



# Design of Fuzzy Logic Based PI Controller for DFIG-based Wind Farm Aimed at Automatic Generation Control in an Interconnected Two Area Power System

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## Abstract

This paper addresses the design procedure of a fuzzy logic-based adaptive approach for DFIGs to enhance automatic generation control (AGC) capabilities and provide better dynamic responses in multi-area power systems. In doing so, a proportional-integral (PI) controller is employed in DFIG structure to control the governor speed of wind turbine. At the first stage, the adjustable parameters of the PI controller are optimized in an offline manner via the genetic algorithm (GA). In the second stage, the outlined fuzzy logic-based adaptive approach is intended for valid adjustment the gains values of PI controller through suitable membership functions in an online manner. To verify the high performance of the designed fuzzy PI controller, a hybrid interconnected two-area power system is considered, taking into account the physical limitations of generation rate constraint non-linearity and governor dead-band effect. Eventually, two scenarios including step and random load changes are selected to establish the success of the proposed fuzzy PI controller in damping of the area frequency and tie-line power oscillations. Simulation results are presented and compared with GA-based PI controller.

*Keywords:* Automatic generation control (AGC), Doubly-fed induction generators (DFIG), Fuzzy logic, PI controller, Multi-area power system.

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## 1. Introduction

Load frequency control (LFC) is the most significant ancillary service for achieving safe and reliable performance under various situations. LFC is generally regarded as a major function of automatic generation control (AGC) and it is responsible for providing active power balancing between supply and demand that leads to restoration of the frequency to the scheduled value in a specified area and affecting the neighboring areas through the interconnected tie-lines [1,2]. There has been a vast body of literature about various LFC issues, in particular, the contribution of doubly-fed induction generator (DFIG) based wind turbines (which is the main topic in this paper) in AGC task.

Development and penetration of wind energy in power systems is going on quickly around the world due to the reduction of fossil energy sources and growing environmental concern [3]. However,

the emergence of the new generation sources such as DFIGs has brought great challenges to the power system. Small-scale participation of DFIGs has the low impact on the dynamic performance of the power system. On the contrary, the establishment of large-scale DFIGs, which are formed by collecting several hundred individual wind turbines, leads to the reduction of system inertia and the increase of the frequency deviations. To tackle these challenges, some studies have been conducted to design different control mechanisms for achieving the effective contribution of DFIGs in LFC problem of power systems [4-9]. The effective inertia and frequency responses of different types of wind turbines using inertial and governor controls have been followed in [4]. In [5], the droop control is carried out in DFIGs and the effect of some techniques on frequency stability in a microgrid is demonstrated. In further attempts, the

comparative investigation of pitch angle, inertia, and droop control approaches is provided in [6,7]. Furthermore, the application of different intelligent methods as a control strategy to search the optimal set of parameters in different control parts of DFIG structure seems necessary. In this regard, the authors in [8] have applied an improved particle swarm optimization (IPSO) method to tune gains of speed controller in DFIGs to enhance the frequency performance in a three-area power system. In [9], the parameters of speed controller are optimized by genetic algorithm (GA) to effectively regulate frequency. Motivated by the aforementioned facts, the ongoing study applies DFIGs in coordination with AGC of a hybrid interconnected two-area power to effectively damp frequency and tie-line power oscillations. As the first step, the adjustable parameters of the speed controller (which is a PI controller) existing in DFIGs are optimized by GA. As the second step, the fuzzy logic-based adaptive approach as an intelligent method is proposed for online tuning of the proportional and integral parameters. Simulation results illustrate the efficiency of the proposed fuzzy PI controller in alleviating frequency and the tie-line power deviations. The results are compared with GA-based PI controller in order to demonstrate the superiority of the proposed fuzzy PI controller.

**2. Modelling of DFIG**

Utilizing DFIGs can be considered as an effective choice for restoring frequency during off-normal conditions. The DFIGs participates in frequency control by releasing the stored kinetic energy in the turbine blades under sudden load changes. Extracting the stored kinetic energy and converting it into electric energy, depends on the inertia of the turbine and controlling of this inertia. Fig. 1 shows the block diagram of DFIG based wind turbine model used in this paper for frequency control [8].

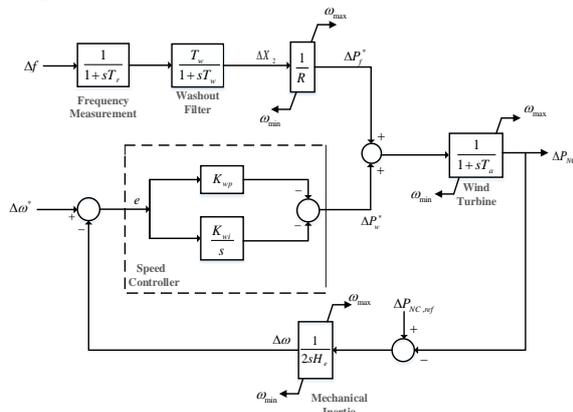


Fig. 1. Block diagram of DFIG based wind turbine model

In this model, an extra signal  $\Delta P_f^*$  tries to adapt the set point power as a function of frequency deviation rate  $\Delta f$ . Also, another signal  $\Delta P_\omega^*$  attempts to maintain the speed of wind turbine at a desired value for producing maximum output. In the considered model,  $e$  is error signal in speed of wind turbine,  $\Delta \omega^*$  and  $\Delta \omega$  are the reference and actual deviations of wind turbine speed, respectively. In order to obtain  $\Delta \omega$ , a mechanical equation can be stated as follows:

$$2H^* \frac{d\Delta\omega}{dt} = \Delta P_{NC,ref} - \Delta P_{NC} \tag{1}$$

Block description related to the calculation of  $\Delta \omega$  is indicated in Fig. 2. Transfer function of wind turbine is specified in (2).

$$\frac{1}{1+sT_a} \tag{2}$$

The effect of the conventional generators frequency changes on DFIG is determined by a filter with time constant  $T_r$ . A washout filter with constant time  $T_w$  is applied to obtain signal  $\Delta P_f^*$  based on equation (3).

$$\Delta P_f^* = \frac{1}{R} \Delta x_2 \tag{3}$$

Where,  $R$  and  $\Delta x_2$  are the parameter of speed regulation and sensed frequency changes, respectively. Finally, Total injected power into the power system can be written as:

$$\Delta P_{NC} = \Delta P_f^* + \Delta P_\omega^* \tag{4}$$

It should be noted that the PI controller for supplementary loop of DFIGs is applied, which is known as speed controller. To tune the parameters of PI controller, fuzzy logic-based adaptive approach is used in this study.

**3. Interconnected Two-Area Power System**

In this research, a hybrid interconnected two-

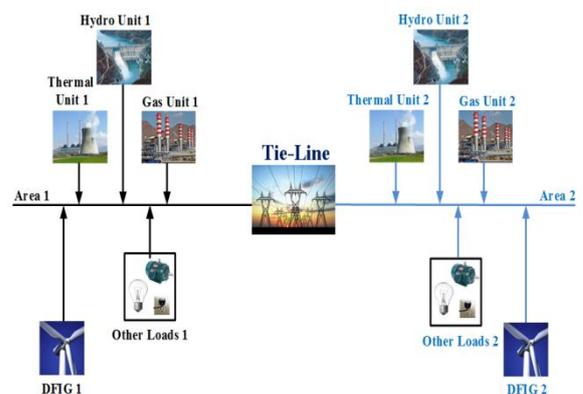


Fig. 2. Schematic diagram of interconnected two-area power system

area power system, containing thermal, hydro and gas units in each control area have been selected as the test bad. The areas are connected together via tie-line, which is responsible for power exchange between them. Fig. 2 shows the schematic of the mentioned power grid with DFIGs which are connected to each area. Furthermore, the schematic of linearized considered power grid equipped with

the DFIGs is demonstrated in Fig. 3. To be more accurate, the physical constraints of the generation rate (GRC) nonlinearity and governor dead-band (GDB) are also included. The parameters description of this power system and values corresponding to these parameters are available in [10].

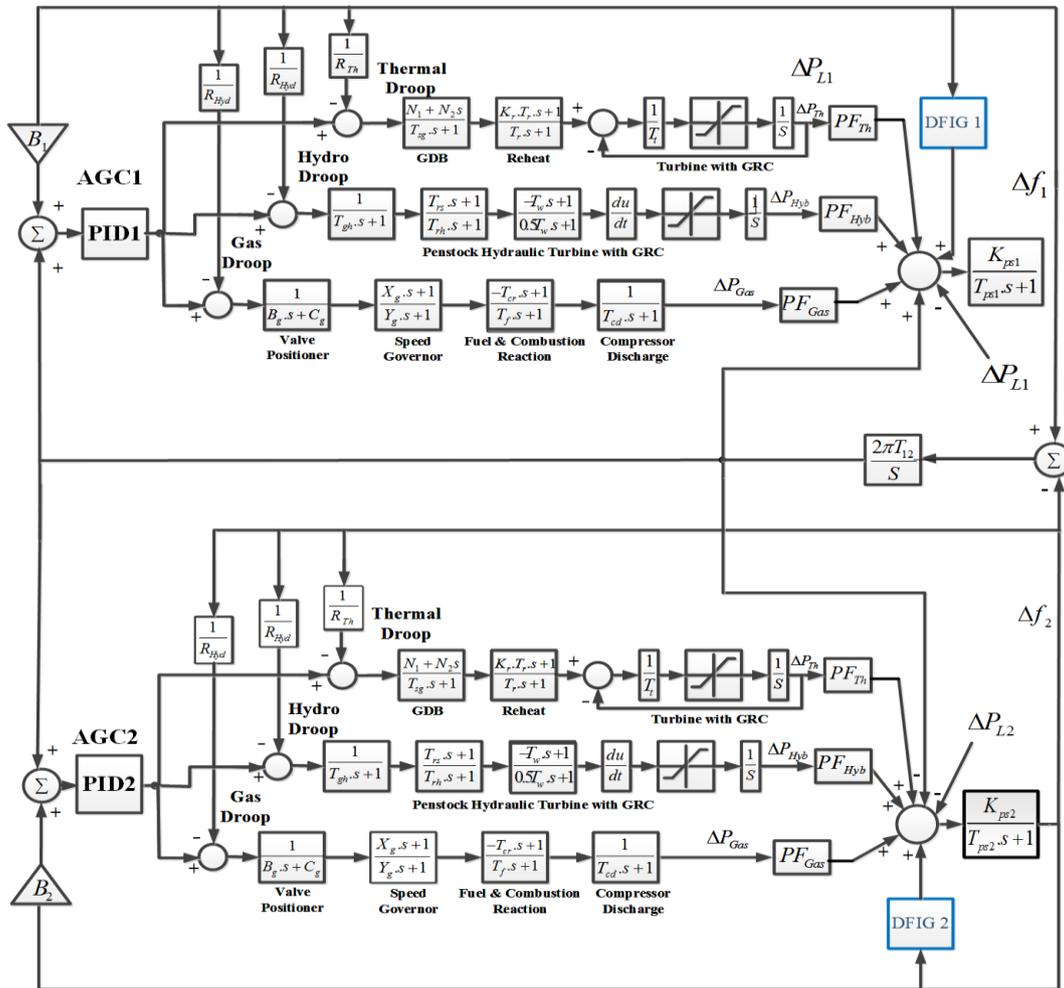


Fig. 3. The linearized TF-based model of two area power system

#### 4. Design of Fuzzy PI Controller

Fuzzy logic method has attracted a lot of tendencies in power systems control especially for frequency regulation purpose [2, 11]. Designing a fuzzy logic controller includes four sections: fuzzification, fuzzy rule base, inference engine, and defuzzification. Fuzzification section, converts the crisp data to a linguistic variable using the membership functions. The responsibility of the defuzzification section is vice versa. The section of fuzzy rule base represents the information storage for linguistic variables as the database. The fuzzy system is specified by a set of linguistic statements in form of “IF-THEN” rules. As well, the inference

engine uses the established “IF-THEN” rules to convert the fuzzy input into the fuzzy output. The designed fuzzy PI controller in this study takes the  $e$  and its derivative as the inputs and gets the proportional and integral gains as the outputs. The membership functions for input and output variables are illustrated in Fig. 4. As seen, the membership functions corresponding to the inputs are arranged as negative (N), zero (Z), and positive (P); the membership functions for the output variable is arranged as negative large (NL), negative small (NS), zero (Z), positive small (PS), and positive large (PL). The fuzzy rules for the proposed fuzzy PI controller are as follows:

IF the  $e$  is N AND the  $de$  is N, THEN the output is PL.

IF the  $e$  is N AND the  $de$  is Z, THEN the output is Z.  
 IF the  $e$  is N AND the  $de$  is P, THEN the output is PL.  
 IF the  $e$  is Z AND the  $de$  is N, THEN the output is NS.  
 IF the  $e$  is Z AND the  $de$  is Z, THEN the output is PS.  
 IF the  $e$  is Z AND the  $de$  is P, THEN the output is NS.  
 IF the  $e$  is P AND the  $de$  is N, THEN the output is PS.  
 IF the  $e$  is P AND the  $de$  is Z, THEN the output is Z.  
 IF the  $e$  is P AND the  $de$  is P, THEN the output is NL.

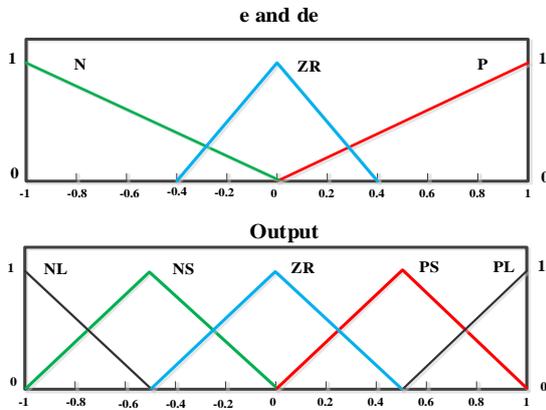


Fig. 4. Membership functions for inputs and outputs

As mentioned earlier, the performance of DFIG equipped with fuzzy-based PI controller is compared with GA-based PI controller. In this study, the GA is coded as .m file and linked with the SIMULINK environment of MATLAB software to obtain the gains of the controllers through minimizing the ITSE index. The ITSE index is defined as follows:

$$ITSE = \int_0^{T_s} t \left[ \Delta f_1^2 + \Delta f_2^2 + \Delta P_{tie}^2 \right] dt \quad (5)$$

In Eq. (5),  $T_s$  is the simulation time.  $\Delta f$  denotes the frequency variations and  $\Delta P_{tie}$  is the tie-line power change. The optimized parameters by GA are illustrated in Table 1.

Table.1. Gains of DFIG controller in both area

	Area1	Area2
$K_p$	0.1204	0.1366
$K_i$	-0.1841	-0.1088

### 5. Simulation Results

To demonstrate the effectiveness of DFIG equipped with fuzzy-based PI controller, two scenarios including step and random load changes are investigated. The penetration level of wind power is increased through reducing the existing generator units by x%, i.e., an x% reduction in the system inertia constant. In the other words, an x% increase in wind power is fulfilled through decreasing the inertia by x%. Here, 10%

penetration by wind source is considered. The simulations are accomplished in MATLAB/Simulink software.

#### A) First Scenario: Step Load Change

As the first scenario, the performance of DFIG equipped with the fuzzy-based PI controller is investigated under a 0.01 p.u. step load change in area 2. The area frequency and tie-line power deviations are illustrated in Fig. 5. As mentioned, the performance of the fuzzy-based PI controller is compared with the GA-based PI controller. As can be seen, the area frequency and tie-line power oscillations are remarkably damped by fuzzy-based PI controller. Although GA-based PI controller in the DFIG' structure reduces the frequency deviation under perturbations, the fuzzy-based PI controller by online gain tuning can adopt the proportional and integral gains to the specific situations.

#### B) Second Scenario: Random Load Change

The second scenario verifies the performance of the fuzzy-based PI controller with a random load perturbation as a more realistic event in real-world power systems.

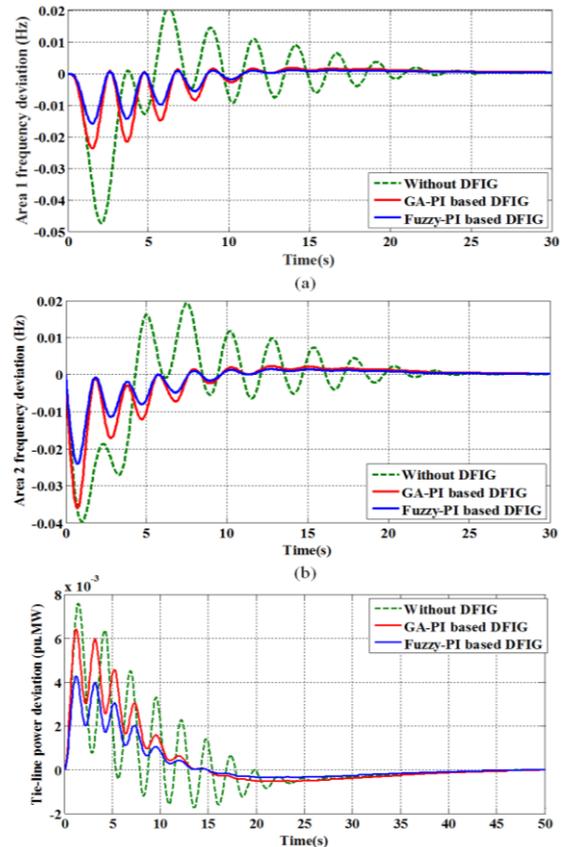


Fig. 5. Frequency deviation and tie-line active power change in first scenario, frequency deviation in area 1 ,frequency deviation in area 2 and tie-line power deviation

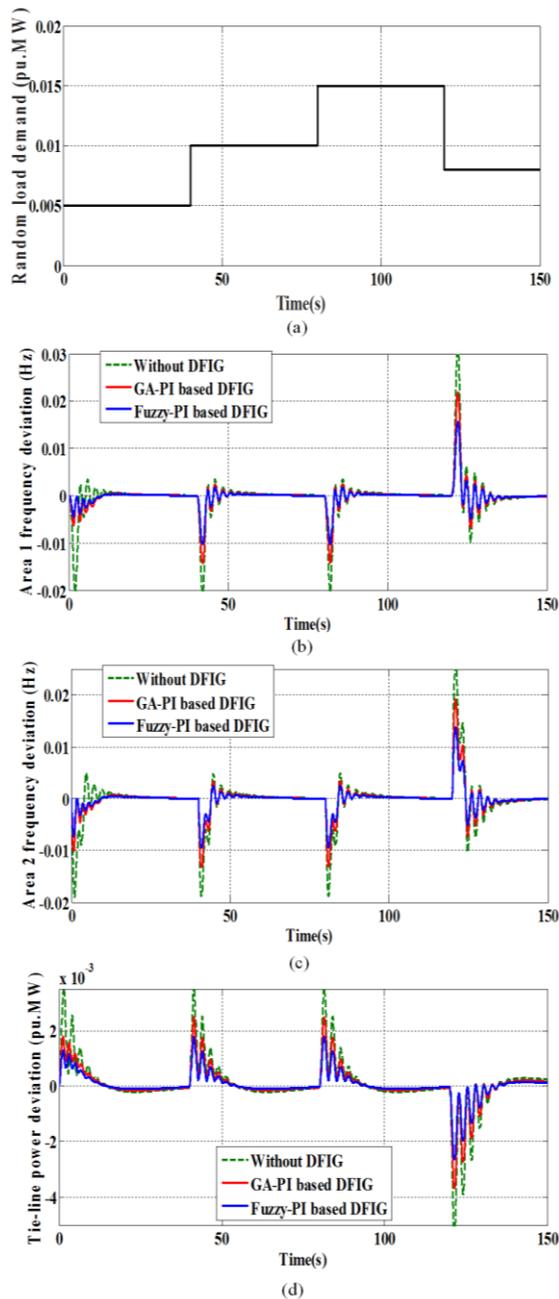


Fig. 6. Random load change, frequency deviation and tie-line active power change in second scenario, random load change, frequency deviation in area 1 ,frequency deviation in area 2 and tie-line power deviation

Random load perturbation is applied in area 2. Fig. 6 depicts this random load perturbation. Following the supposed random load perturbation, the area frequency and tie-line power deviations are also depicted in Fig. 6. As seen, the fuzzy-based PI controller has better performance over GA-based PI controller from viewpoint of the area frequency and tie-line power oscillations reduction.

## 6. Conclusion

In this study, AGC capabilities of a multi-area power system were enhanced through coordination between DFIG and AGC loop. The PI was been applied for controlling the governor speed of the wind turbine in the DFIG' structure. For this aim, a fuzzy logic-based adaptive approach was employed for optimal tuning of the integral and proportional gains in PI controller. The efficiency of the proposed fuzzy-based PI controller was been investigated on the hybrid interconnected two-area power system, in which GRC and GDB constraints were considered. It was illustrated that by employing the fuzzy-based PI controller, area frequency and tie-line power deviations were moderated more effectively compared to GA-based PI controller.

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