PAPER • OPEN ACCESS

Optimization of power output for a wind turbine using methods of artificial intelligence

To cite this article: N V Zubova and V D Rudykh 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **552** 012034

IOP Conf. Series: Materials Science and Engineering **552** (2019) 012034 doi:10.1088/1757-899X/552/1/012034

Optimization of power output for a wind turbine using methods of artificial intelligence

N V Zubova and V D Rudykh

Industrial Power Supply Systems Department, Novosibirsk State Technical University, Karl Marks Ave., 20, Novosibirsk, 630073, Russia

E-mail: zubova@corp.nstu.ru

Abstract. Percentage of wind energy in worldwide power generation increases year after year. At the present time, problems of increasing the energy efficiency of wind turbines (WT) and optimization of WT power output are of great importance due to instability of wind energy. It stimulates the development, investigation and using of intelligent systems for controlling operating regimes of wind turbines. Such systems also involve those systems that are developed using algorithms based on fuzzy logic. This paper presents the results of investigations devoted to searching for optimal membership functions for fuzzy sets of input and output variables. These variables and membership functions are used in fuzzy algorithms developed for enhancing power output of wind turbines under the given operating conditions. After analyzing the obtained results, it may be concluded that the use of symmetrical Gaussian membership functions gives the fastest convergence of the optimal power into the point.

Keywords: wind energy; energy efficiency; artificial intelligence; wind turbine; fuzzy logic; fuzzy sets; membership function; Mamdani algorithm; linguistic variables; fuzzy controller.

1. Introduction

Now, wind power engineering is being widely developed in different countries. Main designs of wind turbine nacelles, other power equipment, converters and inverters for wind turbines (WT) have been already studied. Therefore, investigations in this field are now directed to increasing the efficiency of WT operation to reduce the cost of power from wind energy, thus making wind turbines a competitive source of power related to power plants and units using the traditional fuel (i.e. coal, gas, diesel).

The most interesting way is the development of new intelligent control techniques that allow controlling WT power output depending on different operating conditions[1-3]. These control techniques can be realized by controllers based on fuzzy logic that allow controlling various WT loops, such as turning the nacelle to the wind, changing the angle of attack of the blade, changing the rotor speed, changing the blade length [4-6]. These devices have shown the better application in comparison with standard PI- and PID-controllers, because of having a regulating characteristic being close to the desired one [7-9].

A lot of publications are devoted to investigation and application of methods of artificial intelligence in wind power engineering [10-12]. Many of them contributed to this study.

This paper presents the results of the search for optimal membership functions with the help of controllers for the change of the WT rotor speed using the software package FuzzyLogicToolbox/Simulink/Matlab.

2. Materials and Methods

In any process, there are two main objectives of control – protection and optimization of operation. Being applied to wind turbines, the process of control is very important in different areas, because there is a problem of continually variable, intermittent and unpredictable nature of wind energy. Moreover, specific features of WT control systems differ depending on operating conditions (figure. 1).

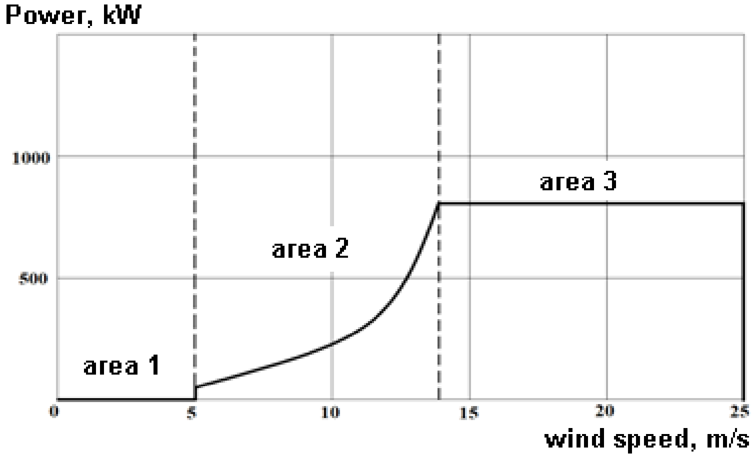

Figure 1. Energy characteristic of a wind turbine.

When a wind turbine is operated in Area 2, the change of the rotor speed is used as a control action for maximizing the useful wind energy to increase the WT energy efficiency. It is possible due to continuous acceleration or deceleration of generator rotation, thus achieving an optimal tip-speed ratio. At the nominal wind speed (Area 3), a control system limits a generator rotation speed. Therefore, generator control generally implies the optimization of wind energy conversion. In several cases, it means that generator torque is changing with the change of a wind speed that may result in additional mechanical loading on an actuator [13-15].

The present paper proposes determination of the most optimal membership functions of fuzzy sets of input and output variables that can be used in fuzzy logic algorithms of WT control loops for changing the rotor speed.

At the present time, instruments of fuzzy logic are widely used for solving the problem of increasing the energy efficiency of WT operating regimes [16-18]. Algorithms have shown good capability of maintaining the stability of network parameters and have increased the quality of energy output [19-21]. By now, several fuzzy inference systems (algorithms) has been proposed. In the present paper, investigations have been carried out using the Mamdani algorithm, which general distinctions from other algorithms are given below:

Activation is realized using the MIN-activation method;

Accumulation for combination of fuzzy sets, corresponding to terms of subconclusions related to the same output linguistic variables, is calculated as [22]:

$$\mu_{AB}(x) = \max\big(\mu_A(x), \mu_B(x)\big). \tag{1}$$

Defuzzification of output parameters is performed using the center of gravity (CoG) method or the center of area (CoA) method [22]. Defuzzification by the COG method is performed in the following way:

IOP Conf. Series: Materials Science and Engineering **552** (2019) 012034 doi:10.1088/1757-899X/552/1/012034

$$y = \frac{\sum_{i=1}^{n} x_i \mu(x_i)}{\sum_{i=1}^{n} \mu(x_i)}, \quad (2)$$

where y – result of defuzzification, x – variable corresponding to the output linguistic variable ω, μ(x) – membership function of the fuzzy set corresponding to the output variable ω after accumulation.

The structure of a fuzzy controller is illustrated in figure 2.

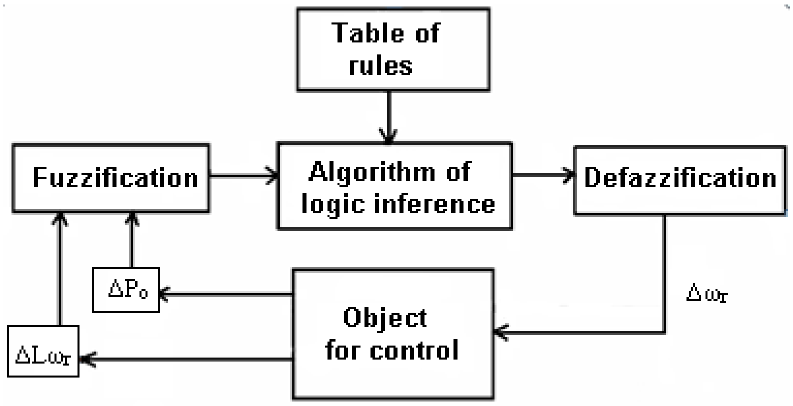

Figure 2. Structure of the algorithm for realization of generator speed control based on a fuzzy inference (ΔP_o – the change of an output power, $\Delta L\omega_r$– a step for the change of a generator speed, $\Delta\omega_r$ – the change of an output generator speed).

Figure 3 illustrates the variety of energy characteristics of a wind turbine depending on a WT wheel rotation speed and a wind speed.

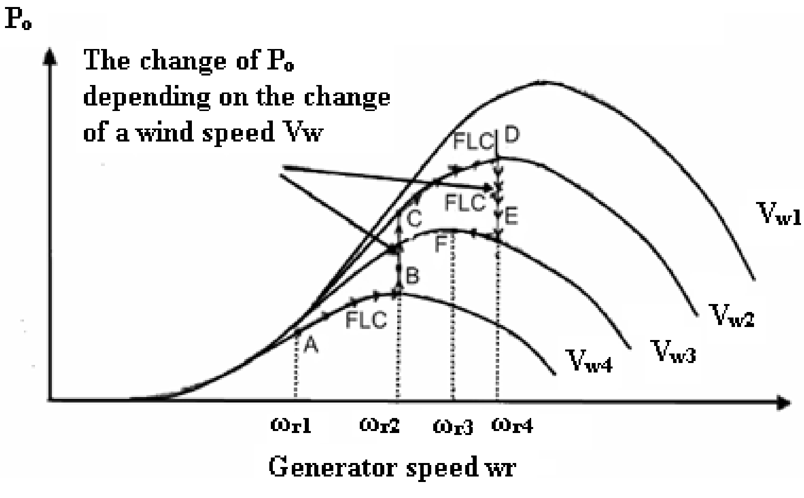

Figure 3. Dependence of output power on generator speed at various wind speeds.

It should be noted that an operating point, where the output power is maximum, has a different position for each wind speed. The main objective of control is to force a wind turbine generator to operate at this point. The change of a membership function allows achieving the maximum possible power at each wind speed.

IOP Conf. Series: Materials Science and Engineering **552** (2019) 012034 doi:10.1088/1757-899X/552/1/012034

The algorithm based on fuzzy logic for maximization of WT power generation is proposed in [23]. For certain values of a wind speed, an optimal generator speed is determined using the algorithm, until the system reaches the point of maximum power generation. For example, if generator speed is ω_{r1}, then an output power is in point A at wind speed V_{w4}. Based on a fuzzy logic inference, a generator speed is changing, until it reaches speed ω_{r2}, at which an output power has the maximum value (point B). If a wind speed increases up to V_{w2}, an output power will move to point C, then, according to the algorithm, an operating point will move to point D, thus changing a generator speed to ω_{r4}. The strategy for changing a wind speed is similar. If a wind speed decreases to V_{w3}, an output power will change and move to point E. A generator speed will decrease to the optimal value of ω_{r3} (point F), where an output power has the maximum value.

Input variables, the change of an output power ΔP_o and the following change of a generator speed $L\omega_r$, are firstly converted into corresponding fuzzy sets having human descriptive and intuitive values in the form of terms, such as "big", "medium", "small", "zero". This is realized in the "fuzzification block", where variables ΔP_o (the change of an output power), $\Delta\omega_r$ (the change of a generator speed) and $L\Delta\omega_r$ (the following change of a generator speed) are described by corresponding membership functions.

3. Results and Discussion

Under the present study, the algorithm was investigated with the use of a piecewise linear function (figure 4), a sinusoidal function (figure 5) and a Gaussian function (figure 6) [22]. Rules of a logic inference are applied using the following principle: "if the last change of an output power ΔP_o during the search for the maximum power is positive and big and the last change of the desired generator speed $L\Delta\omega_r$ is positive, then monitoring for the maximum power will be continued with the same positive direction with the big increase of $\Delta\omega_r$". Similar rules are included in the block "table of rules" and given in table 1.

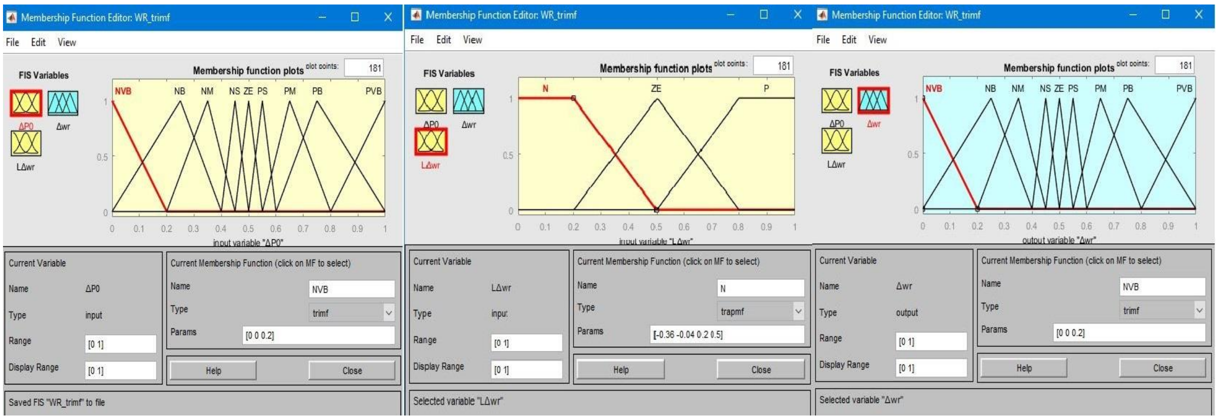

Figure 4. Piecewise linear (triangular) membership functions of input variables ΔP_0, $L\Delta w_r$ and an output variable Δw_r for the algorithm based on fuzzy logic, controlling the change of a rotor speed.

To clarify the designations presented in Table 1, their definition should be done for the change of input and output variables: PVB – Positive Very Big, PBIG – Positive Big, PMED – Positive Medium, PSMA – Positive Small, ZE – Zero (no changes), NSMA – Negative Small, NMED – Negative Medium, NBIG – Negative Big, NVB – Negative Very Big, P – Positive, ZE – Zero (no changes), N – Negative change, respectively.

As a result, output fuzzy sets demonstrating the change of a generator speed $\Delta\omega_r$ are transmitted into the "defuzzification block" where they are converted into the real values [24]. It means that output variables, such as "BIG", "MEDIUM", "SMALL", are converted into the numbers indicating measurable (normalized) values of a generator speed.

The choice of the optimal membership function is the fastest achievement of the operating point, at which the generated power has the maximum value.

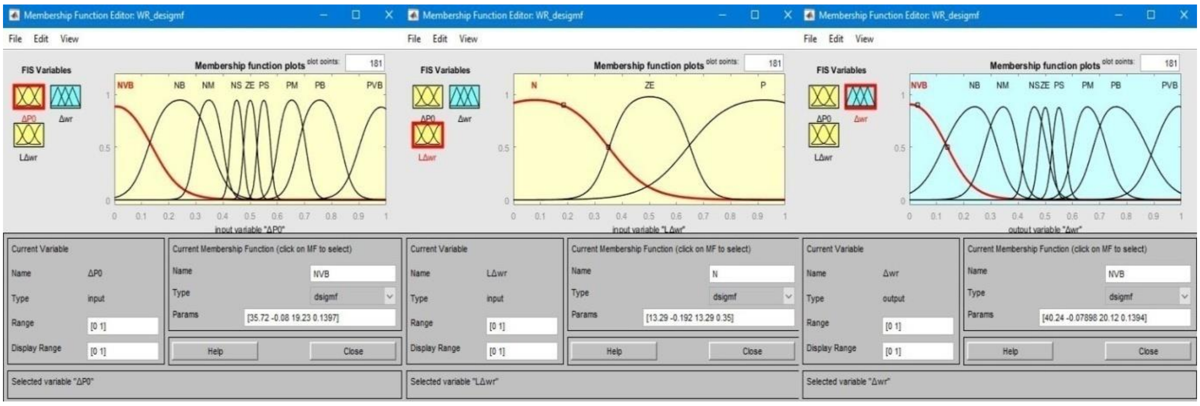

Figure 5. Sigmoid membership functions of input variables ΔP_0, $L\Delta w_r$ and an output variable Δw_r.

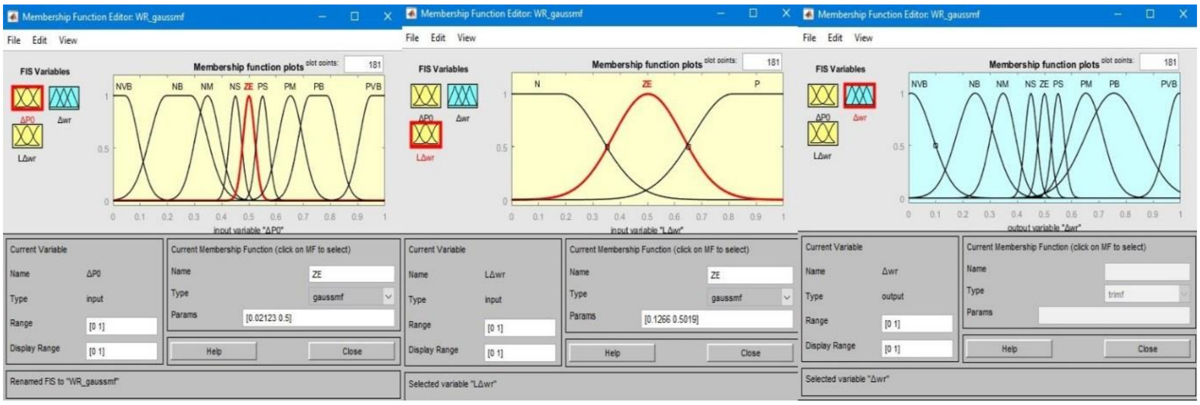

Figure 6. Gaussian membership functions of input variables ΔP_0, $L\Delta w_r$ and an output variable Δw_r.

Table 1. Rules for the algorithm based on fuzzy logic.

Δw_r \ ΔP_0	P	ZE	N
PVB	PVB	PVB	NVB
PBIG	PBIG	PVB	NBIG
PMED	PMED	PBIG	NMED
PSMA	PSMA	PMED	NSMA
ZE	ZE	ZE	ZE
NSMA	NSMA	NMED	PSMA
NMED	NMED	NBIG	PMED
NBIG	NBIG	NVB	PBIG
NVB	NVB	NVB	PVB

Experiments conducted in FuzzyLogicToolbox/Simulink/Matlab have shown that, assuming that input variables are equal, the most optimal change of an output generator speed $\Delta\omega_r$ is achieved by using a symmetrical Gaussian membership function. This result shows that, if using this function, the system can move to the point of the maximum power output in the fastest way.

The path to the fuzzy algorithms was registered from fuzzy controllers embedded in the control system of a wind turbine in a model built using Simulink/ Matlab (figure 7).This made it possible to evaluate their performance directly in the control system with specified constraints. The program uses a generator with a rated power of 1.5 MW [25].

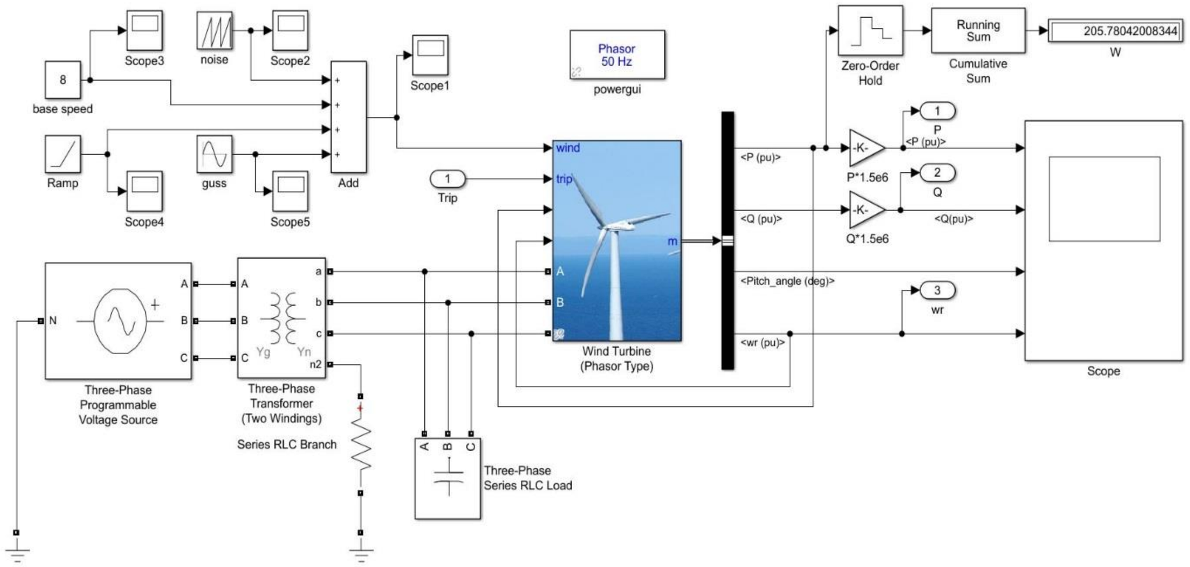

Figure 7. General view of the wind turbine model in Simulink/Matlab.

The unit for changing the rotor speed using an algorithm based on fuzzy inference is presented in figure 8. A fis-file is connected to the "Fuzzylogiccontrollerwr" block, which contains information about the corresponding control action. Input values are fed to the controller input: the last change of power and the last change of the rotor speed of the generator. In accordance with the characteristic of changes in power output of wind turbine depending on the rotor speed at various wind speeds, it is obvious that in order to reach the maximum power output: when the wind speed increases, an increase in the rotor speed should be observed and the rotor should slow down as the wind speed decreases.

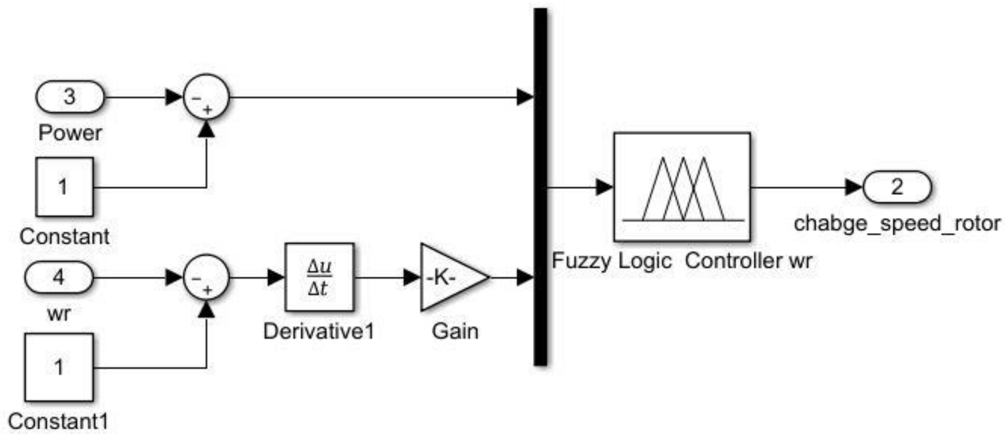

Figure 8. The control unit changes the speed of rotation of the rotor.

Table 2 shows the data of the generated energy for the same time interval under the condition of the same variability of the wind flow for different membership functions.

Table 2. Energy generated by wind turbine for different membership functions of the rotor speed controller

Membership function	W_{WT}, r.u.
Triangular	201.357
Sigmoid	202.986
Gaussian	205.781

For "Fuzzylogiccontrollerwr", there is an increase in the energy output of the wind turbine when using the Gaussian membership function with all other conditions being equal. This result shows that when using this function, the system comes to the point of maximum power generation faster than using other functions.

4. Conclusion

Advantages of fuzzy control are evident. It provides the desired step size during the search that gives fast convergence. In addition, a controller can operate with inaccurate and distorted signals. Controllers based on fuzzy logic, which membership functions of fuzzy sets of input and output variables are defined by the Gaussian distribution, can provide the maximum energy efficiency of wind turbines due to the fast tracking of the maximum power point.

Acknowledgments
The reported study was supported by Russian Foundation for Basic Research, research project No. 31 16-38-60080\15 mol_a_dk.

References

[1] Petković D 2014 Adaptive neuro-fuzzy maximal power extraction of wind turbine with continuously variable transmission *Energy* **64** pp 868 – 74
[2] Petković D, Shamshirband S, Anuar N B, Naji S, Miss L. Mat Kiah and Gani A 2015 Adaptive neuro-fuzzy evaluation of wind farm power production as function of wind speed and direction *Stochastic Environmental Research and Risk Assesment* **29(3)** pp 793 – 802
[3] Bing H, Lawu Z., Yang F and Xiang Z 2016 Individual Pitch Controller Based on Fuzzy Logic Control for Wind Turbine Load Mitigation *IET Renewable Power Generation* **10 (5)** pp 687-93
[4] Bharani R and Jayasankar K C 2015 Yaw Control of Wind Turbine Using Fuzzy Logic Controller *Power Electronics and Renewable Energy Systems* **326** pp 997-1006
[5] Macêdo A V and Mota W S 2012 Wind turbine pitch angle control using Fuzzy Logic *Transmission and Distribution: Latin America Conference and Exposition* **4**
[6] Hossain A 2013 Energy efficient wind turbine system based on fuzzy control approach *5th BSME International Conference on Thermal Engineering* **56** pp 637 – 42
[7] Udalov S N 2016 *Vozobnovlyayemaya energetika* [Renewable power engineering] (Novosibirsk: NGTU) [In Russian]
[8] Aissaouia A G, Tahourb A, Abida M, Essounboulic N and Nollet F 2013 Power control of wind turbine based on Fuzzy controllers *Energy Procedia* **42** pp 163-72
[9] Suganthi L, Iniyan S and Samuel A 2015 Applications of fuzzy logic in renewable energy systems *Renewable and Sustainable Energy Reviews* **48** pp 585-607
[10] Badran O, Abdulhadi E and El-Tous Y 2011 Fuzzy logic controller for predicting wind turbine power generation *International Journal of Mechanical and Materials Engineering (IJMME)*

6(1) pp 51-66
[11] Farh H M and Eltamaly A M 2013 Fuzzy logic control of wind energy conversion system *Journal of Renewable and Sustainable Energy* **5(2)**
[12] Shamshirband S, Petković D, Hashim R and Motamedi S 2014 Adaptive neuro-fuzzy methodology for noise assesment of wind turbine *PLoS ONE* **9(7)** p 9
[13] Rocha M M, Patrocinio da Silva J and Barbosa de Sena F das Ch 2018 Simulation of a Fuzzy Control Applied to a Variable Speed Wind System Connected to the Electrical Network *IEEE Latin America Transactions* **16(2)** pp 521-6
[14] Costa P J, Carvalho A S and Martins A J 2010 Fuzzy Logic as a Method to Optimize Wind Systems Interconnected with the Grid *Wind Power Systems, Green Energy and Technology* pp 383–405
[15] Elkhadiri S, Pr. Lamiaa Elmenzhi and Pr. Abdelouahid Lyhyaoui 2018 Fuzzy logic control of DFIG-based wind turbine *International Conference on Intelligent Systems and Computer Vision (ISCV), IEEE Conferences* pp 1-5
[16] Elfergani A, Elsharif M A A, Hamd R H A, Saad M, Naser El Naily and Faisal A. Mohamed 2018 Advanced self-tuned pitch angle control based on fuzzy logic for grid connected variable-speed wind turbine system *9th International Renewable Energy Congress (IREC), IEEE Conferences* pp 1-6
[17] Shrinath K, Paramasivam S and Palanisamy K 2017 An intelligent self-tuning fuzzy logic controller for pitch angle control for a wind turbine fed induction generator *Innovations in Power and Advanced Computing Technologies (i-PACT), IEEE Conferences* pp 1 – 5
[18] Sahoo S, Subudhi B and Panda G 2016 Pitch Angle Control for Variable Speed Wind Turbine Using Fuzzy Logic *International Conference on Information Technology (ICIT), IEEE Conferences* pp 28-32
[19] Pamuji F A and Miyauchi H 2016 A new control design of maximum power point tracking by fuzzy logic controller for wind turbine connected to low voltage grid *International Seminar on Intelligent Technology and Its Applications (ISITIA), IEEE Conferences* pp 369-72
[20] Ana Vitoria de Almeida Macêdo A V A and Wellington S M 7-10 Dec. 2014 Real time simulations of wind turbine with pitch angle control using FuzzyLogic *11th IEEE/IAS International Conference on Industry Applications* pp 1-7
[21] Van T L, Nguyen T H and Lee D C 2015 Advanced Pitch Angle Control Based on Fuzzy Logic for Variable-Speed Wind Turbine Systems *IEEE Transactions on Energy Conversion* **30(2)** pp 578-87
[22] Leonenkov A V 2005 *Nechetkoye modelirovaniye v MATLAB i fuzzyTECH* [Fuzzy modeling in MATLAB and fuzzyTECH] (St. Petersburg: BHV) p 736 (In Russian)
[23] Adzic E, Ivanovic Z, Adzic M and Katic V 2009 Maximum Power Search in Wind Turbine Based on Fuzzy Logic Control *Acta Polytechnica Hungarica* **6(1)** pp 131– 49
[24] Bimal K and Ronald J 1997 Fuzzy logic based intelligent control of a variablespeed cage machine wind generation system *IEEE Transactions on powerelectronics* **12** No.1 pp 87-95
[25] 2018 S D Shtovba "Vvedenie v teoriyu nechetkix mnozhestv i nechetkuyu logiku" [Introduction to the theory of fuzzy sets and fuzzy logic] URL http://matlab.exponenta.ru