

Enhancement of frequency transient response using fuzzy-PID controller considering high penetration of doubly fed induction generators

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Article Info

Article history:

Received Apr 14, 2023

Revised Oct 10, 2023

Accepted Feb 12, 2024

Keywords:

Automatic generation control

Clean energy technology

Frequency stability

Fuzzy-proportional integrator derivative

Wind power plant

ABSTRACT

In modern power systems, renewable-based power plant such as wind power system is integrated significantly. Among numerous types of wind power systems doubly fed induction generators (DFIG) is becoming favorable in the last few years. However, adding a wind power plant could give a new challenge to the power system, especially in frequency stability. Hence, it is important to control the frequency of the power system to be able to find its initial condition in every condition. Generally, the frequency of the power system can be controlled by using automatic generation control (AGC). AGC is used to maintain the balance between generating capacity and the load by adding integral control to the governor. However, with more and more wind power systems in the grid conventional AGC is unsuitable. Hence, it is important to have an advanced AGC based on the artificial intelligence method. This paper proposed the application of fuzzy-proportional integrator derivative (fuzzy-PID) for AGC in power systems considering the high penetration of wind power systems. From the simulation results, it is found that the proposed method can reduce the overshoot and accelerate the settling time of frequency better than using conventional AGC.

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1. INTRODUCTION

Fossil energy that is used continuously will cause a decrease in the availability of the said fossil energy [1]. This is due to the limited availability of this energy in nature and cannot be renewed shortly. Therefore, the use of fossil energy is starting to be replaced with new renewable energy (NRE). This is under the commitment of the Indonesian government to project NRE to reach 29% of the total national primary energy needs [2]. Wind energy is one of the promising alternatives to renewable energy. Wind power plants (WPP) have developed quite rapidly. The use of wind energy as an energy source for power generation is increasing due to the development of infrastructure, technology, and low operating costs [3]. WPP utilizes wind energy which rotates wind turbines to produce mechanical energy. Furthermore, the mechanical energy obtained from the rotation of the turbine is converted into electrical energy through a generator.

The Centre of Research and Development of Electricity Technology, New Renewable Energy, and Energy Conservation states that there are 61,972 MW of total power that can be generated from wind energy in Indonesia [4]. However, this untapped wind energy has unstable wind speeds [5]. Therefore, we need a system that can control the output power of the WPP without being affected by changes in wind speed. A doubly fed induction generator (DFIG) is one of the turbine generator system models that is often used in WPP. This is because DFIG has advantages in controlling the active and reactive power of generators, producing energy efficiently, improving power quality, and increasing dynamic performance when a disturbance occurs [6], [7].

To connect the WPP system with various other generators can be connected using an electrical network system that functions to regulate and control the electrical grid system. This system will connect various generators synchronously. An electrical network system can be considered synchronous if it has the same frequency. The determination of power generated by the generator depends on the load supplied by the system. This active power adjustment is done by adjusting the magnitude of the generator drive coupling. Therefore, a control system scheme functions to maintain the frequency at a certain point divides the flow of power to the load between generators, and controls the power exchange schedule in the electric power system is needed, this system is known as automatic generation control (AGC) [8].

Generally, AGC can be done by adding an integral controller on the governor. However, with more and more renewable-based power plant integration and uncertainty of the load this traditional concept is out of date. Hence, intelligent AGC based on artificial intelligence is essential to handle the new problem in power systems. The application of whale optimization algorithms (WOA) for designing PID controllers as AGC is reported in [9]. From the paper, it is found that the PID controller is superior to the integral controller for AGC. In addition, WOA can be used to optimally design the PID for enhancing the frequency performance of the power system. The research effort in [10], proposed an AGC method using auction-based algorithms. To make the system more complicated high renewable energy integration is considered in the system. From the simulation results, it is found that the frequency can be maintained stable under high penetration of renewable energy when AGC is designed using auction-based algorithms. The application of pathfinder algorithms for AGC is reported in [11]. The multi-source power system is used as the test system for testing the proposed method. From the simulation results, it is found that the proposed method can enhance the frequency of multi-source power systems significantly. Soni *et al.* [12] proposed a hybrid method between grey wolf optimization and pattern search algorithms for AGC. It is reported that the concept is successful in enhancing the frequency performance of the power system. However, metaheuristic algorithms have a disadvantage in terms of simulation time. They must always run the simulation every time the operating condition of the system is changing. Hence, it is not suitable for a system with high uncertainty and non-linearity. Hence, it is essential to design an AGC that is robust from any kind of uncertainty and non-linearity.

Among numerous types of AGC controller fuzzy-proportional integrator derivative (fuzzy-PID) method. Fuzzy logic control (FLC) is a system control method that is currently widely used. In designing FLC, it is not necessary to have a mathematical model of the system being controlled. This is one of the advantages of FLC because the control system will always adjust to the existing input [13]. The application of FLC for a unified power flow controller (UPFC) is reported in [14]. From the paper, it was found that by designing UPFC using FLC, the power quality of the system can be enhanced significantly. The application of FLC as the droop control of microgrids is reported in [15]. It was found that by designing the droop controller of the microgrid using FLC, the voltage and the frequency of the system can be enhanced. The research effort in [16] proposed a concept of solar system battery charging using a fuzzy logic PI controller. Zerouali *et al.* proposed a new method for improving the performance of automatic voltage regulator using the fuzzy-controller as reported in [17]. From the simulation, it was found that their proposed method could enhance the transient response of the power system voltage. Maghfiroh *et al.* [18] proposed a novel method for reducing energy consumption using hybrid FLC and PID. The combination of fuzzy and PID regulators for frequency regulators in a smart grid is reported in [19]. From the literature review above, it is noticeable that FLC-PID could bring a positive impact in terms of enhancing controller performance.

This paper proposed the application of fuzzy-PID for AGC considering the high penetration of wind power systems. The rest of the paper is organized as follows: section 2 presented the method of designing fuzzy-PID. Results and discussion are highlighted in section 3. Section 4 shows the contribution and the conclusion of the paper.

2. METHOD

2.1. Fuzzy-proportional integrator derivative

Fuzzy is a problem-solving method that uses operations in the form of a rule base to convert multiple inputs and outputs into synchronous basic rules on non-linear or complex systems [20]. The

Mamdani fuzzy inference method is commonly used, whereas PID is a conventional control system that can control linear systems. However, the PID control system is not well suited to non-linear systems [21].

The steady-state error in response to changes in load must be zero or meet predetermined standards in load frequency control (LFC), the power exchange in tie-line power must be zero under normal conditions so that each generating system can meet the power requirements of each load, and areas that require additional power in an emergency must be able to provide power for other area generating systems. As a controller signal, the integral control system will use integral error control. As a result, frequency deviation becomes stable at a steady state but exhibits poor dynamic performance [22]. As a result, the fuzzy-PID control system is used to replace conventional control systems, resulting in a more stable oscillation of the generating system's output frequency. Fuzzy-PID does not alter the previous controller system's parameters but instead generates a control signal directly based on the existing error signal [23].

The fuzzy-PID control system combines the FLC and PID control systems. The fuzzy-PID direct action type is one type of control system. The fuzzy-PID direct-action type operates in such a way that the control system's output control signals are controlled directly by fuzzy logic control based on predetermined rule bases and memberships, while the PID is the control system's gain. Figure 1 depicts a direct-action type fuzzy-PID block diagram [24].

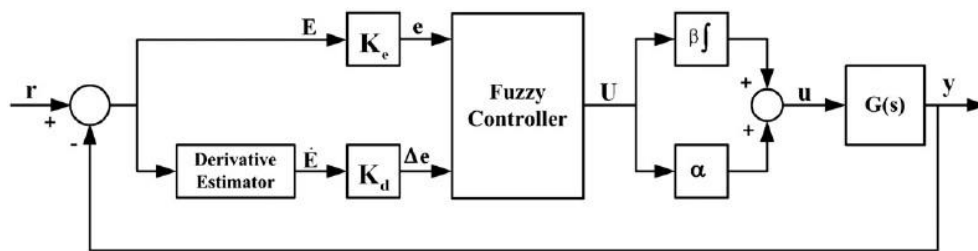


Figure 1. Direct-action type fuzzy-PID

From Figure 1 a mathematical equation can be made:

$$u = \alpha U + \beta \int U dt \quad (1)$$

where U is the output of FLC. For the fuzzy product-sum crisp type, namely the inference method, the defuzzification method, the center point, and the membership function at the input and output can be made with (2) [25]:

$$U = A + PE + D\dot{E} \quad (2)$$

Where $E = K_e e$ and $\dot{E} = K_d \dot{e}$. So that the value of the PID control system is obtained into:

Proportional gain $= \alpha K_e p + \beta K_d D$

Integral gain $= \beta K_e P$

Derivative gain $= \alpha K_d D$

2.2. Procedure of designing the controller

Three membership functions are used in this control system: error f and delta error f as inputs and control signal as outputs. The triangular shape is used by the membership function. Two membership functions, negative and positive, are used in the input error f . Two membership functions, negative and positive, are used for the input delta error f . In the output, three membership functions will be used: negative, zero, and positive. This reference point is calculated using the integrator control system's frequency response and an integrator gain of 0.3. Figures 2 to 4 depict the input and output of the membership limit.

In the graph, the maximum and minimum values to be set for input 1 fuzzy (frequency error), input 2 fuzzy (delta frequency error), and fuzzy output (u) are 1 and -1. Because the load in this system is 0.3 pu, this value is greater than the graph's peak value. To prepare a larger load, take the number that exceeds the graph. The values for each membership function are as described in Tables 1 to 3.

In addition, the membership function will be given a rule base that will be implemented in the system later. The fuzzy system is to be designed as four rule bases. These rules are as follows:

- If f is negative and df is negative then u negative
- If f is negative and df positive then u zero

- If f is positive and df negative then u zero
- If f is positive and df is negative then u positive

To determine the gain value on the PID which has changed to K_e , K_d , α , and β . Trial and error are carried out until a stable system response is found.

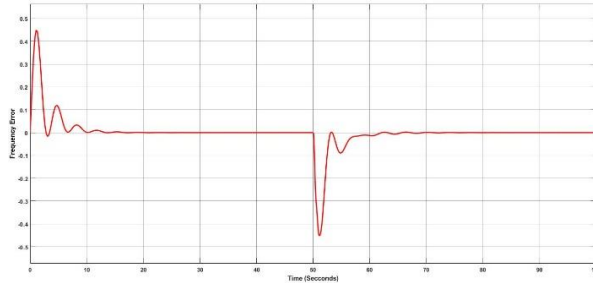


Figure 2. Membership limit of input 1 fuzzy (frequency error)

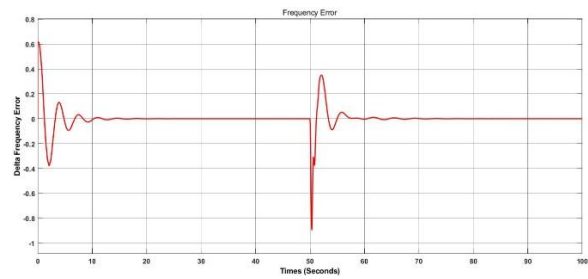


Figure 3. Membership limit of input 1 fuzzy (delta frequency error)

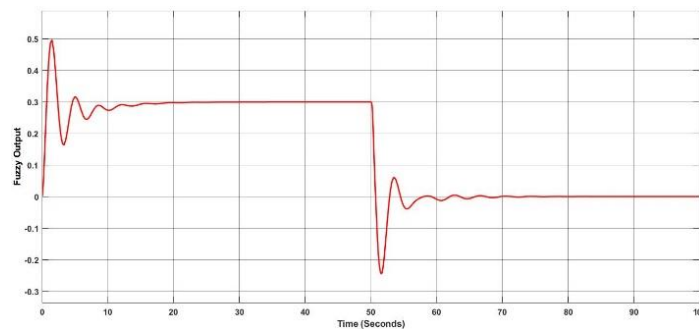


Figure 4. Fuzzy output membership limit (u)

Table 1. Membership function input 1 fuzzy (frequency error)

Input 1 (f)	
Triangular type positive	$[-1, 1, 2]$
Triangular type negative	$[-2, -1, 1]$

Table 2. Membership function input 2 fuzzy (delta frequency error)

Input 2 (df)	
Triangular type positive	$[-1, 1, 2]$
Triangular type negative	$[-2, -1, 1]$

Table 3. Membership function output fuzzy (u)

Output (u)	
Triangular type positive	$[1, 1, 1]$
Triangular type zero	$[0, 0, 0]$
Triangular type negative	$[-1, -1, -1]$

3. RESULTS AND DISCUSSION

3.1. Case study 1

Based on the control system that has been determined, the performance of the AGC system is seen in two areas in this case study: the integral controller system, the controller system in the form of a combination of integral and proportional, and the fuzzy-PID controller system. The performance of the frequency deviation in each area and the tie-line power are observed in this analysis. The AGC system applies a static load of 0.3 pu to area one and a static load of 0.4 pu to area two. Table 4 shows a comparison of the controller's ability to dampen and stabilize the frequency, while Figure 5 shows the transient response of frequency in area 1.

According to Figure 5, the additional load on the two-area AGC system causes the frequency to drop briefly before returning to a stable point. The AGC control system in the two-area LFC system influences the frequency to return to a stable point. When there is a load, this control system adjusts the valve opening so that more steam flows. The valve's opening is directly proportional to the demand for power to supply the load; the greater the load, the greater the valve's opening. This opening causes the rotor to rotate faster, producing power with a frequency closer to the normal point. The valve opening adjustment will be stopped

once the frequency is stable. The frequency oscillations that occur can be damped better with the fuzzy-PID control system than with the integrator system controller and the PI system controller. In addition, the fuzzy-PID control system can return the system to normal faster than other control systems. Furthermore, Figure 6 displays a graph of the frequency response in the two areas using different control systems and Table 5 described the detailed features of Figure 6.

Table 4. Comparison of overshoot and settling time of frequency deviation on different control systems in the area

No	Controller	Overshoot (pu)	Settling time (s)	Steady state error (pu)
1	Integrator	0.0224	20.51	-1.75×10^{-9}
2	PI	0.021	12	-4.6×10^{-7}
3	Fuzzy-PID	0.006	4.36	-4×10^{-9}

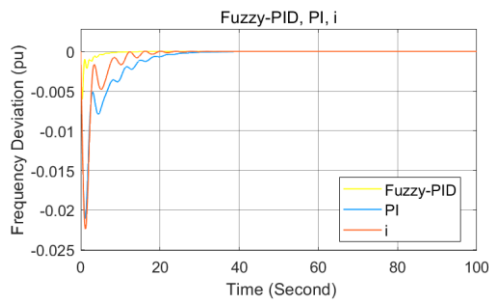


Figure 5. Frequency deviation in area 1 with different control systems

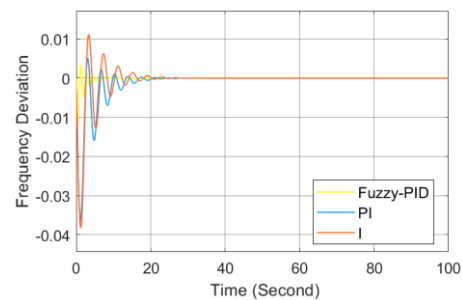


Figure 6. Frequency deviation in area 2 with different control systems

Table 5. Comparison of overshoot and settling time frequency deviation in the control system is different in area 2

No	Controller	Overshoot (pu)	Settling time (s)	Steady state error (pu)
1	Integrator	0.0383	19.2	-0.4×10^{-8}
2	PI	0.0362	16.5	-4.4×10^{-8}
3	Fuzzy-PID	0.012	3.9	2.4×10^{-8}

According to Figure 6, the additional load on the two-area AGC system causes the frequency to drop briefly before returning to a stable point. The AGC control system in the two-area LFC system influences the frequency's return to the stable point. The control system will increase the size of the valve opening on the steam turbine, causing the rotor to move faster than before. This change in rotor rotation causes the frequency to rise again, returning to the stable point depicted in Figure 6. When the frequency deviation is zero, we have reached the stable point. The frequency oscillations that occur can be damped better with the fuzzy-PID control system than with the integrator system controller and the PI system controller. In addition, the fuzzy-PID control system can return the system to normal faster than other control systems.

From Tables 4 and 5 it is noticeable the conventional control system has a very high overshoot, almost close to the overshoot limit at the permitted frequency of 0.0386 pu, as specified in the design specifications. The overshoot frequency in the fuzzy-PID control system was successfully extinguished with a value of 0.012 pu. When a disturbance occurs, the conventional control system is unable to reach a stable value under the specified standard, namely at the maximum of the tenth second, it must reach a stable point on the fuzzy-PID system, which can stabilize at 3.9 seconds. For steady state error, all three systems can maintain a stable position, and the error is significantly greater than the predetermined standard of 0.002963 pu. When compared to the integrator and PI control systems, the fuzzy-PID control system has a better response and can dampen frequency oscillations. The performance index for each control in the Table 6 supports this. Table 6, shows the performance indices comparison between the proposed method and existing solution.

Table 6. Performance value of case one error

No	Control system	ISE	IAE	ITAE	ITSE
1	Fuzzy-PID	0.007814	0.1481	0.2803	0.005655
2	PI	0.2725	1.5	7.72	0.5987
3	Integrator	0.2597	1.022	3.01	0.3705

3.2. Case study 2

The performance of the AGC system in two areas will be examined in this case study, based on the control system that has been determined, namely the integral controller system, the controller system in the form of a combination of integral and proportional, and the fuzzy-pi controller system. The performance of the frequency deviation in each area and the tie-line power are observed in this analysis. The static load in area one is 0.3 pu, the static load in area two is 0.4 pu, and the penetration of DFIG-based WPP in the 50th second is 0.1 pu in the two-area AGC system. Figure 7 shows the transient response of frequency in area 2 with different controllers, while Table 7 shows the detailed features of Figure 7.

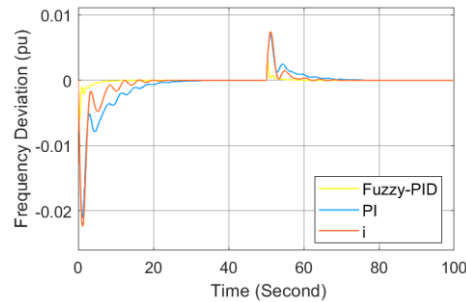


Figure 7. Frequency deviation in area 1 with a different control system in case 2

Table 7. Comparison of the frequency deviation in different control systems in area 1

No	Controller	Second=0 (pu)	Second=50 (pu)
1	Integrator	0.0383	0.00745
2	PI	0.0362	0.00705
3	Fuzzy-PID	0.012	0.0029

According to Figure 7, the additional load on the two-area AGC system causes the frequency to drop briefly before returning to a stable point. When the WPP provides power at the 50th second, the frequency rises and returns to a stable level. The AGC control system in the two-area LFC system influences the frequency's return to a stable point. The frequency oscillations that occur can be dampened better with the fuzzy-PID control system than with the integrator system controller and the PI system controller. When compared to other control systems, the fuzzy-PID control system improves the system to a normal point faster and has a lower overshoot value. The table below shows a comparison of the controller's ability to dampen and stabilize the frequency.

Furthermore, in Figure 8, it displays a graph of the frequency response in the two areas using different control systems. According to Figure 8, the additional load on the two-area AGC system causes the frequency to drop briefly before returning to a stable point. When the WPP provides power at the 50th second, the frequency rises and returns to a stable level. The AGC control system in the two-area LFC system influences the frequency's return to a stable point.

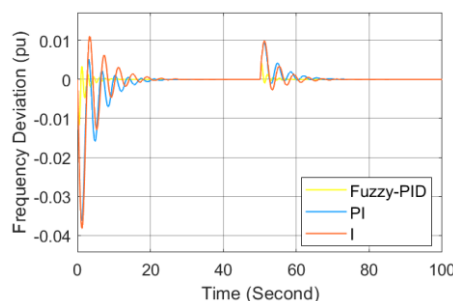


Figure 8. Frequency deviation in area 2 with a different control system in case 2

The frequency oscillations that occur can be dampened better with the fuzzy-PID control system than with the integrator system controller and the PI system controller. When compared to other control

systems, the fuzzy-PID control system improves the system to a normal point faster and has a lower overshoot value. The frequency in the fuzzy-PID control system returns to its normal point in the 15th second, whereas the frequency stabilizes in the 30th second in the integrator system controller and the PI system controller. Table 8 shows a comparison of the controller's ability to dampen and stabilize the frequency.

The fuzzy-PID control system has a better response and can maintain frequency stability compared to the integrator control system and the PI control system. This is supported by the performance index for each control in the Table 9.

Table 8. Comparison of frequency deviations in different control systems in area 1

No	Controller	Second=0 (pu)	Second=50 (pu)
1	Integrator	0.0383	0.00985
2	PI	0.0362	0.0094
3	Fuzzy-PID	0.012	0.00418

Table 9. Case one error performance value

No	Control system	ISE	IAE	ITAE	ITSE
1	Fuzzy-PID	0.009256	0.2075	3.297	0.07584
2	PI	0.3036	2	35.27	2.23
3	Integrator	0.2895	1.36	20.88	1.912

4. CONCLUSION

This paper proposed an intelligent method for enhancing the frequency stability of power systems using the fuzzy-PID controller. To make the system more realistic and up-to-date wind power system-based DFIG is added to the system. Two area power system is used as the test system of this paper. Non-linear time domain simulation is used to test the performance of the proposed method. From the simulation results it is found that the frequency stability of the power system can be enhanced significantly (ISE: 0.01132; IAE: 0.3234; ITAE: 18.92; ITSE: 0.334). For further research, different test systems can be used to investigate the efficacy of the proposed method. In addition, for further research designing the fuzzy PID using type-2 fuzzy logic controller can be considered to enhance the transient response of power systems.

ACKNOWLEDGMENT

The corresponding author wishes to express gratitude to Universitas Airlangga for funding this study by the "Penelitian Dosen Pemula" grant (No. 416/UN3.1.17/PT/2023).

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BIOGRAPHIES OF AUTHORS



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