International Journal of Power Electronics and Drive System (IJPEDS)
Vol. 10, No. 3, Sep 2019, pp. xx~xx
ISSN: 2088-8694, DOI: 10.11591/ijpeds.v10.i3.pp-pg

The Fuzzy-PID Based-Pitch Angle Controller for Small-Scale Wind Turbine

Quang-Vi Ngo[1, 2], Chai Yi[2], Trong-Thang Nguyen[3]
[1]Faculty of Electronic and Electrical Engineering, Haiphong Private University, Vietnam
[2]College of Automation, Chongqing University, China
[3]Faculty of Electrical and Electronic Engineering, Thuyloi University, Vietnam

Article Info

Article history:

Received Apr 17, 2019
Revised Jul 22, 2019
Accepted Aug 3, 2019

Keywords:

Wind turbine
Pitch control
Fuzzy Logic
PID
Small-Scale

ABSTRACT

This paper aims to design the pitch angle control based on proportional–integral–derivative controller (PID) controller combined with fuzzy logic for small-scale wind turbine systems. In this control system, the pitch angle is controlled by the PID controller with their parameter is tuned by the fuzzy logic controller. This control system can compensate for the nonlinear characteristic of the pitch angle and wind speed. A comparison between the fuzzy-PID-controller with the conventional PID controller is carried out. The effectiveness of the method is determined by the simulation results of a small wind turbine using a permanent magnet generator (PMSG).

Corresponding Author:

Trong-Thang Nguyen,
Faculty of Energy Engineering, Thuyloi University,
175 Tay Son, Dong Da, Hanoi, Vietnam
Email: nguyentrongthang@tlu.edu.vn

1. INTRODUCTION

The wind energy is increasingly being studied by scientists around the world [1], [2], [3]. Especially, a Small-Scale Wind Turbine (SSWT) is an important research topic, because of the SSWT is a renewable, clean, sustainable power source. Electricity production from SSWT is installed in some far places such as islands with the decentralized grid systems [4], [5]. The exploitation of wind power based on pitch angle control is proposed through research [6], [7], [8]. The pitch angle control method can eliminate the elements such as a dump load [9], a passive pitch controller [10] and a furling system [11], so it reduces the system cost and the cumbersome while controlling wind turbines.

Pitch angle control of SSWT likes large-scale wind turbine systems. The change of the pitch angle depends on the two operating regions of the wind speed. The low-speed region is that the wind speed is lower than the norm wind speed. In this region, the turbine speed is controlled in order that the extracted energy from the wind turbine reaches a maximum. The high-speed region is that the wind speed exceeds the norm wind speed. In this region, the output power of the generator is limited in order that the norm value by controlling the angle of inclination due to the generator power and converter being limited in output power.

The conventional control method of pitch angle has been proposed in research [12], [13], it used the PI and PID controller. These controllers are widely used, but its disadvantage is that when the operating point is changed, the performance of the system deteriorates. These controllers have also been improved by nonlinear PI and PID controllers in the research [14], [15], but it is necessary to set up accurate mathematical models for wind-turbines, so it is difficult to implement in practice.

The predictive control model has been given in research [16], the future control signals are calculated based on the past and present signals to produce the appropriate pitch angle signals with reality. But this method has the disadvantage that when there is a large deviation in output power, the system will be unstable.

Another method used in the pitch angle control is the sliding control method, which is given in the paper [17]. This is a high speed method of pitch angle control system. However, the disadvantage of this method is that the efficiency of the system depends on the accuracy of the mathematical model of wind turbines and there is the chattering.

The adaptive controller has been given in research [18], the gain scheduling controller is used to adjust the PID parameters. This controller is built in order that the system works optimally in a certain sampling period, but the wind turbine model is nonlinear, so the times for determining the parameters of the controller are long.

Fuzzy logic control (FLC) was proposed to control of large-scale wind turbine systems [19], [20], [21], with the input parameters of the controller are generator power and wind speed. FLC method is reliable, sustainable with nonlinear characteristics of the pitch angle of wind turbines. However, this system needs a speed-sensor [22], [23], which increases the cost of the system.

There is very little research on pitch angle control of the SSWT system. The main research of SSWT only solves the limit of wind power capacity by methods such as a dump load, a passive controller and a furling system [9], [10], [11]. Therefore, in this research, the authors will design the fuzzy self-tuning of the PID controller for adjusting the pitch angle applied for SSWT. This control method is a combination of traditional PID control and fuzzy-logic control. It has the advantages of the PID controller, which are the fast response and the simple structure. It also has the advantages of the fuzzy controller because that the author's experience is included in the system. The results obtained by the Fuzzy self-tuning PID controller are compared to the traditional PID controller. The results show that the Fuzzy self-tuning PID controller has better properties.

2. THE WIND TURBINE SYSTEMS

2.1. The classification of turbine systems

The paper [5] showed that wind turbines with these diameters of 3m to 10m and powers of 1.4kW - 20kW are called SSWT. Table 1 shows the classification of the rotor diameter and the power range of horizontal axis wind turbine. The research object of this paper is the Household type.

Table 1: The classification of horizontal axis wind turbine [5]

Type		Rotor diameter (m)		Swept area (m^2)		Standard power rate (kW)	
Small sacle	Micro	0.5	1.25	0.2	1.2	0.004	0.25
	Mini	1.25	3	1.2	7.1	0.25	1.4
	Household	3	10	7	79	1.4	16
Small commercial		10	20	79	314	25	100
Medium commercial		20	50	314	1963	100	1000
Large commercical		50	100	1963	7854	1000	3000

2.2. The model of the wind turbine system

The torque of the turbine is calculated as follows [8]:

$$T_w = \frac{1}{2}\pi\rho R^3 \frac{C_P(\lambda,\beta)}{\lambda} v_w^2 \quad (1)$$

Where: ρ is the air density ($^{kg}/_{m^3}$); R is the radius of blade (m); v_ω is the wind speed (m/s); β is the pitch angle; λ is the tip-speed ratio.

The energy conversion coefficient C_P is determined by the following equation [24]:

$$C_P(\lambda,\beta) = c_1\left(\frac{c_2}{\lambda_i} - c_3\beta - c_4\right)e^{\frac{-c_5}{\lambda_i}} + c_6\lambda \quad (2)$$

Where:

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{1+\beta^3}$$

$$c_1 = 0.5176, c_2 = 116, c_3 = 0.4, c_4 = 5, c_5 = 21 \text{ and } c_6 = 0.0068$$

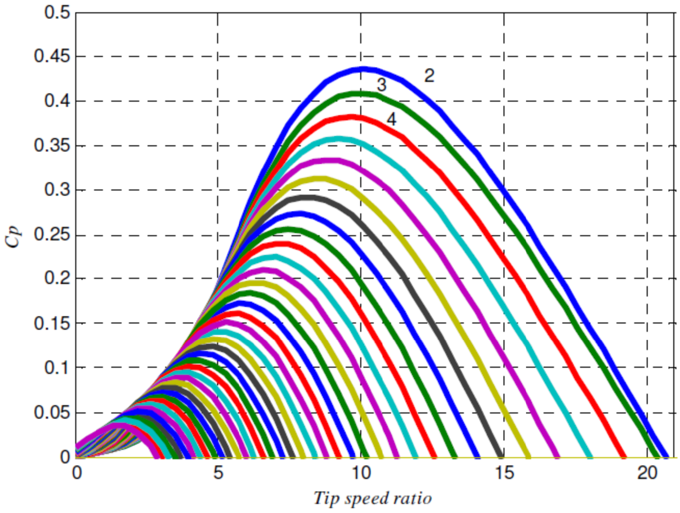
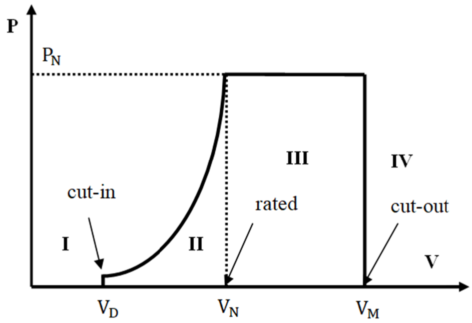


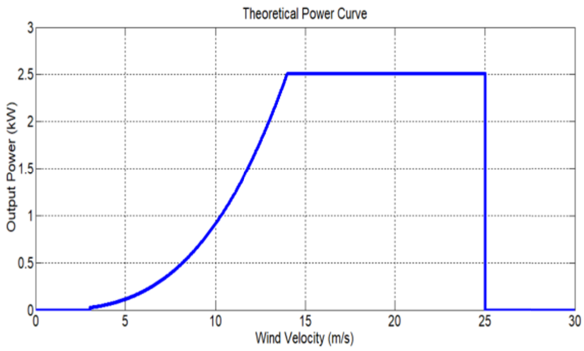
Figure 1. The power coefficient $C_P(\lambda, \beta)$

2.3. The characteristics of wind turbines

During operation, it is necessary to regularly adjust the speed of the turbine according to the speed of the wind and the energy into the blade of the turbine. The system work in order to receive the maximum energy at low wind speeds and at high wind speeds, and to ensure safety for turbine systems [21]. The characteristics of power depended the wind speed of the adjustment process are shown as Fig.2.



a) The power control regions of wind turbine P(V) [6,21,23]



b) The power control regions of wind turbine P(V) with the power of 2.5kW

Figure 2. The wind turbine power depending on wind speed

The operation of a turbine in Fig.2 has 4 main regions:

- The first region is that the wind speed is smaller than the cut-out wind speed of a turbine (V_D). In this case, wind turbines are inactive and do not generate electricity.
- The second region is the wind speed in the range (V_D, V_N). This is the optimal region of energy transformation where the wind speed is needed to control in order the system get the maximum power.
- The third region has increased wind power, but the turbine's power is limited by the rated power (P_N). In this region, the pitch angle control system will operate.
- In the fourth region, the wind speed exceeds the maximum speed that the turbine can withstand. The turbine will be stopped by the mechanical braking system to protect the system.

2.4. Identifying the control object of the pitch angle control system

The object must be controlled that is the hydraulic system or electromechanical devices [8]. We chose the motor servo for the pitch actuator for easy-to-adjust the characteristics as well as a simple mathematical model of simulation.

The pitch angle control with the pitch servo is modeled as an Integrator or a first-order delay system, with the time constant T_servo is in the range of *0.2 - 0.3 (s)* and β is in the range of -2 to 30 degrees [24].

The differential equation of the servo motor is as follows [20]:

$$\frac{d\beta}{dt} = -\frac{1}{T_{servo}}\beta + \frac{1}{T_{servo}}\beta_{ref} \quad (3)$$

The transfer function of a servo motor is as follows:

$$\frac{\beta(s)}{\beta_{ref}(s)} = \frac{1}{T_{servo}s + 1} \quad (4)$$

Where:

$$\beta_{min} \leq \beta \leq \beta_{max}$$
$$\dot{\beta}(t)_{min} \leq \dot{\beta}(t) \leq \dot{\beta}(t)_{max}$$

β_{min} and β_{max} are the minimum and maximum of pitch angles.

3. THE CONTROLLERS USED FOR THE SSWT

Today, because of the achievements of control science and technology, there are many types of conventional and modern controllers, which have met the requirement of control efficiency such as fuzzy, neuron, adaptive, optimization, predictive and sliding controllers. Special, PID and FLC are applied much to SSWT because it features simple structure and does not need to know the exact mathematical model of the object. These controllers have the following structure.

Conventional PID controller:

The PID controller adjusts the generator's rotor speed or the output power of generator by changing the pitch angle. The error signal of the generator speed or generator power is the input of the PID controller. The PID output signal (β_ref) is expressed as follows equation [21]:

$$\beta_{ref}(t) = K_P e(t) + K_I \int e(t)dt + K_D \frac{de(t)}{dt} \quad (5)$$

Where: K_P, K_I and K_D are the parameter of the PID controller.

The error signal *e(t)* is:

$$e(t) = -\omega_r^{ref}(t) + \omega_r(t) \quad (6)$$

Where: e is the error signal of generator speed, ω_r^{ref} is the reference speed and ω_r is the generator speed. The control system is shown in Fig.3.

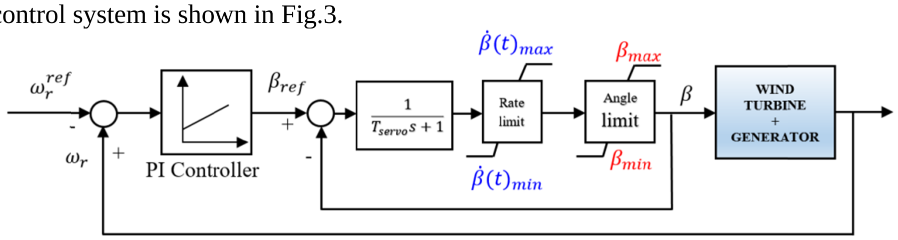


Figure 3. The control scheme of the pitch angle using the PID controller

Fuzzy logic controller (FLC):

The control scheme used fuzzy logic is shown as Fig.4. The output power of the generator or the wind speed is the input signal of the FLC [23], [25].

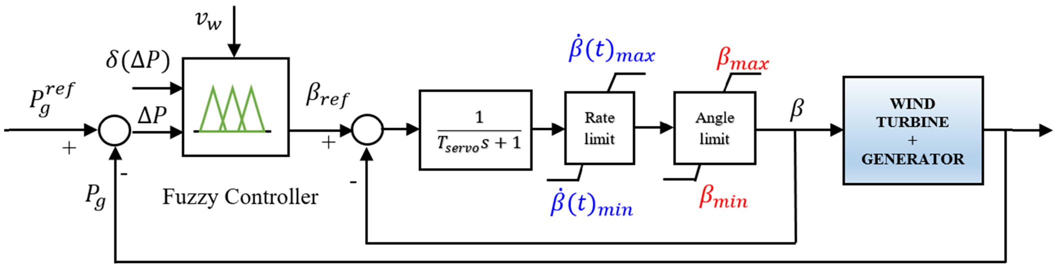


Figure 1. The control scheme of the pitch angle using the FLC

4. DESIGNING THE FUZZY-PID CONTROLLER FOR THE SSWT

FLC is based on the human experience through a set of experiential design rules, it also does not require the exact mathematical model of the control object. In this research, the authors design the Fuzzy-PID controller for a small wind turbine system. The control system is shown in Fig.5. The fuzzification of the input and output variables are shown in Fig.6. Input and output variables have triangular forms for higher sensitivity, especially when the variables reach zero. The width of the variable can be adjusted according to system parameters.

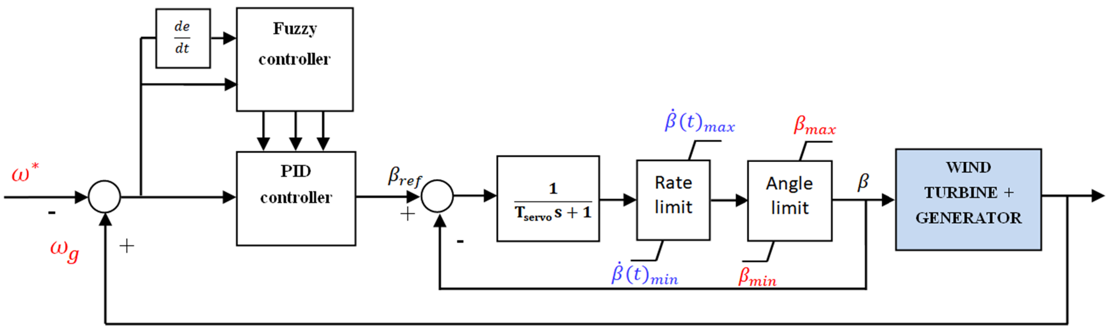


Figure 2. The pitch angle control system using the Fuzzy-PID controller

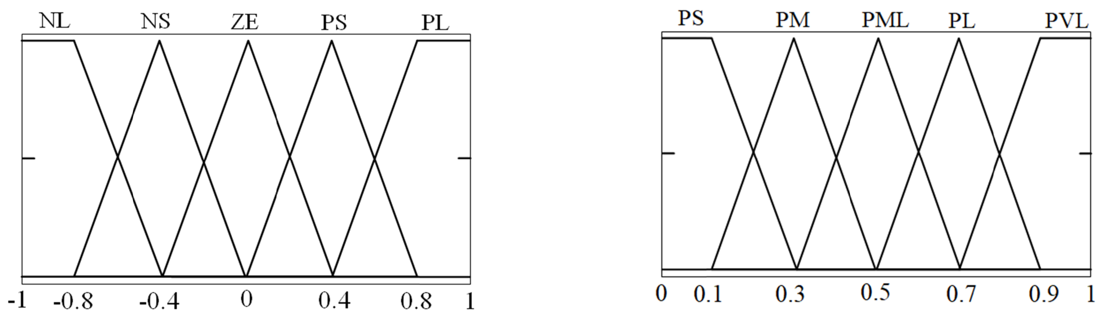
Design of a fuzzy controller has the following steps:

- Fuzzification: Converting the input variable from the real value to the fuzzy value.
- Setting the fuzzy logic rules "*if ...then*"
- Defuzzification: Converting output value from the fuzzy value to the real value for controlling the object.

The Fuzzy-PID the controller operates based on the error between of generator speed (ω_g) and MPPT speed (ω^*):

$$\Delta\omega = \omega_g - \omega^* \quad (7)$$

The input value has five linguistic levels with the following names: negative low (NL), negative small (NS), Zero (ZE), positive small (PS) and positive large (PL). The output value also has five linguistic levels with the following names: positive small (PS), positive medium (PM), positive medium-large (PML), positive large (PL), positive large (PL) and positive very-large (PVL). The authors propose 75 control rules for FLC which are shown in Table.3, Table 4, and Table 5. These control rules are defined by experience and expert knowledge of the authors.



a) The linguistic levels of input signal (e and $\dot{e}$) b) The linguistic levels of output signal (K_P, K_I, K_D)

Figure 3. The membership functions of the fuzzy logic controller

Table 2. The system responding when changing the parameters [26], [27]

	Overshoot	Settling time	Steady State error
Increasing Kp	Increase	Small Increase	Decrease
Increasing Ki	Increase	Large	Large Decrease
Increasing Kd	Decrease	Decrease	Minor Change

Table 3. The rule base for K_p tuner

Kp		e				
		NL	NS	ZE	PS	PL
$\dot{e}$	NL	PS	PS	PS	PM	PML
	NS	PS	PM	PM	PM	PML
	ZE	PS	PM	PML	PL	PL
	PS	PML	PL	PL	PL	PVL
	PL	PML	PML	PL	PL	PVL

Table 4. The rule base for K_i tuner

Ki		e				
		NL	NS	ZE	PS	PL
$\dot{e}$	NL	PVL	PVL	PVL	PM	PS
	NS	PVL	PL	PML	PML	PML
	ZE	PL	PL	PML	PS	PS
	PS	PL	PML	PL	PL	PVL
	PL	PML	PM	PS	PS	PS

Table 5. The rule base for K_d tuner

Kd		e				
		NL	NS	ZE	PS	PL
$\dot{e}$	NL	PS	PS	PS	PM	PML
	NS	PS	PM	PM	PML	PVL
	ZE	PM	PM	PML	PL	PL
	PS	PM	PML	PL	PL	PVL
	PL	PML	PML	PVL	PVL	PVL

Parameters of the wind turbine system and PMSG generator are shown in Table 6 and Table 7.

Table 6. The The parameters of small wind turbine

Rated power	Blade radius	Air density	Max.power conv. Coefficient	Cut-in speed	Cut–out speed	Rated wind speed
2.5(kW)	*1.65(m)*	*1.225(kg/m^3)*	*0.47*	*3(m/s)*	*25 (m/s)*	*14 (m/s)*

Table 7. The parameters of PMSG

Rated power	Number of pole-pares	Rotor speed (ω)	Stator resistance (R_s)	Stator inductance (L_s)	Permanent magnetic flux
2.5(kW)	*8*	104 (rad/s)	*0.36 (Ω)*	*1.2 (mH)*	*0.25 (Wb)*

5. THE SIMULATION RESULTS

Fig.7 shows the speed of the wind source from 10m/s to 16m/s. Fig.8 shows the speed of the generator, a comparison between the PID controller and Fuzzy-PID controller is given. In which, the red line is generator speed in the case of Fuzzy PID controller. The blue broken line is generator speed in the case of the PID controller. The result of Fig.8 shows that the Fuzzy PID controller has a less oscillation than the PID controller.

The output power of PMSG is shown in Fig.9. The power characteristic at the time *t=2s* show that the speed of the wind source is 10m/s, the output power of generator is still stable. In the case of low wind power, the Fuzzy-PID controller gives better output power than the PID controller.

The pitch angle of the turbine is shown in Fig.10. The result shows that when the wind power changes, the ability to set and stabilize the value of Fuzzy-PID controller is better than the PID controller.

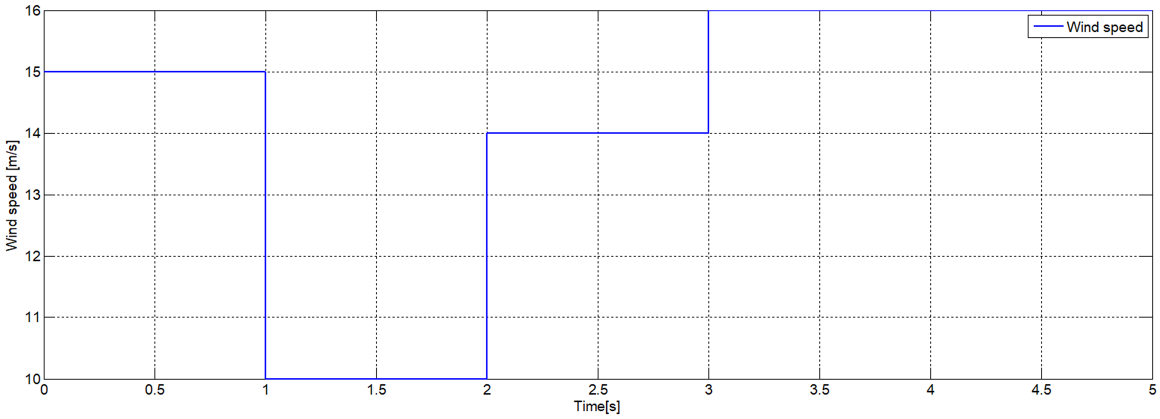


Figure 4. The wind source profile with wind speed is valid from 10m/s -16m/s

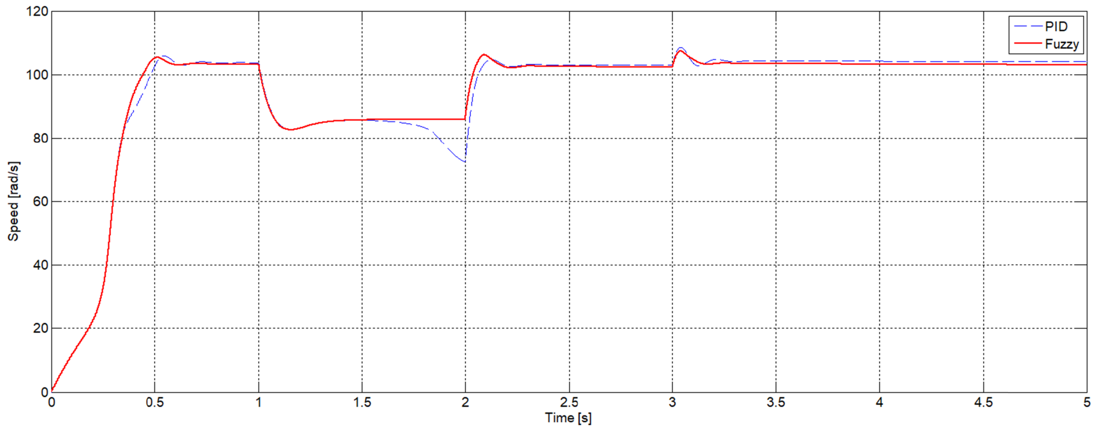


Figure 5. The generator speed of PMSG

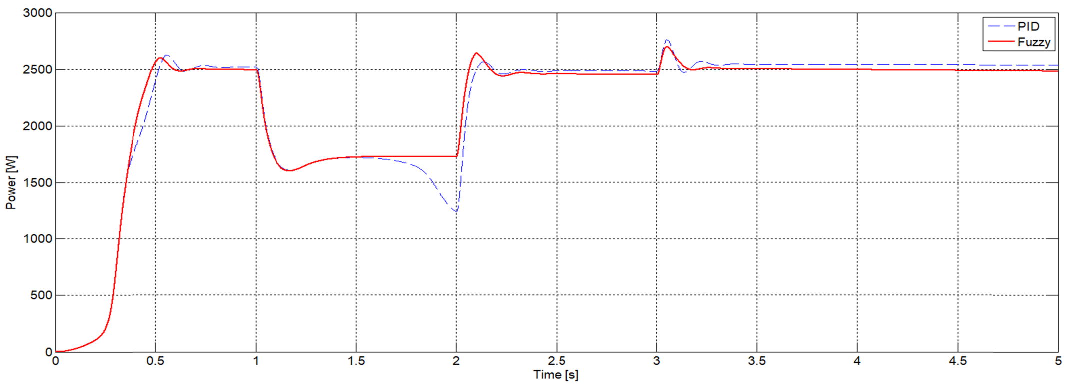


Figure 6. The output power of PMSG

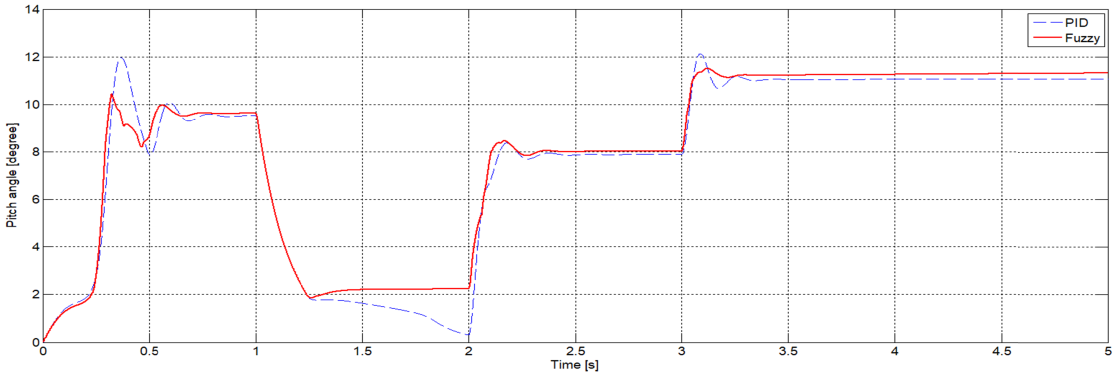


Figure.7. The pitch angle of wind turbine

6. CONCLUSION

The pitch angle control of the blade is the most common method to control the aerodynamic energy generated by the blades of wind turbines. The authors have successfully proposed the Fuzzy-PID-based controller for the pitch angle control of SSWT. This control system has removed the auxiliary systems such as the dump load, the passive pitch and the furling. In the research, a comparison between the Fuzzy- PID controller and the traditional PID controller is shown. The results show that the better characteristics of the Fuzzy-PID controller compared to the PID controller. Therefore, this proposal is necessary and practical.

REFERENCES

[1] BOUDERBALA, Manale, et al. Direct and indirect vector control of a doubly fed induction generator based in a wind energy conversion system. *International Journal of Electrical and Computer Engineering*, 2019, 9(3), pp. 1531-1540.

[2] Sakthi, S. S., Santhi, R. K., Krishnan, N. M., Ganesan, S., & Subramanian, S. (2017). Wind Integrated Thermal Unit Commitment Solution using Grey Wolf Optimizer. *International Journal of Electrical & Computer Engineering*, 7(5), pp. 2309-2320.

[3] RABYI, Kaoutar; MAHMOUDI, Hassane. Energy storage of DFIG based wind farm using D-STATCOM. *International Journal of Electrical and Computer Engineering*, 2019, 9(2), pp. 761-770.

[4] R. H. Eckstein, T. B. Lazzarin and I. Barbi, "Proposed power and control system for small scale wind turbines connected to the grid," *3rd Renewable Power Generation Conference (RPG 2014)*, Naples, 2014, pp. 1-6.

[5] Tummala A , Velamati R K , Sinha D K , et al. A review on small scale wind turbines. *Renewable and Sustainable Energy Reviews*, 2016, 56, pp.1351-1371.

[6] Rocha P A C , Carneiro d A J W , Lima R J P , et al. The effects of blade Pitch angle on the performance of small-scale wind turbine in urban environments. *Energy*, 2018, 148, pp. 169-178.

[7] Nagai B M , Ameku K , Roy J N . Performance of a 3 kW wind turbine generator with variable Pitch control system[J]. *Applied Energy*, 2009, 86(9), pp. 1774-1782.

[8] F. Scherillo, L. Izzo, D. P. Coiro and D. Lauria, "Fuzzy logic control for a small Pitch controlled wind turbine", *International Symposium on Power Electronics Power Electronics, Electrical Drives, Automation and Motion*, Sorrento, 2012, pp. 588-593.

[9] Hee-Sang Ko, Gi-Gap Yoon, Won-Pyo Hong and Juri Jatskevich, "Control of hybrid wind power generation system with dump load using advanced fuzzy-robust controller," *International Conference on Electrical Machines and Systems (ICEMS)*, Seoul, 2007, pp. 219-226.

[10] Chen Y J , Tsai Y F , Huang C C , et al. The Design and Analysis of Passive Pitch Control for Horizontal Axis Wind Turbine. *Energy Procedia*, 2014, 61, pp. 683-686.

[11] Audierne E , Elizondo J , Bergami L , et al. Analysis of the furling behavior of small wind turbines. *Applied Energy*, 2010, 87(7), pp. 2278-2292.

[12] Anwar M N , Pan S , Ghosh S . PI controller design for Pitch control of large wind turbine generator, *International Conference on Energy*. IEEE, 2016, pp.1-6.

[13] Hwas A , Katebi R . Wind Turbine Control Using PI Pitch Angle Controller. *IFAC Proceedings Volumes*, 2012, 45(3), pp. 241-246.

[14] Liu, X., Yu, W., Yang, L., & Ma, Q. (2017, October). Research on variable-pitch control strategy of wind turbine based on the nonlinear PID. *In 2017 Chinese Automation Congress (CAC)*, pp. 299-303.

[15] Ren Y , Li L , Brindley J , et al. Nonlinear PID control for variable Pitch wind turbine. *Control Engineering Practice*, 2016, 50, pp. 84-94.

[16] Pahasa J , Ngamroo I . Model predictive control-based wind turbine blade Pitch angle control for alleviation of frequency fluctuation in a smart grid, *Electrical Engineering Congress. IEEE*, 2014, pp. 1-4.

[17] Lee S H , Joo Y J , Back J , et al. Sliding mode controller for torque and Pitch control of wind power system based on PMSG, *International Conference on Control Automation & Systems. IEEE*, 2010, pp. 1079-1084.

[18] Luo Q , Yang Q , Han C , et al. Pitch angle controller of variable-speed wind turbine based on L1 adaptive control theory. *IEEE 2014 International Conference on Mechatronics and Control (ICMC) - Jinzhou*, China 2014, pp. 955-960.
[19] A. V. de Almeida Macêdo and W. S. Mota, Real time simulations of wind turbine with Pitch angle control using Fuzzy Logic, *11th IEEE/IAS International Conference on Industry Applications*, Juiz de Fora, 2014, pp. 1-7.
[20] A. Abir, D. Mehdi and S. Lassaad, Pitch angle control of the variable speed wind turbine, *17th International Conference on Sciences and Techniques of Automatic Control and Computer Engineering (STA)*, Sousse, 2016, pp. 582-587.
[21] A. S. Al-Toma, G. A. Taylor and M. Abbod, Intelligent Pitch angle control scheme for variable speed wind generator systems, *52nd International Universities Power Engineering Conference (UPEC)*, Heraklion, 2017, pp. 1-6.
[22] D. C. Vega, J. A. Marin and R. T. Sánchez, Pitch angle controllers design for a horizontal axis wind turbine, *IEEE International Autumn Meeting on Power, Electronics and Computing (ROPEC)*, Ixtapa, 2015, pp. 1-6.
[23] Jianzhong Zhang, Ming Cheng, Zhe Chen and Xiaofan Fu, Pitch angle control for variable speed wind turbines, *Third International Conference on Electric Utility Deregulation and Restructuring and Power Technologies*, Nanjing, 2008, pp. 2691-2696.
[24] T. L. Van, T. H. Nguyen and D. Lee, Advanced Pitch Angle Control Based on Fuzzy Logic for Variable-Speed Wind Turbine Systems, *IEEE Transactions on Energy Conversion*, 30(2), pp. 578-587.
[25] Naik, K. A., & Gupta, C. P. Fuzzy logic based pitch angle controller/or SCIG based wind energy system. *In Recent Developments in Control, Automation & Power Engineering (RDCAPE)*, IEEE, 2017, pp. 60-65.
[26] Trong T N , Tien B N , Thanh H N , et al. The Controller of DFIG Power Fed into the Grid Basing on the Rotor Similar Signal Method. *Applied Mechanics and Materials*, 2013, 415, pp. 245-249.
[27] Vaishnav, S. R., & Khan, Z. J. (2010). Performance of tuned PID controller and a new hybrid fuzzy PD+ I controller. *World Journal of Modelling and Simulation*, 6(2), pp. 141-149.