of 2% in both the areas having controller (a) area-1 (b) area-2 respectively. The turbine oscillation is very less in the unit having FLC controller as compare to the unit having PI controller. The waveform results show the robustness of FLC controller. FLC controller works more efficiently as compared to the PI controller during different speed variations.

Figure 9 shows the area frequency responses with and without DFIG in both areas. The DFIG provides system frequency support in initial intervals of disturbance only, The DFIG releases the kinetic energy stored in its rotating masses to provide quick frequency support by decreasing its speed. The frequency responses of two areas are presented for the cases where DFIG is participating in frequency control and when it not participating in frequency control for a load perturbation of 2% in area-1 at 0.1second. It can be observed that that frequency response of both the areas are better in terms of lesser settling time and smaller lower peak excursion when DFIG is participating in frequency control. However, without DFIG the overshoots and undershoots are higher and settling time also is larger. Undershoot in area-1 where load perturbation takes place is higher as compared to area-2.

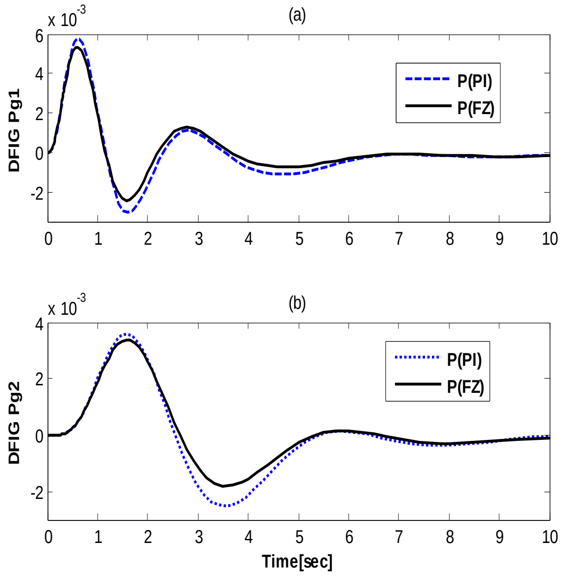

Fig.7. Generation Response of DFIGs unit having PI and Fuzzy Logic Controller (a) area-1 (b) area-2

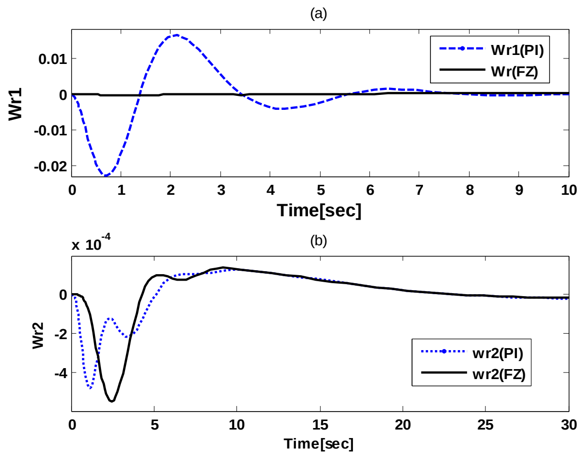

Fig.8. DFIG based wind turbines speed variations following a load change of 2% in both Areas having controller (a) area-1 (b) area-2

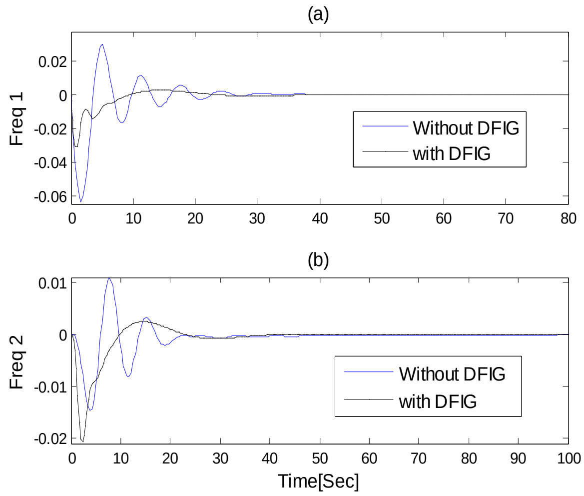

Fig.9. Area frequency responses with and without DFIG (a) area-1 (b) area-2

6. CONCLUSION

Power system performance is affected by frequency control support during disturbances. With large share of renewable energy, the fast acting DFIG units can be very useful in providing the inertial support to the slow conventional units. The controllers must be suitably selected to meet the need of system under disturbance. The fuzzy controller has been found better in performance in terms of peak overshoots and settling time in AGC problem of two area systems integrated with wind units. As the load and wind unit power output are variable in nature, the fuzzy controller is suitable to handle these sort of controlling applications. The fast response of wind units and fuzzy controller performance help the system tackle the load perturbation in a much better way. The system performance can be analyzed further by applying optimal controllers in a system with more renewable and storage devices connected to it.

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