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Research Article

Control of Pitch Angle in Wind Turbine Based on Doubly Fed Induction Generator Using Fuzzy Logic Method

Ehsan Hosseini [a,b], Neda Behzadfar [a,b*], Mahnaz Hashemi [a,b], Majid Moazzami [a,b], Majid Dehghani [a,b]

[a] *Department of Electrical Engineering, Najafabad Branch, Islamic Azad University, Najafabad, Isfahan, Iran.*
[b] *Smart Microgrid Research Center, Najafabad Branch, Islamic Azad University, Najafabad, Isfahan, Iran.*

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ABSTRACT

Wind turbines can be controlled by controlling the generator speed and adjusting the blade angle and the total rotation of a turbine. Wind energy is one of the main types of renewable energy and is geographically extensive, scattered and decentralized and is almost always available. Pitch angle control in wind turbines with Doubly Fed Induction Generator (DFIG) has a direct impact on the dynamic performance and oscillations of the power system. Due to continuous changes in wind speed, wind turbines have a multivariate nonlinear system. The purpose of this study is to design a pitch angle controller based on fuzzy logic. According to the proposed method, nonlinear system parameters are automatically adjusted and power and speed fluctuations are reduced. The wind density is observed by the fuzzy controller and the blade angle is adjusted to obtain appropriate power for the system. Therefore, the pressure on the shaft and the dynamics of the turbine are reduced and the output is improved, especially in windy areas. Finally, the studied system is simulated using Simulink in MATLAB and the output improvement with the fuzzy controller is shown in the simulation results compared to the PI controller. Fuzzy control with the lowest cost is used to control the blade angle in a wind turbine. Also, in this method, the angle is adjusted automatically and it adapts to the system in such a way that the input power to the turbine is limited. Compared to the PI controller, by calculating different parameters, the power quality for fuzzy controller is enhanced from 2.941 % to 4.762 % for wind with an average speed of 12 meters per second.

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1. INTRODUCTION

Dynamics governs most industrial processes and the real system is nonlinear. The analysis and design of the control system in the nonlinear mode is very difficult [1]. The power system is a very complex system whose equations are nonlinear and its parameters may vary due to various factors such as noise and local loads [2, 3]. Considering the environmental and economical concerns, energy should be produced at places away from consumption centers [4, 5].

In today's world, due to the decline of non-renewable energy reserves, renewable energy has gained importance due to its significant role and much research has been done to exploit these resources [6, 7]. So far, many studies have stressed the importance and application of new energies [8, 9].

Wind energy is used as a sustainable energy [10, 11]. One of the main types of renewable energy is wind energy, which is geographically extensive, scattered, decentralized, and widely accessible [12, 13]. To get maximum energy from the wind and according to the aerodynamic requirements of the generators, it is important to provide an accurate controller resistant to disturbances [14, 15].

When the wind speed and the speed of the turbine exceed their nominal values, the angle controller operates and decreases the power received from the wind by increasing the angle [16, 17]. To this end, various control methods such as proportional controller-integrator-derivative (PID) [18], linear matrix of inequality [19], fuzzy logic [20], quadratic linear equations [21], conventional predictive control [22], and a sliding mode control scheme [23] are proposed. In [24] and [25], the advantages and disadvantages of some examples of controllers were listed.

Effects of various environmental and mechanical factors on increased energy extraction by wind farm systems in [26] were investigated using artificial network modeling, which is the best model of artificial neural network based on annual wind speed changes and diameter, in order to predict the energy increase rate from wind farm. Turbine rotor and turbine power were used.

A step angle control strategy using fuzzy logic control for the DFIG wind turbine system was presented in [27], which did not require system information and wind speed. Also, an adaptive PI control loop was added to the fuzzy logic control

*Corresponding Author's Email: n.behzadfar@pel.iaun.ac.ir (N. Behzadfar)
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and used as a step angle controller in a variable-speed wind turbine system.

The most common controller in variable-speed wind turbines to obtain the desired output power is the blade angle controller. Blade angle control in wind turbines has a direct impact on a machine's dynamic performance and power system oscillations. Wind turbines have a nonlinear and multivariate system; hence, it is very important to design controllers that adapt to the system at any time [28].

In this paper, fuzzy control is used to control the blade angle. In this method, the blade angle is automatically adjusted and adapts to the system in a way that increases the input power to the system by taking into account the aerodynamic conditions.

Compared to previous designs, the designed fuzzy controller features no wind speed at the fuzzy input, which eliminates the need for an anemometer. Using a regular pattern wind speed is another feature of the proposed method which is suitable for gaining a better understanding of the performance of controllers. Several previous studies have pointed out that the use of irregularly patterned wind speeds causes no differences in the output of controllers in case of sudden wind changes. Based on a comparison between the simulation results, the superiority of the fuzzy controller is proven. The use of the proposed controller in wind farms will increase the efficiency and service life of mechanical parts and ensures cheaper maintenance.

2. WIND TURBINE SYSTEM MODEL

Wind turbines consist of two main parts: mechanical power generation and conversion of mechanical power to electrical, done by the turbine and the generator, respectively [29]. In this section, their relations and equations are briefly mentioned.

2.1. Turbine

The two-mass model is used in the study of transient stability to model the mechanical and electrical connection between the generator and the wind turbine [30]. If T_M, T_S, and T_E are considered as mechanical, axial, and electrical torques in the turbine, respectively, the equations are:

$$\frac{d\omega_r}{dt} = \frac{1}{2H_R}(T_E + T_S) \tag{1}$$

$$\frac{d\omega_t}{dt} = \frac{1}{2H_T}(T_M + T_S) \tag{2}$$

$$\frac{d\beta}{dt} = \omega_b(\omega_t + \omega_r) \tag{3}$$

where H_T is the moment of inertia of the turbine, H_R the moment of inertia of the turbine rotor, ω_r the frequency angle of the rotor and turbine, and β the angle of the pitch tip. Wind kinetic energy is proportional to the second power of wind speed while wind power is proportional to the cubic speed of wind. Therefore, upon increasing wind speed, wind power will increase. Technical use of wind energy is possible when the average wind speed is in the range of 5 meters per second to 25 meters per second (90 Km/h). The mechanical equation of the turbine is given below [31, 32]:

$$P_W = \frac{1}{2}\pi\rho C_P(\lambda,\beta)R^2V_w^3 \tag{4}$$

where ρ (kg/m^3), R (m), V_w (m/s), and S_b (VA) are air density, pitch diameter, wind speed, and apparent power, respectively. Wind turbine power factor (C_p) is equal to [33]:

$$C_P(\lambda,\beta) = c_1(\frac{c_2}{\lambda_i} - c_3\beta - c_4)e^{\frac{-c_5}{\lambda_i}} + c_6\lambda \tag{5}$$

where β is the pitch tip angle and the coefficient λ_i is equal to:

$$\lambda_i = [\frac{1}{\lambda + c_7\beta} - \frac{c_8}{\beta^3+1}]^{-1} \tag{6}$$

Blade tip speed to wind speed ratio (λ) is [34]:

$$\lambda = \frac{\omega_t R}{V_\omega} \tag{7}$$

Therefore, at a given wind speed, there is only one specific angular velocity for maximum power.

Wind speed is a determining factor in power reference, torque, or turbine speed. Depending on the wind speed, the operation of the turbine can be divided into four general modes. The mechanical output power of a wind turbine is divided into four regions in terms of wind speed, as shown in Figure 1 [23].

The angular velocity of the turbine is set to be less than the nominal wind speed in $C_{p,max}$. When the wind speed is higher than the nominal wind speed, the blade angle control is activated and by adjusting the blade and limiting the energy received from the wind, the blade angle can be adjusted to determine the proper power of the generator and gearbox. The blade control mechanism can be modeled using the following fixed time system (T_β) [35, 36]:

$$\frac{d\beta_P}{dt} = \frac{1}{T_\beta}(\beta_{Pref} - \beta_P) \tag{8}$$

When the wind speed is less than the nominal wind speed, β_{pref} is maintained at zero; however, when it exceeds the nominal value, the actual power is modeled by the PI controller via the following relations [37]:

$$\beta_{pref} = K_{P\beta}(P_t - P_{tref}) + x_\beta \tag{9}$$

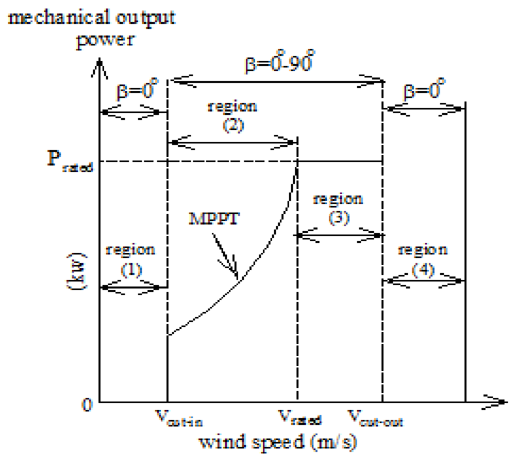

Figure 1. Wind turbine operating areas in terms of wind speed

$$\frac{dx_{\beta}}{dt} = K_{I\beta}(P_t - P_{tref}) \quad (10)$$

where $K_{I\beta}$ and $K_{P\beta}$ are the integral interest rates, which are proportional. The blade angle control block diagram in Figure 2 shows that the PI controller is used for adjustment. The speed or mechanical power of the generator is expressed by X. A summary of the parameters used to model the turbine is given in Table 1.

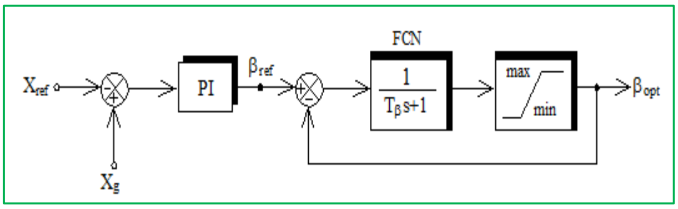

Figure 2. Application of PI controller to controlling blade angle

Table 1. Turbine modeling parameters

Parameter	Symbol	Unit
Frequency angles of the rotor	ω_r	Rad/s
Mechanical torque	T_M	N.m
Axial torque	T_S	N.m
Electrical torque	T_E	N.m
Wind turbine power factor	C_P	-
Angles of the pitch tip	β	degree
Moment of inertia of the turbine	H_T	s
Moment of inertia of the turbine rotor	H_R	s
Apparent power	S_b	VA
Air density	ρ	kg/m^3
Pitch diameter	R	M
Wind speed	V_w	m/s

2.2. DFIG wind turbine system

Figure 3 shows the block diagram of the system under study, including the wind turbine and the controller. The turbines used are Horizontal-Axis Wind Turbines (HAWTs). HAWTs are typically either two- or three-bladed and operate at high blade tip speeds [38, 39]. The system model is derived from the mechanical model of the blades, hub, and shaft; a magnetic model of a three-phase transformer; and a back-to-back converter of transmission line and network [40, 41]. The back-to-back converter is formed of separate parts on the side of the device and the network that are connected to each other via a DC connector capacitor [42, 43].

2.3. Control with fuzzy logic

Fuzzy generator, inference motor, fuzzy rules, and non-fuzzy generator are the four main parts of a fuzzy controller. A fuzzy inference system has fuzzy inputs and outputs; however, the inputs and outputs of the target system are numerical [44, 45]. Based on the experience, language variables are used to set fuzzy rules. All calculations and rules are done and considered at the heart of the fuzzy system, the inference engine [46, 47]. In the studied system, the multiplication inference engine, singleton fuzzy maker, and center interpolation maker are used. The block diagram using fuzzy logic is shown in Figure 4. The error in the generator output power (ΔP), the variation of the output power error (δΔp), and rotor speed (ω_r) are considered as inputs for the proposed fuzzy controller [48].

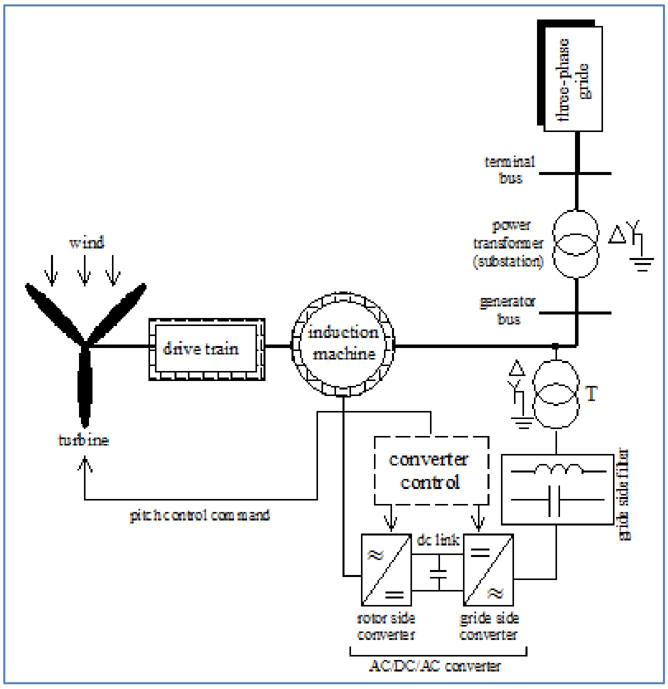

Figure 3. Target system block diagram

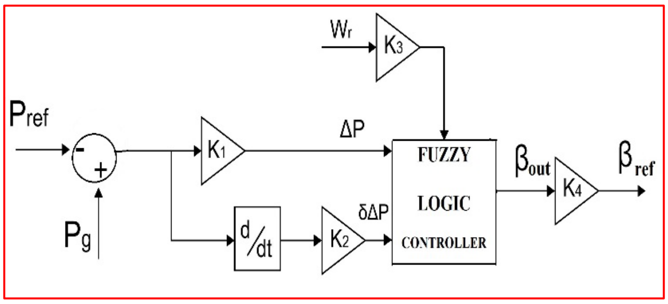

Figure 4. Block blade angle control diagram using fuzzy logic

3. SIMULATION RESULTS

In this section, to demostrate different performances of the controllers, two wind speeds with averages of 12 m/s and 16 m/s were used. The system parameters including turbine, generator, and network are given in Tables 2 and 3. The power coefficient of wind turbines depends on the wind speed and is not constant. In the simulation, the maximum value for Cp is 0.48. Fuzzy controller input and output adjustment constants are K_1=0.44×10-6, K_2=0.0035, K_3=0.006, and K_4=100.

The membership functions of the first fuzzy input (output power) in the range of [-1 – +1] are considered. Generator output power is in the MW limit and by multiplying it by K_1, it becomes the desired input for the fuzzy. The wind speed pattern, which has an average value of 12 meters per second as shown in Figure 5, is given below, including mechanical torque in Figure 6, output power in Figure 7, dc link voltage in Figure 8, reactive power in Figure 9, rotor speed in Figure 10, and angle blades in Figure 11. Rotor speed and reactive power are given in terms of pu. In case of sudden changes in the wind speed, its effects are seen on each of the system parameters. Two fuzzy and PI controllers were used to compare the results. Increase in active power input, rotor speed, and torque is well known in the fuzzy controller. Also, reducing the DC link voltage fluctuations and the reactive transmission power are other advantages of this controller. All of these advantages result from the lower blade angle engagement.

Table 2. System and generator parameters

Component	Value
Nominal value of power	9×10^3 W
Network voltage	575 V
Network frequency	60 Hz
Voltage in infinite bus	120 KV
Magnetic inductance	3 pu
Resistance in stator	7×10^{-3} pu
Inductance in stator	17×10^{-2} pu
Number of poles	3
Moment of inertia	5.04
Maximum converter power	0.5 pu
Network side coupled indicator	0.15-0.0015 pu
Nominal voltage of dc bus	1.2×10^3 V
Capacitor in dc link	6×10^{-2} F
Network side control pins (Kp Ki)	1.25-300
Rotor side control pins [Kp Ki]	1-100
Line length	20×10^3 m

Table 3. Nominal parameters of the turbine

Component	Value
Power rate	9 MW
Wind speed rate	12 m/s
Maximum blade angle	45°
Maximum blade angle changes	2°/s
Wind cut-off speed	24 m/s

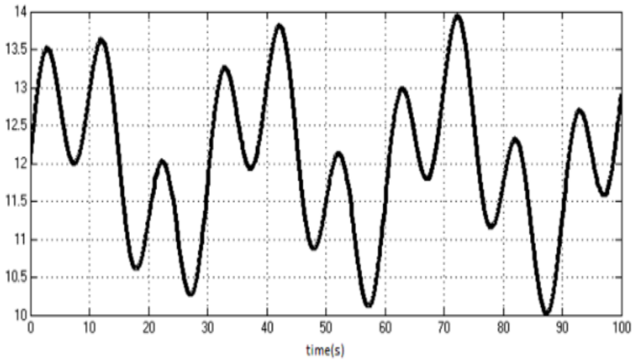

Figure 5. Display wind speed with an average value of 12 m/s

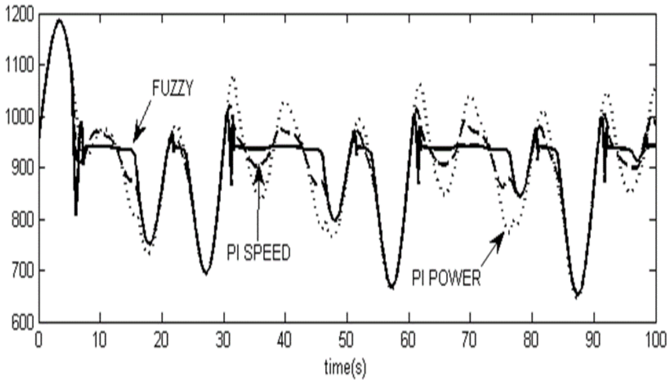

Figure 6. Mechanical torque (Nm) with an average value of 12 m/s

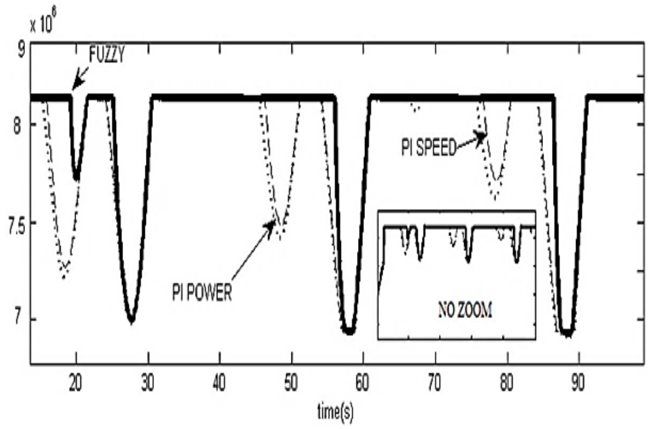

Figure 7. Output power (w) with an average value of 12 m/s

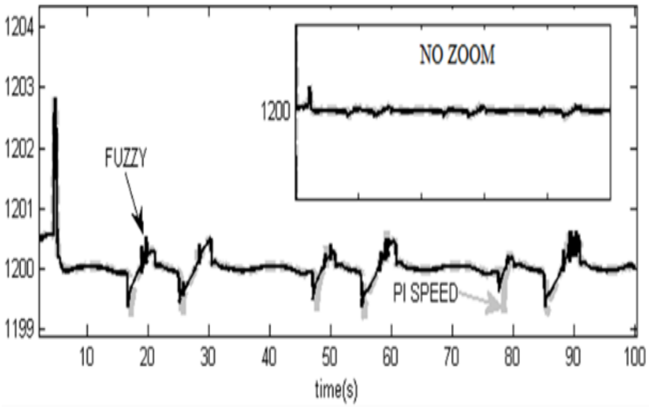

Figure 8. DC link voltage with an average value of 12 m/s

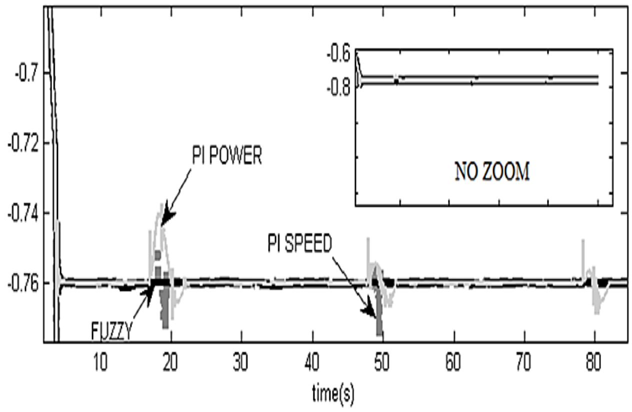

Figure 9. Reactive power with an average value of 12 m/s

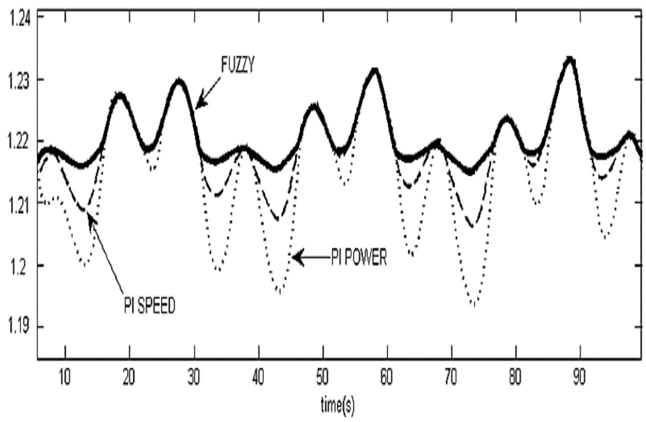

Figure 10. Rotor speed (pu) with an average value of 12 m/s

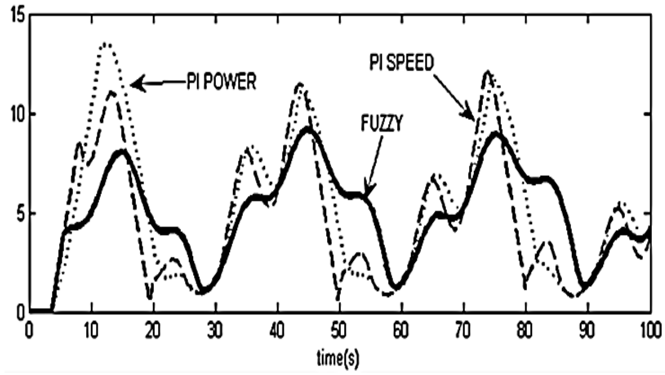

Figure 11. Pitch angle at an average value of 12 m/s with fuzzy and PI controllers

Next, the wind speed pattern with an average of 16 meters per second is given in Figure 12; in addition, simulation results for mechanical torque, transmission power, rotor speed, and pitch angle are shown in Figures 13, 14, 15, 13, respectively. The speed of the rotor is given in terms of prionite. In this wind speed pattern, PI power and speed controllers as well as fuzzy ones are used to compare the results better. The blade angle control is adjusted to increase wind power. This increase rate augments the mechanical torque and speed of the rotor. The fuzzy controller does not experience unnecessary fluctuations in the PI control of the blade angle. For this reason, it has increased the efficiency of the system. By changing the angle control gain, the superiority of the fuzzy controller over the PI is shown in Figures 14 and 15.

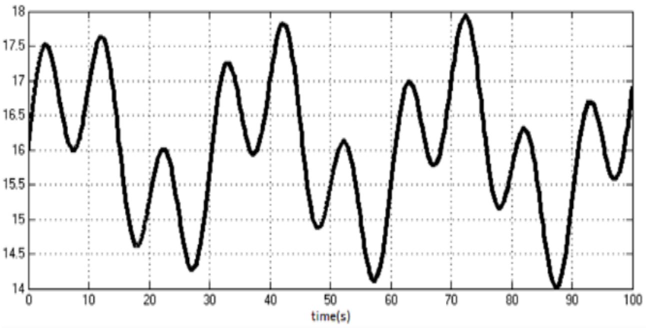

Figure 12. Display wind speed with an average value of 16 m/s

The application of an anemometer to have wind speed information increases costs and reduces system reliability. The use of fuzzy logic control to control the pitch angle is reliable and robust in terms of nonlinear pitch angle properties with wind speed. The advantages of fuzzy logic controllers over conventional controllers include the following: cheap development, coverage of a wide range of operating conditions, and easy customizability in terms of natural language.

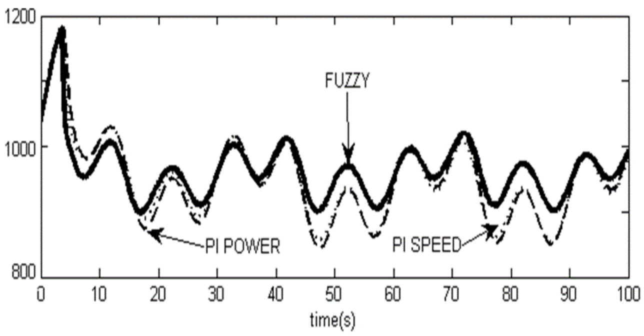

Figure 13. Mechanical torque (Nm) at an average value of 16 m/s

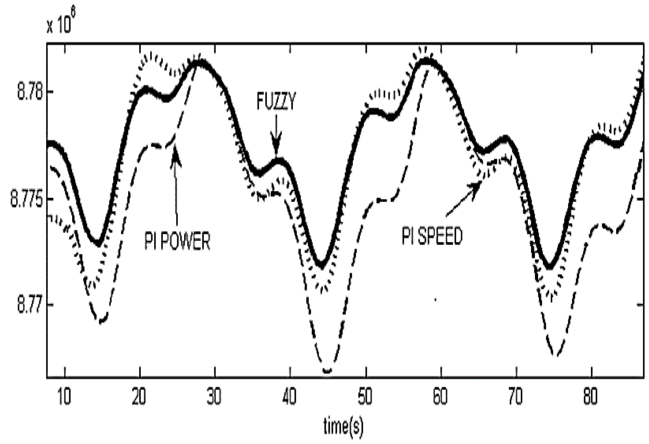

Figure 14. Zoom output power at an average value of 16 m/s

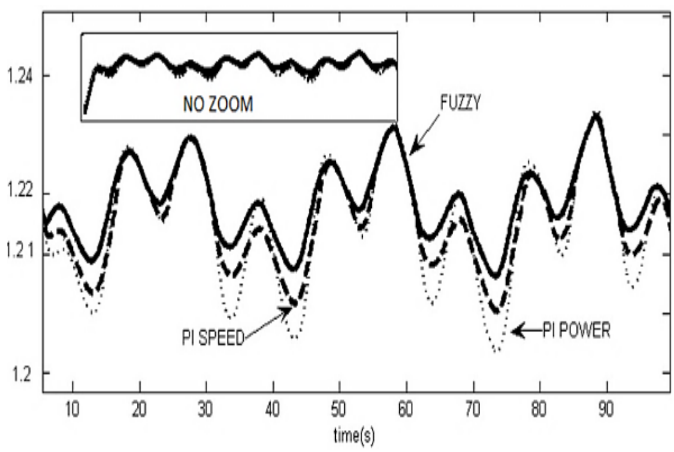

Figure 15. Rotor speed (pu) at an average value of 16 m/s

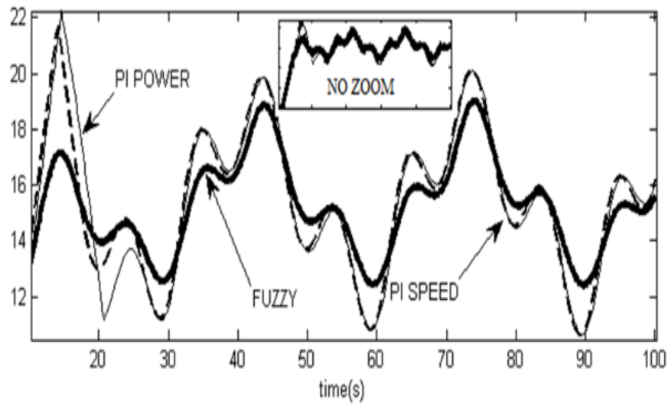

Figure 16. Pitch angle in wind speed with an average value of 16 m/s

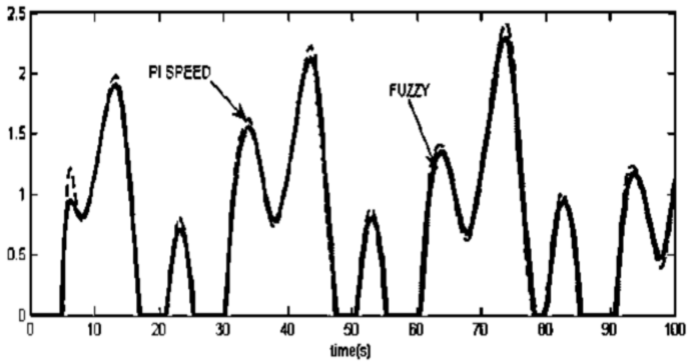

Figure 17. Pitch angle at an average value of 16 m/s withh fuzzy and PI controller

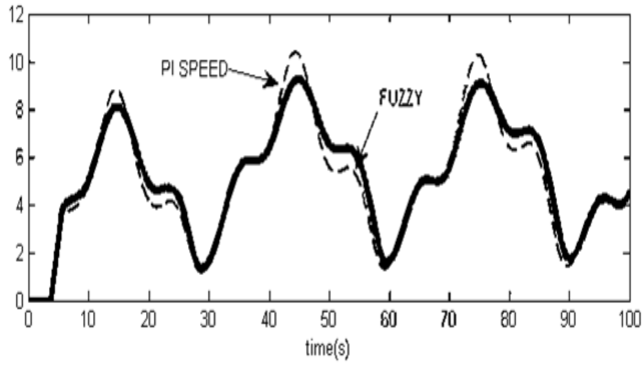

Figure 18. Pitch angle at an average value of 16 m/s with fuzzy and PI controllers

4. CONCLUSIONS

The aim of this paper is to model and simulate a DFIG-based wind turbine. An automatic controller based on fuzzy algorithm was designed for wind turbine and it was compared with traditional PI controllers. This controller enjoys independence from wind speed at the fuzzy input. The simulation results were obtained and demonstrated using MATLAB software Simulink. The superiority of the fuzzy controller in the simulation results was quite clear in case of sudden wind changes. Turbine power stability and reliable dynamic response resulted from the application of the proposed controller. By comparing various parameters, including the minimum values, and the ratio of harmonic distortions to the principal component, power quality was improved from 2.941 % to 4.762 % for the fuzzy controller, compared to the PI controller, at an average wind speed of 12 m/s. At a wind speed of 16 m/s, the quality improvement of 2 % to 45.5 % was observed for the fuzzy controller, compared to the PI controller.

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REFERENCES

1. Hashemi, M. and Shahgholian, G., "Distributed robust adaptive control of high order nonlinear multi agent systems", ***ISA Transactions***, Vol. 74, (2018), 14-27. (https://doi.org/10.1016/j.isatra.2018.01.023).
2. Jafari, E., Marjanian, A., Silaymani, S. and Shahgholian, G., "Designing an emotional intelligent controller for IPFC to improve the transient stability based on energy function", ***Journal of Electrical Engineering and Technology***, Vol. 8, No. 3, (2013), 478-489. (https://doi.org/10.5370/JEE¬T.2013.8.3.478).
3. Shahgholian, G., Arezoomand, M. and Mahmoodian, H., "Analysis and simulation of the single-machine infinite-bus with power system stabilizer and parameters variation effects", ***Proceedings of the IEEE/ICIAS***, Kuala Lumpur, Malaysia, Vol. 1, (2007), 167-171. (https://doi.org/10.1109/ICIAS.2007.4658368).
4. Khosravi, A., Malekan, M., Pabon, J.J.G., Zhao, X. and Assad, M.E.H., "Design parameter modelling of solar power tower system using adaptive neuro-fuzzy inference system optimized with a combination of genetic algorithm and teaching learning-based optimization algorithm", ***Journal of Cleaner Production***, Vol. 244, (2020), Article Number: 118904. (https://doi.org/10.1016/j.jclepro.2019.118904).
5. Aghadavoodi, E. and Shahgholian, G., "A new practical feed-forward cascade analyze for close loop identification of combustion control loop system through RANFIS and NARX", ***Applied Thermal Engineering***, Vol. 133, (2018), 381-395. (https://doi.org/10.1016/j.applthermaleng.2018.01.075).
6. Kiani, A., Fani, B. and Shahgholian, G., "A multi-agent solution to multi-thread protection of DG-dominated distribution networks", ***International Journal of Electrical Power and Energy Systems***, Vol. 130, (2021), Article Number: 106921. (https://doi.org/10.1016/j.ijepes.2021.106921).
7. Fani, B., Dadkhah, M. and Karami, A., "Adaptive protection coordination scheme against the staircase fault current waveforms in PV-dominated distribution systems", ***IET Generation, Transmission and Distribution***, Vol. 12, No. 9, (2018), 2065-2071. (https://doi.org/10.1049/iet-gtd.2017.0586).
8. Rahmani, M., Faghihi, F., Moradi-Cheshmeh-Beigi, M. and Hosseini, S., "Frequency control of islanded microgrids based on fuzzy cooperative and influence of STATCOM on frequency of microgrids", ***Journal of Renewable Energy and Environment (JREE)***, Vol. 5, No. 4, (2018), 27-33. (https://doi.org/10.30501/jree.2018.94119).
9. Ahmadi, S., Sadeghkhani, I., Shahgholian, G., Fani, B. and Guerrero, J.M., "Protection of LVDC microgrids in grid-connected and islanded modes using bifurcation theory", ***IEEE Journal of Emerging and Selected Topics in Power Electronics***, Vol. 9, (2019), 2597-2604. (https://doi.org/10.1109/JESTPE.2019.2961903).
10. Mahdavian, M. and Behzadfar, N., "A review of wind energy conversion system and application of various induction generators", ***Journal of Novel Researches on Electrical Power***, Vol. 8, No. 4, (2020), 55-66. (http://jeps.iaud.ac.ir/article-1-255-en.html).
11. AlShabi, M. and Assad, M.E.H., "Chapter 16- Artificial intelligence applications in renewable energy systems", ***Design and Performance Optimization of Renewable Energy Systems***, Vol. 1, (2021), 251-295. (https://doi.org/10.1016/B978-0-12-821602-6.00018-3).
12. Shahgholian, G., Khani, K. and Moazzami, M., "Frequency control in autanamous microgrid in the presence of DFIG based wind turbine", ***Journal of Intelligent Procedures in Electrical Technology***, Vol. 6, No. 21, (2015), 3-12. (https://dorl.net/dor/20.1001.1.23223871.1394.6.23.1.9).
13. Zou, J., Peng, C., Xu, H. and Yan, Y., "A fuzzy clustering algorithm-based dynamic equivalent modeling method for wind farm with DFIG", ***IEEE Transactions on Energy Conversion***, Vol. 30, No. 4, (2015), 1329-1337. (https://doi.org/10.1109/TEC.2015.2431258).
14. Sedaghat, A., Assad, M.E.H. and Gaith, M., "Aerodynamics performance of continuously variable speed horizontal axis wind turbine with optimal blades", ***Energy***, Vol. 77, (2014), 752-759. (https://doi.org/10.1016/j.energy.2014.09.048).
15. Sedaghat, A., Samani, I., Ahmadi-Baloutaki, M., Assad, M.E.H. and Gaith, M., "Computational study on novel circulating aerofoils for use in Magnus wind turbine blades", ***Energy***, Vol. 91, (2015), 393-403. (https://doi.org/10.1016/j.energy.2015.08.058).
16. Prasad, R. and Padhy, N.P., "Synergistic frequency regulation control mechanism for DFIG wind turbines with optimal pitch dynamics", ***IEEE Transactions on Power Systems***, Vol. 35, No. 4, (2020), 3181-3191. (https://doi.org/10.1109/TPWRS.2020.2967468).
17. Xiahou, K.S., Liu, Y., Li, M.S. and Wu, Q.H., "Sensor fault-tolerant control of DFIG based wind energy conversion systems", ***International Journal of Electrical Power and Energy Systems***, Vol. 117, (2020), Article 105563. (https://doi.org/10.1016/j.ijepes.2019.105563).
18. Fan, L., Kavasseri, R., Miao, Z.L. and Zhu, C., "Modeling of DFIG-based wind farms for SSR analysis", ***IEEE Transactions on Power Delivery***, Vol. 25, No. 4, (2010), 2073-2082. (https://doi.org/10.1109/TPWRD.2010.2050912).
19. Duong, M.Q., Grimaccia, F., Leva, S., Mussetta, M. and Ogliari, E., "Pitch angle control using hybrid controller for all operating regions of SCIG wind turbine system", ***Renewable Energy***, Vol. 70, (2014), 197-203. (https://doi.org/10.1016/j.renene.2014.03.072).
20. Naik, K.A., Gupta, C.P. and Fernandez, E., "Design and implementation of interval type-2 fuzzy logic-PI based adaptive controller for DFIG based wind energy system", ***International Journal of Electrical Power and Energy Systems***, Vol. 115, (2020), Article 105468. (https://doi.org/10.1016/j.ijepes.2019.105468).
21. Hossain, M.J., Pota, H.R. nad Ramos, R.A., "Improved low-voltage-ride-through capability of fixedspeed wind turbines using decentralised control of STATCOM with energy storage system", ***IET Generation,***

Transmission and Distribution, Vol. 6, No. 8, (2012), 719-730. (https://doi.org/10.1049/iet-gtd.2011.0537).

22. Merabet, A., Beguenane, R., Thongam, J.S. and Hussein, I., "Adaptive sliding mode speed control for wind turbine systems", ***Proceedings of the IEEE/IECON***, (2011), 2461-2466. (https://doi.org/10.1109/I-ECON.2011.6119696).
23. Hyun, S.H. and Wang, J., "Pitch angle control and wind speed prediction method using inverse input-output relation of a wind generation system", ***Journal of Electrical Engineering and Technology***, Vol. 8, No. 5, (2013), 1040-1048. (https://doi.org/10.5370/JEET.2013.8.5.1040).
24. Van, T.L., Nguyen, T.H. and Lee, D.C., "Advanced pitch angle control based on fuzzy logic for variable-speed wind turbine systems", ***IEEE Transactions on Energy Conversion***, Vol. 30, No. 2, (2015), 578-587. (https://doi.org/10.1109/TEC.2014.2379293).
25. Hosseini, E. and Shahgholian, G., "Different types of pitch angle control strategies used in wind turbine system applications", ***Journal of Renewable Energy and Environment (JREE)***, Vol. 4, No. 1, (2017), 20-35. (http://dx.doi.org/10.30501/jree.2017.70103).
26. Abidoye, L.K, Bani-Hani, E., Assad, M.E.H., AlShabi, M., Soudan, B. and Oriaje, A.T., "Effects of environmental and turbine parameters on energy gains from wind farm system: Artificial neural network simulations", ***Wind Engineering***, Vol. 44, No. 2, (2020), 181-195. (https://doi.org/10.1177/0309524X19849834).
27. Van, T.L., Dang, N.K., Doan, X.N., Truong, T.H. and Minh, H.N., "Adaptive fuzzy logic control to enhance pitch angle controller for variable-speed wind turbines", ***Proceedings of the 10th International Conference on Knowledge and Systems Engineering (KSE)***, Ho Chi Minh City, Vietnam, (2018), 225-229. (https://doi.org/10.1109/KSE.2018.8573332).
28. Hosseini, E. and Shahgholian, G., "Partial- or full-power production in WECS: A survey of control and structural strategies", ***European Power Electronics and Drives***, Vol. 27, No. 3, (2017), 125-142. (https://doi.org/10.1080/09398368.2017.1413161).
29. Wu, F., Zhang, X.P., Godfrey, K. and Ju, P., "Small signal stability analysis and optimal control of a wind turbine with doubly fed induction generator", ***IET Generation, Transmission and Distribution***, Vol. 1, No. 5, (2007), 751-760. (https://doi.org/10.1049/iet-gtd:20060395).
30. Yang, L., Xu, Z., Ostergaard, J. and Dong, Z.Y., "Advanced control strategy of DFIG wind turbines for power system fault ride through", ***IEEE Transactions on Power Systems***, Vol. 27, No. 2, (2012), 713-722. (https://doi.org/10.1109/TPWRS.2011.2174387).
31. Yang, L., Xu, Z., Ostergaard, I. and Dong, Z.Y., "Oscillatory stability and eigenvalue sensitivity analysis of a DFIG wind turbine system", ***IEEE Transactions on Energy Conversion***, Vol. 26, No. 1, (2011), 328-339. (https://doi.org/10.1109/TEC.2010.2091130).
32. Shaker, M.S. and Patton, R.J., "Active sensor fault tolerant output feedback tracking control for wind turbine systems via T–S model", ***Engineering Applications of Artificial Intelligence***, Vol. 34, (2014), 1-12. (https://doi.org/10.1016/j.engappai.2014.04.005).
33. Lin, W.M. and Hong, C.M., "Intelligent approach to maximum power point tracking control strategy for variable-speed wind turbine generation", ***Energy***, Vol. 35, No. 6, (2010), 2440-2447. (https://doi.org/10.1016/j.energy.2010.02.033).
34. Lin, W.M., Hong, C.M., Ou, T.C. and Chiu, T.M., "Hybrid intelligent control of PMSG wind generation system using pitch angle control with RBFN", ***Energy Conversion and Management***, Vol. 52, No. 2, (2011), 1244-1251. (https://doi.org/10.1016/j.enconman.2010.09.020).
35. Linus, R.M. and Damodharan, P., "Maximum power point tracking method using a modified perturb and observe algorithm for grid connected wind energy conversion systems", ***IET Renewable Power Generation***, Vol. 9, No. 6, (2015), 682-689. (https://doi.org/10.1049/iet-rpg.2014.0070).
36. Bhukya, J. and Mahajan, V., "Optimization of damping controller for PSS and SSSC to improve stability of interconnected system with DFIG based wind farm", ***International Journal of Electrical Power and Energy Systems***, Vol. 108, (2019), 314-335. (https://doi.org/10.1016/j.ijepes.2019.01.017).
37. Duong, M.Q., Grimaccia, F., Leva, S., Mussetta, M. and Ogliari, E., "Pitch angle control using hybrid controller for all operating regions of SCIG wind turbine system", ***Renewable Energy***, Vol. 70, (2014), 197-203. (https://doi.org/10.1016/j.renene.2014.03.072).
38. Hyams, M.A., 20- Wind energy in the built environment, Metropolitan sustainability: Understanding and improving the urban environment, Woodhead Publishing Series in Energy, (2012), 457-499. (https://doi.org/10.1533/9780857096463.3.457).
39. Lampinen, M.J., Kotiaho, V.W. and Assad, M.E.H., "Application of axial fan theory to horizontal-axis wind turbine", ***International Journal of Energy Research***, Vol. 30, No. 13, (2006), 1093-1107. (https://doi.org/10.1002/er.1208).
40. Shahgholian, G., "Analysis and simulation of dynamic performance for DFIG-based wind farm connected to a distrubition system", ***Energy Equipment and Systems***, Vol. 6, No. 2, (2018), 117-130. (https://doi.org/10.22059/ees.2018.31531).
41. Jafari, A. and Shahgholian, G., "Analysis and simulation of a sliding mode controller for mechanical part of a doubly-fed induction generator based wind turbine", ***IET Generation, Transmission and Distribution***, Vol. 11, No. 10, (2017), 2677-2688. (https://doi.org/10.1049/iet-gtd.2016.1969).
42. Mahvash, H., Taher, S.A. and Rahimi, M., "A new approach for power quality improvement of DFIG based wind farms connected to weak utility grid", ***Ain Shams Engineering Journal***, Vol. 8, No. 3, (2017), 415-430. (https://doi.org/10.1016/j.asej.2015.09.001).
43. Samanes, J., Gubia, E., Lopez, J. and Burgos, R., "Sub-synchronous resonance damping control strategy for DFIG wind turbines", ***IEEE Access***, Vol. 8, (2020), 223359-223372. (https://doi.org/10.1109/ACCESS.2020.3043818).
44. Shahgholian, G., Maghsoodi, M. and Movahedi, A., "Fuzzy proportional integral controller design for thyristor controlled series capcitor and power system stabilizer to improve power system stability", ***Revue Roumaine Des Sciences Techniques***, Vol. 61, No. 4, (2016), 418-423. (http://revue.elth.pub.ro/index.php?action=details&id=627).
45. Shahgholian, G., Maghsoodi, M., Mahdavian, M., Janghorbani, M,. Azadeh, M., and Farazpey, S., "Analysis of speed control in DC motor drive by using fuzzy control based on model reference adaptive control", ***Proceedings of the 13th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON)***, Chiang Mai, Thailand, (2016). (https://doi.org/10.1109/ECTICon.2016.7561239).
46. Ouyang, J., Tang, T., Yao, J. and Li, M., "Active voltage control for DFIG-based wind farm integrated power system by coordinating active and reactive powers under wind speed variations", ***IEEE Transactions on Energy Conversion***, Vol. 34, No. 3, (2019), 1504-1511. (https://doi.org/10.1109/TEC.2019.2905673).
47. Fooladgar, M., Rok-Rok, E., Fani, B. and Shahgholian, G., "Evaluation of the trajectory sensitivity analysis of the DFIG control parameters in response to changes in wind speed and the line impedance connection to the grid DFIG", ***Journal of Intelligent Procedures in Electrical Technology***, Vol. 5, No. 20, (2015), 37-54. (In Farsi). (http://jipet.iaun.ac.ir/index.php/images/article_555948.html?lang=en).
48. Hosseini, E. and Shahgholian, G., "Output power levelling for DFIG wind turbine system using intelligent pitch angle control", ***Automatika***, Vol. 58, No. 4, (2017), 363-374. (https://doi.org/10.1080/00051144.2018.1455017).
49. Sharmila, V., Rakkiyappan, R. and Joo, Y.H., "Fuzzy sampled-data control for dfig-based wind turbine with stochastic actuator failures", ***IEEE Transactions on Systems, Man, and Cybernetics: Systems***, Vol. 51, No. 4, (2021), 2199-2211. (https://doi.org/10.1109/TSMC.2019.2946873).