Comparison of Interval Type-2 Fuzzy Logic Controller with PI Controller in Pitch Control of Wind Turbines

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Abstract-Pitch control of a wind turbine is important in its designing, optimizing the generator output power, and reducing the fatigue load of its inner parts. Moreover, pitch control is applied to eliminate possible dangers due to an unpredicted increase of wind speed, and consequently, sudden increase of the output power. The most common approach is to change the rotor speed through adjusting its blades angle with applying PID controllers. Regarding irregular winds and nonlinear behavior of blades in wind turbines, designing PID controllers would be difficult. Therefore, fuzzy controllers have been used in the most recent methods. A point of note in the present study is applying Interval Type-2 Fuzzy Logic (IT2FL) in designing fuzzy controllers instead of PID controllers to work around nonlinearity of the pitch control problem. IT2FL controllers have all the benefits of Type-1 fuzzy controller, i.e. independency from the model of the studied system. In addition, IT2FL theory shows uncertainties of the parameters better than Type-1 and causes more accurate results. In comparison with previous methods, our results indicated that applying IT2FL along with the maximum number of influential parameters in regulating the wind turbine output power has made the blades to change their angle at the right time, and has resulted in proper rotor speed adjustment, and consequently, of the output power. Furthermore, results presented that the IT2FL controller in compare with PI controller has better improvement in adjustment of pitch angle, and also in control of the rotor speed and the output power to achieve rated power of the generator.

Key Words: Wind Turbine, Pitch Control, Interval Type-2 Fuzzy Logic, PI Controller.

1. Introduction

Environmental pollution and energy shortage have put development of technologies of generating clean and renewable energy at the first priority. Among all, wind energy has more become under focus. Generating Electrical energy from wind goes to 100 years back. Initial motivation in studying power generation from wind was to mechanize agriculture. Increased amount of Electrical energy produced from wind energy reflects the significance of using wind energy in comparison with other renewable energies [3]. Regarding the significance of wind energy, wind turbines have been built in different shapes to harness this energy. The first type of wind turbines was designed in Ohio in 1888, and the first 100-kw wind turbine started to work in a 6300-volt local network in YALTA, a city in southern part of Ukraine [4]. In 2006, the capacity of generating Electrical energy from wind turbines was estimated to be 75 Giga Watts, roughly 1% of the whole consumption of energy in the world [4].

In view of the increasing use of wind turbines in the world, and their increased capacity of generating Electrical energy, it is substantially needed to control output power of each turbine to maximize the energy production and ensure safety.

Most of the modern wind turbines have horizontal axis with three blades, Horizontal Axis Wind Turbine (HAWT), usually mounted upwind at the top of towers [5] with an anemometer at the top of the nacelle to measuring wind speed for multiple purposes [6]. Wind turbines are mounted not separately, but along with each other in a wind park or farm, making a network of the capacity of generating hundreds of Mega Watts. In these new wind turbines, to increase the size and output power, optimize the output power for preventing the generator from overloading or from suddenly reducing the output power, pitch control method is applied [7]. In this method, rotor speed is changed through changing the blade angle.

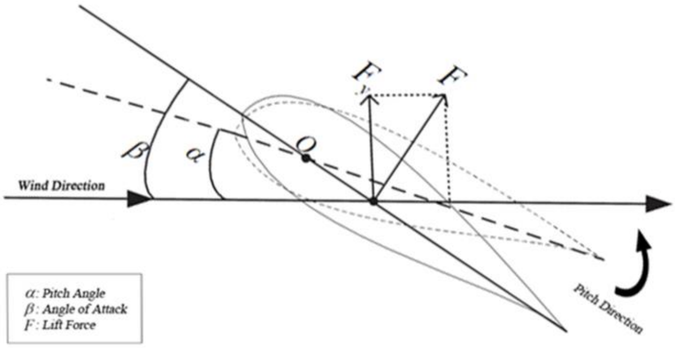


Fig. 1.Relation between the Pitch Angle and the Angle of Attack [1]

Therefore, the angle of the rotor blades is changed around its longitudinal axis through using a pitch controller. This method is mostly implemented through PID controllers with the use of functions like gain scheduling [8]. Neural networks [9] and network training have also been used for this purpose [10], while simpler and more cost-effective methods could also be found to control such process, which is strongly nonlinear due to aerodynamic behavior of rotor blades and irregular compression of wind (wind speed changes). One approach is to adjust pitch angles of turbines with the use of fuzzy controllers [11, 12] as a novel system [13]. To design a fuzzy controller, depends on circumstance, different algorithms like PSO (Particle Swarm Optimization) can be used [14]. When wind's speed is less than the allowed predicted value, the pitch angle is reduced, and then, the angle between the wind direction and blade surface, called the angle of attack, is increased so that wind's power is optimally used, and the lift force is increased. On the other hand, when wind's speed exceeds a predicted threshold, the pitch angle is increased so that the angle of attack is reduced to become zero. This results in lowering the lift force and rotor speed to prevent possible dangers. Similar to the present work, the definition of the pitch angle is dependent upon the pitch design or the rotation direction of the pitch actuator. To understand the function of the pitch angle, either its increase or its decrease is considered to be at the same direction that the angle of attack is increased or decreased (Fig. 1).

A fuzzy type-1 controller can bring about the desired change in the pitch angle without any ambiguity or complexity [15]. Interval type-2 fuzzy logic (IT2FL) controllers have all the benefits of Type-1 fuzzy controller, i.e. independency from the model of the studied system. In addition, IT2FL theory shows uncertainties of the parameters better than Type-1 and causes more accurate results. The aim of the present study is to obtain the suitable angle by the use of the designed controller based on the IT2FL Theory. In the first step, the pitch control system and the relation of the controller to other components are identified. In the next step, the controller will be designed in full details and finally, the performance of our controller in comparison to the most common controller which is PI controller, will be evaluated.

2. Research Methodology

2.1. Pitch Control in Wind Turbines

Fig. 2 presents the general illustration of a pitch control system in wind turbines. After obtaining the suitable angle for pitch adjustment from the current values of the wind speed, rotor speed, and output power, the obtained angle is sent to pitch actuators. Then, the blades are rotated to their suitable positions with respect to the wind speed value, and the required lift and drag forces fitting to the current positions of the rotor blades is applied to them by the wind, and the torque required to be applied to the blades is adjusted. This torque is transferred through the gearbox to the generator within the nacelle so that the output power is adjusted.

2.2. Interval Type-2 Fuzzy Logic Controller

Modern turbines are made of three main mechanical, electronic, and software components, making a complete mechatronic system [16]. Fuzzy controllers are discussed as the software component of wind turbines, functioning based on fuzzy logic rules, and a form of multi-value logic. Type-2 fuzzy logic systems are more complicated and harder to understand as compared to classic fuzzy logic systems (type-1). Though type-1 fuzzy logic systems can be applied to uncertain inputs, they have limited applicability for different kinds of these inputs which are related to a knowledge database [17]. Therefore, the type-2 fuzzy logic is more general than the type-1. Generally, a fuzzy system is a function mapping input variables to out variables. This mapping is done with the use of a knowledge base made of fuzzy rules. These rules represent general adjustments of systems of type-2 fuzzy logic. In type-2 fuzzy logic, each input variable is related to one or more fuzzy sets called type-2 fuzzy sets. These sets are

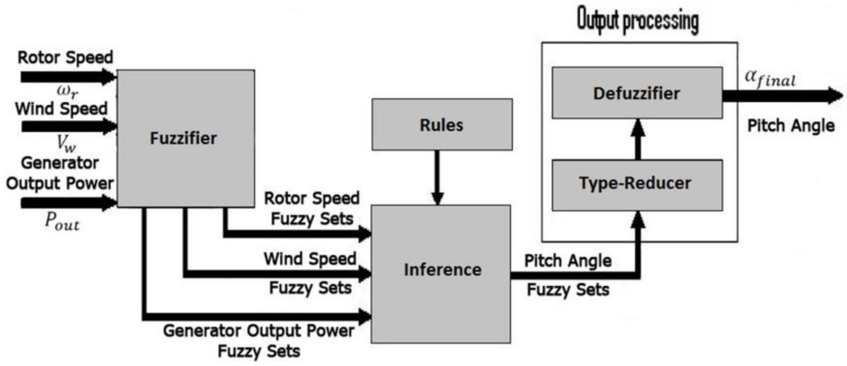


Fig. 3.The structure of the inference system of the fuzzy controller

composed of different elements. Indeed, when we cannot identify the membership degree of an element in a set based on 0 and 1, we need to use type-1 fuzzy sets; similarly, when the membership degree of an element can be hardly identified with a number in the range 0-1, type-2 fuzzy sets are used. Moreover, type-1 and type-2 fuzzy sets are respectively viewed as first- and second- order approximations for identifying uncertainty [18]. These sets indicate the concept of uncertainty related to ideas given by experts in the field under consideration, but this uncertainty involves to complicate calculations. To tackle this problem, Interval type-2 fuzzy sets are used. Indeed, the fuzzy sets used for linguistic variables in type-2 fuzzy logic of range-type are limited between maximum and minimum values of type-1 fuzzy sets, respectively named as the maximum ($\overline{X}$) and minimum ($\underline{X}$) membership functions; the range between these two values is called footprint of uncertainly (FOU) [19]. Linguistic variables in fuzzy logic are managed with the use of specific functions used for input and output variables. Functions of input variables are mapped to their corresponding functions of output variables using some rules and depend on the fuzzy inference system. After undergoing type reduction and defuzzification as the final step in the fuzzy inference process, the resulted values in outputs are converted into crisp value acceptable for using and suitably controlling outputs [20].

In Fig. 3, the wind speed (V_w), the feedback of the current rotor speed (ω_r), and the feedback of the current value of the output power (P_{out}) are specified as controlling inputs, and the pitch angle (α_{final}) is defined as the output. Up to this stage, the system and its complicacy have not been considered; therefore, a fuzzy controller is suitable, when we do not know the dynamic of the system, or it has some nonlinear characteristics, similar to effects of irregular wind speeds. In advanced methods of controlling, reducing the fatigue load in the system has also been taken into account. Fuzzy controllers' logic is based on human decision-making behavior, and therefore, their rules include experience and expertise of the people who are knowledgeable about the system under consideration, which helps reduce the fatigue load.

2.3. Wind Turbine Characteristics

To define the range of values of each linguistic variable, and to observe simulation's results, 2-MW wind turbine from Vestas® Company with the characteristics given in Table 1 has been considered. The Cut-in Wind Speed is the speed below which no power can be obtained from the wind turbine. The Nominal Rotor Speed and the Rated Wind Speed are respectively the speeds of the rotor and the wind, at which the wind turbine is working with highest possible power and safety. The maximum speed predicted to satisfy these conditions is called the Cut-out Wind Speed, more than which is unnecessary for the wind turbine.

The maximum speed of the wind tolerable by the turbine, called the Survival Wind Speed, is the speed more than which bring irreparable damages to the turbine. The Nominal Output Power of the Generator is the suitable output power defined for the wind turbine. The Maximum Output Power of the Generator is the maximum output obtainable by the generator, more than which brings damage to the generator.

2.4. Linguistic Variables, Values And Types

Here we have four main linguistic variables, three of which are input variables, including the wind speed measured by an anemometer, the generator output power, and the rotor speed regulated based on the operation speed of the wind turbine. The only linguistic variable at the output is the pitch angle.

Following tables (tables 2 to 5) give the types and numerical ranges of these linguistic variables based on table 1.

2.5. Fuzzy Sets Determination

To define a fuzzy set for variables, different functions of different forms can be used, depending on the nature of the variable and the expected results. The most common forms are triangular and trapezoidal functions representing the knowledge of the expert on the variable, and making the calculations simpler. However, to improve the

Table 1.The characteristics of the wind turbine [2]

Parameter Name (Unit)	***Value***
Rotor Diameter (Meter)	80 m
Nominal Rotor Speed (Round Per Minute)	16.7 rpm
Cut-in Wind Speed (Meter/Second)	4 m/s
Rated Wind Speed (Meter/Second)	15 m/s
Cut-out Wind Speed (Meter/Second)	25 m/s
Survival Wind Speed (Meter/Second)	60 m/s
Nominal Output Power of the Generator (kilo-Watt)	2000 kW
Maximum Output Power of the Generator (kilo-Watt)	2200 kW
Hub Height (Meter)	100 m
Wind Turbine Weight including Tower, Nacelle and Rotor (Ton)	334 t

Table 2.The linguistic variable of the wind speed, and its values

Input Linguistic Variable: Wind Speed (V_w)		
Linguistic Value	**Notation**	**Numerical Range (m/s)**
Very Light	VL	[0, 6]
Light	L	[4, 14]
Normal	N	[12, 18]
Heavy	H	[17, 25]
Stormy	S	[24, 60]

Table 3.The linguistic variable of the output power, and its values

Input Linguistic Variable: Generator Output Power (P_{out})		
Linguistic Value	**Notation**	**Numerical Range (kW)**
Very Low	VL	[0, 800]
Low	L	[500, 1700]
Optimum	Opt	[1600, 2200]
High	H	[2100, 2400]
Very High	VH	[2300, 2500]

performance of the system in tuning stages, the type of the functions can be changed, taking other factors into account. Since type-2 fuzzy sets are applied, the range of the values of FOU for specifying uncertainty of each variable and improving the performance of the system is defined based on the degrees of freedom, which is suggested by the experts for membership functions of the variable; for example, for the linguistic variable, the wind speed and its value given as Normal, the value given for its nominal speed cannot be considered within this range, and its practically varying between a maximum and minimum, giving the desired result; therefore, its value in the range Normal cannot be just a number, and is defined based on the FOU.

2.6. Fuzzy Rules

In general, there are four methods to obtain controlling rules and defining fuzzy rules for designing fuzzy controllers [21].

- The most common method is to use the knowledge of experts and control engineers.
- Another method studies the performance of operators involving a system. The operations performed by an operator for controlling a system relates inputs and outputs of the system to each other; this relation gives the required controlling rules.
- The third method of obtaining fuzzy rules is to make use of the fuzzy model. The rules obtained

Table 4.The linguistic variable of the rotor speed, and its values

Input Linguistic Variable: Rotor Speed (ω_r)		
Linguistic Value	**Notation**	**Numerical Range (rpm)**
Very Low	VL	[0, 6]
Low	L	[5, 16]
Operational	Ope	[15, 19]
High	H	[18, 25]
Very High	VH	[24, 30]

Table 5.The linguistic variable of the pitch angle, and its values

Output Linguistic Variable: Pitch Angle (α_{final})		
Linguistic Value	**Notation**	**Numerical Range (degree)**
Negative Extreme	NE	[-90, -70]
Negative Very Large	NVL	[-75, -40]
Negative Large	NL	[-45, -28]
Negative Medium	NM	[-30, -10]
Negative Small	NS	[-12, -4]
Negative Tiny	NT	[-5, -1]
Zero	Z	[-2, 2]
Positive Tiny	PT	[1,5]
Positive Small	PS	[4, 12]
Positive Medium	PM	[10, 30]
Positive Large	PL	[28, 45]
Positive Very Large	PVL	[40, 75]
Positive Extreme	PE	[70, 90]

Table 6.The fuzzy rules for controlling the pitch angle in the wind turbine

V_w	VL					L					N					H					S				
P_{out}	VL	L	Opt	H	VH	VL	L	Opt	H	VH	VL	L	Opt	H	VH	VL	L	Opt	H	VH	VL	L	Opt	H	VH
ω_r																									
VL	PE	PVL	PL	PM	PS	PVL	PL	PM	PS	PT	PL	PM	PS	PT	Z	PM	PS	PT	Z	NT	PS	PT	Z	NT	NS
L	PVL	PL	PM	PS	PT	PL	PM	PS	PT	Z	PM	PS	PT	Z	NT	PS	PT	Z	NT	NS	PT	Z	NT	NS	NM
Ope	PL	PM	PS	PT	Z	PM	PS	PT	Z	NT	PS	PT	Z	NT	NS	PT	Z	NT	NS	NM	Z	NT	NS	NM	NL
H	PM	PS	PT	Z	NT	PS	PT	Z	NT	NS	PT	Z	NT	NS	NM	Z	NT	NS	NM	NL	NT	NS	NM	NL	NVL
VH	PS	PT	Z	NT	NS	PT	Z	NT	NS	NM	Z	NT	NS	NM	NL	NT	NS	NM	NL	NVL	NS	NM	NL	NVL	NE

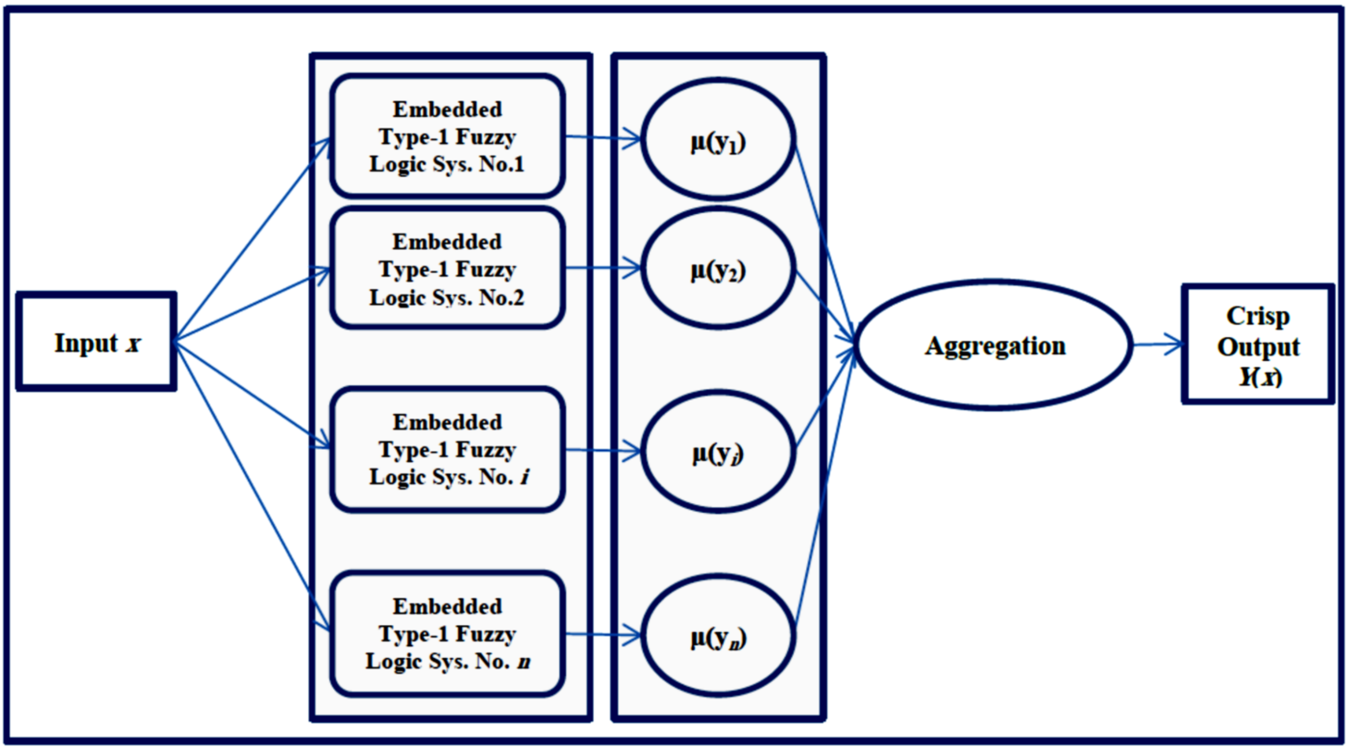


Fig. 4.The steps of type reduction and defuzzificaion.

Table 7.The fuzzy sets of the pitch angles based on Sugeno inference engine (Zero-order)

Pitch Angle Membership Function Values	
Function Name	**Value**
NE	-80
NVL	-57.5
NL	-36.5
NM	-20
NS	-8
NT	-3
Z	0
PT	3
PS	8
PM	20
PL	36.5
PVL	57.5
PE	80

by this method are known as linguistic rules, and are considered as an indirect model of the controlled process. The drawback of this method is that it is limited to systems of low orders. However, this method is an explicit solution for open- or closed-loop systems whose fuzzy models are available.

- Finally, learning methods can also be used for obtaining fuzzy rules. For instance, in independent controllers and neural networks, fuzzy rules can be obtained after learning stages.

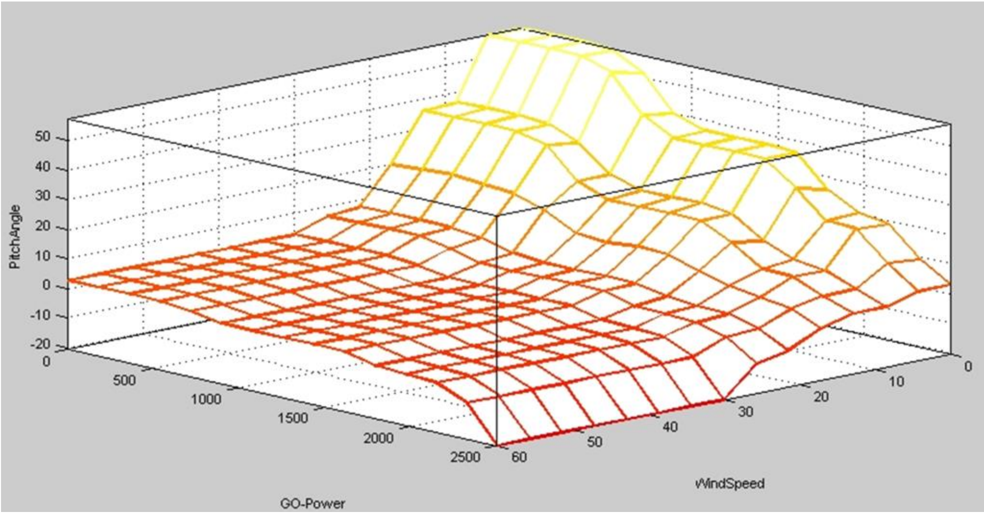
Here the first and second methods are used. Applying experiences of engineers and experts on controlling wind turbines and investigation of their operational procedures; that is, through studying previous works, and visiting wind power stations in Iran, acquiring valuable information from experts, operators, and reports on operational details of wind turbines, the following 125 rules have been extracted. These rules are in the form of IF-THEN, and are presented in structures like fuzzy rule table or fuzzy associative matrix. Here, due to the large number of the rules, we have made use of a fuzzy rule table (table 6).
Two examples of the rules represented at table 6 can be stated as follows:

i) If the wind is in N (Normal) condition, the rotor speed is in Ope (Operational) mode, and the output power of the generator is L (Low), then the pitch angle within a tiny range (Positive Tiny) is adjusted to increase the lift force on rotor blades, and

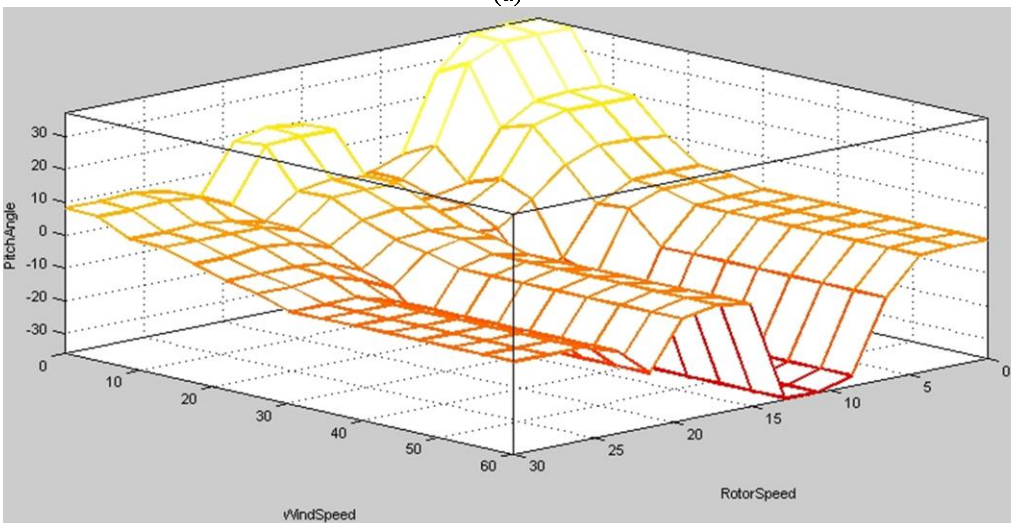
ii) If the wind is in N (Normal) condition, the output power of the generator is Opt (Optimum), and the rotor speed is H (High), then the pitch angle within a tiny range (Negative Tiny) is adjusted to decrease the lift force on rotor blades.

2.7. Fuzzy Inference Engine

In view of nonlinear nature of the system and some of its parameters, Sugeno method seems more applicable to use. On the other hand, Mamdani method is the most common approach to represent human experiences [22]. Therefore, both methods will be compared and the most suitable approach for the studied system will be suggested. It should be noted that the output of Mamdani method is a



(a)



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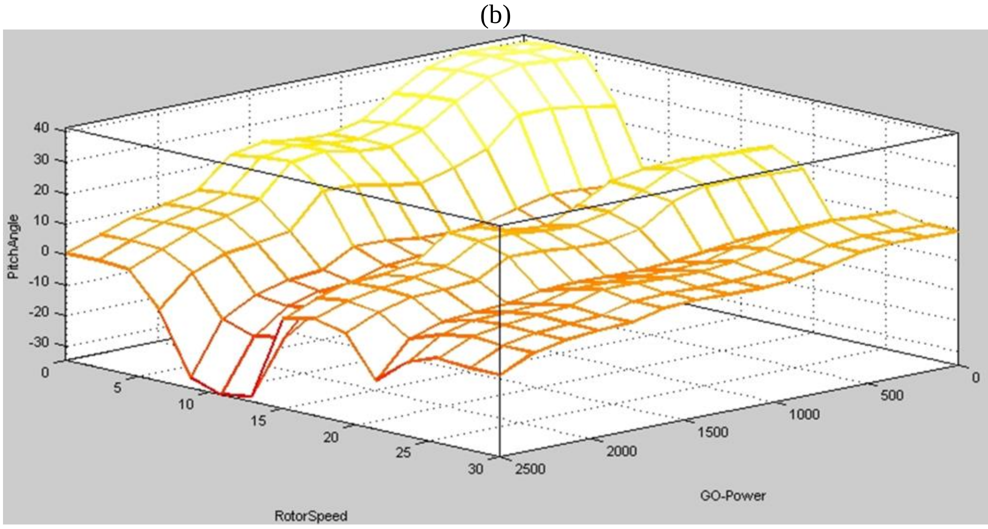

(c)

Fig. 6.(a)The relation of the wind speed and the output power of the generator with the pitch angle for a nominal rotor speed of 16.7 rpm.(b)The relation of the wind speed and the rotor speed with the pitch angle for the nominal output power of 2000 kW.(c)The relation of the rotor speed and the output power of the generator with the pitch angle for the predicted speed of wind of 15 m/s

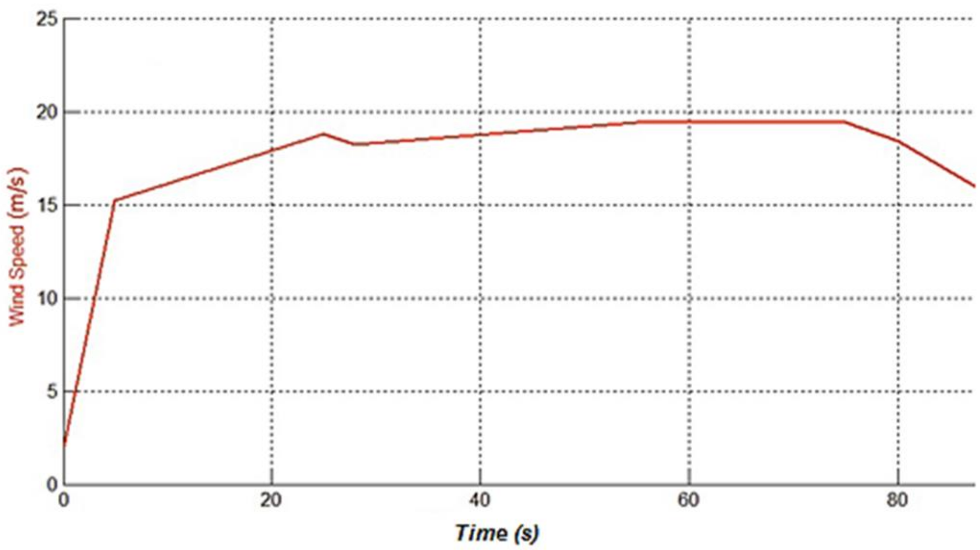

Fig. 7.The wind speed

collection of fuzzy sets, while Sugeno method gives the output in the form of a function.

2.8. Type Reduction and Defuzzificaion

Here, the aim is to obtain a crisp value in the output. First, type-2 fuzzy sets are converted into type-1 using the type reducer. The most common method for type reduction is the center-of-sets method [23]. Then, in defuzzifiation step, the desired crisp value in the output is obtained using the centroid method [18]. These steps have been illustrated in Fig. 4.
The output crisp value is calculated using:

$$y(\mathbf{x}) = [\sum_{k=1}^{\alpha} y_k \mu_Y(y_k)]/[\sum_{k=1}^{\alpha} \mu_Y(y_k)] \qquad (1)$$

2.9. Implementing The IT2FL Controller

To implement the fuzzy controller, the interval type-2 fuzzy logic toolbox of MATLAB has been used [24]. After defining all 125 rules in the rule editor of the toolbox and declaring fuzzy sets, the results for predicted inputs obtained with the use of this toolbox in the Mamdani type inference engine.

2.10. System Tuning

The last and most important step in designing a fuzzy controller is its evaluation and tuning. In this step, it is evaluated whether the designed fuzzy controller meets the expected controlling needs. To this end, the surface diagrams shown above are used to analyze the performance of the system. These diagrams indicate that the fuzzy controller appropriately reacts in crucial situations to generate suitable angles in the output for adjusting the pitch angles. However, it can be further improved using the following suggested approaches.
One approach to improve the performance of the system in this step is to increase the number of values used for each linguistic variable, and consequently, to reduce the length of the range of their specified values. Indeed, through this approach, new sets are defined for each linguistic variable, and thus, the number of the rules used is increased. From the beginning, we have specially considered this point, and defined linguistic variables with the maximum number of suitable values; therefore, we did not need to apply this approach. Another method for increasing the performance of the system is to study overlaps of adjacent fuzzy sets, which has been considered here in designing the system. Moreover, increasing the number of rules can also improve the performance of the system. The large number of rules in designing our system has been considered from the beginning. The shape of the fuzzy sets can also be changed to increase the system's performance. Changing the membership functions of input or output from triangular to Gaussian can help to make sudden variations of the output uniform; therefore, the output of different inputs will be closer to each other. As the result, the membership functions in the input will be as follows (Fig. 5).
Furthermore, in view of the nonlinear nature of the problem, through changing the inference system from Mamdani to Sugeno, the accuracy of the calculations can be increased. This lets to convert the values of the linguistic variables in the output to a series of constant numbers according to the suggestion of the expert, and to implement them with the use of the zero-order Sugeno, which is the most commonly used type.
It should be noted that the values in the table 7 have been obtained from the average of the numerical interval of those values in the triangular functions in the output. Moreover, to keep the highest compatibility of the method used in the defuzzification and type reduction steps with the use of the selective inference, the center-of-sum method has been used in these two steps. The diagrams

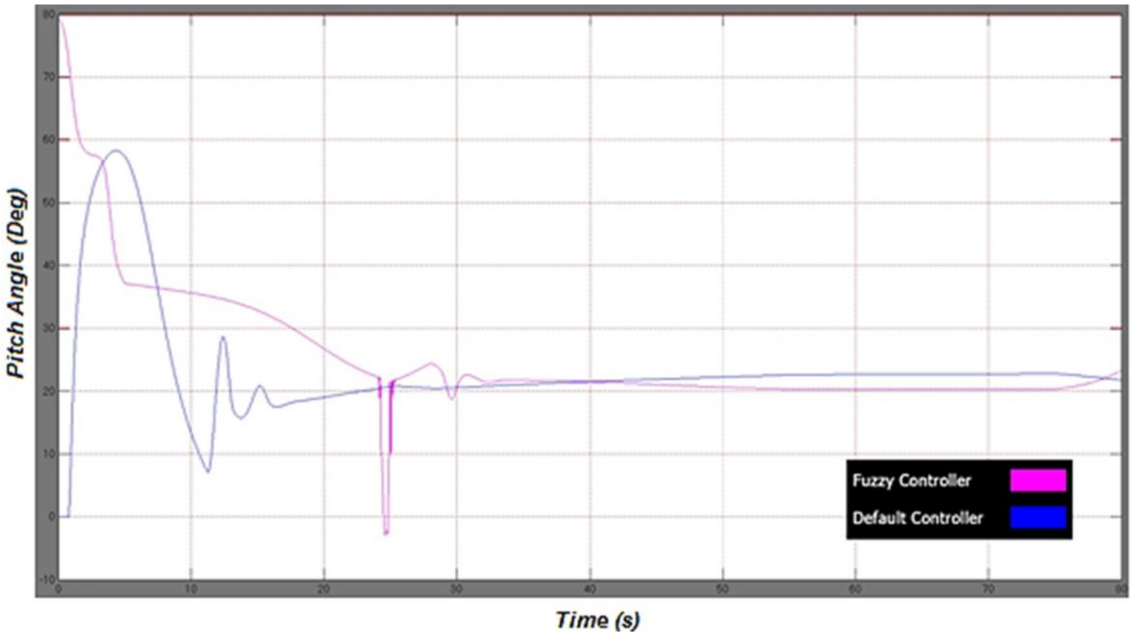

Fig. 8.The variations of the pitch angle for each controller

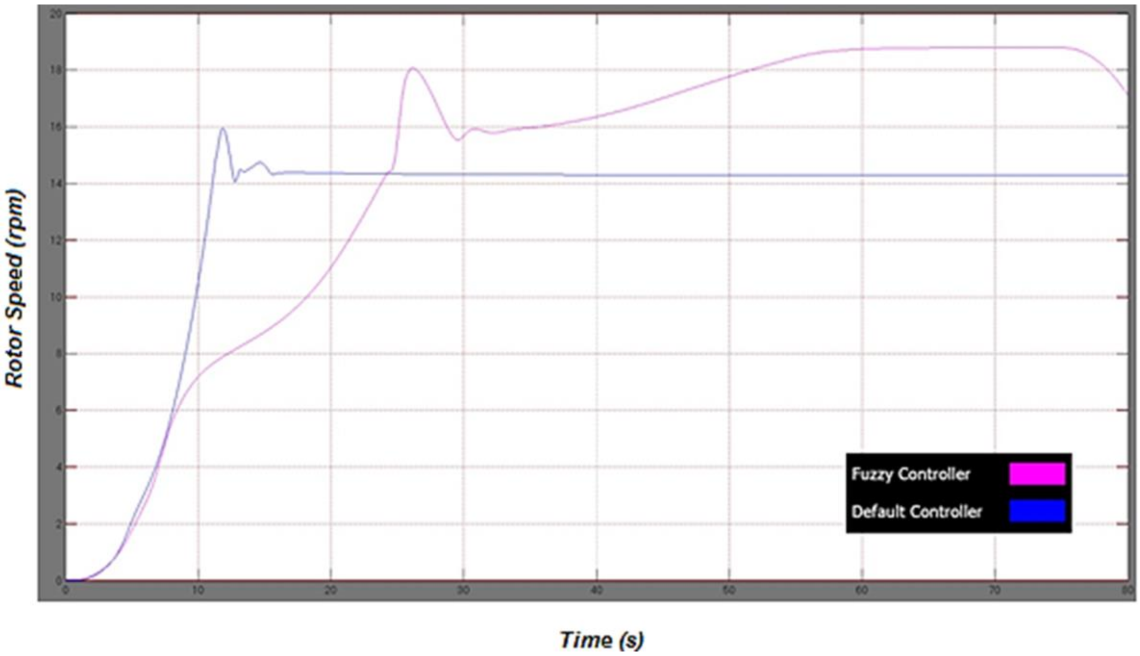

Fig. 9.The variations of the rotor speed for each controller

obtained after these changes have been illustrated in the following (Fig. 6).

The Diagrams show evaluating and tuning the system have increased the ratio of the changes of the pitch angle to the other parameters in each diagram. This reflects an increase in the sensitivity of the controller to changes in the input for producing a suitable output, or in other words, an increase in the accuracy of the controller in performing calculations in different conditions. Therefore, the tuning step of fuzzy systems not only is an effective step for the present controller but also its proper application is necessary in all fuzzy logic problems.

3. Results and Discussion

3.1. IT2FL Controller Compared To PI Controller

Here, the results obtained from the Interval Type-2 Fuzzy Logic (IT2FL) controller are compared with those found using PI controller in the simulated model presented in the file exchange center website of MathWork company. To this end, the wind speed has been considered as given in Fig. 7. When this wind speed is applied to the wind turbine, each controller adjusts the pitch angle using the input values within the first 80 seconds as shown in Fig. 8. This pitch angle adjustment results in adjusting the rotor

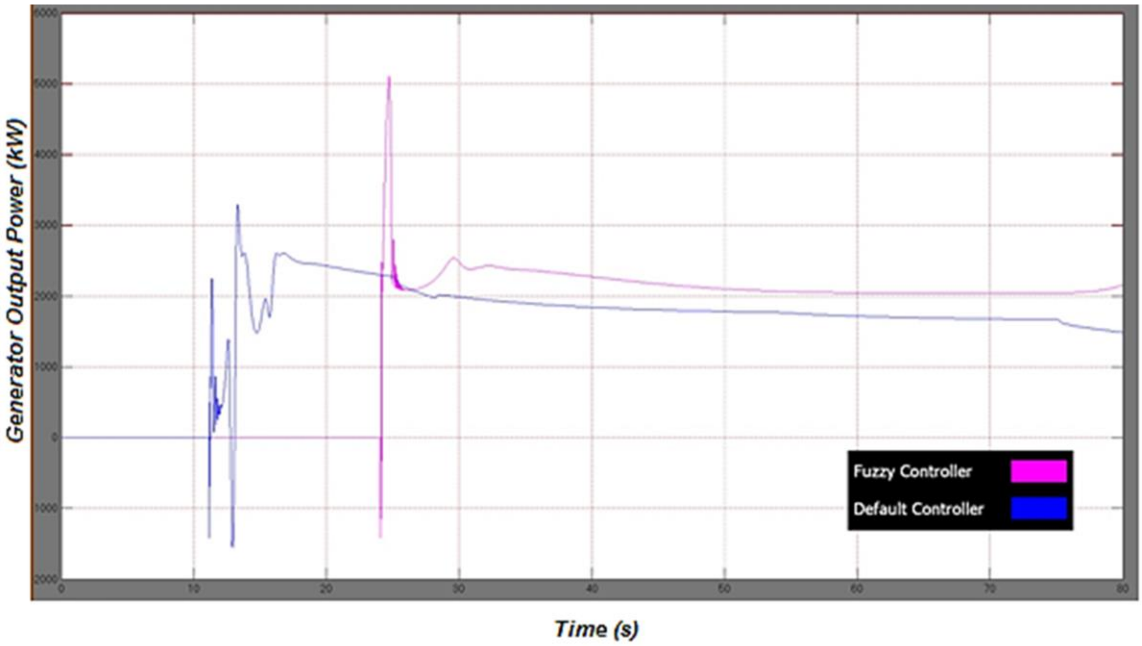

Fig. 10.The variations of the output power for each controller

speed as indicated in Fig. 9. As a result, the generator output power is indicated in Fig 10. In all the diagrams, the green and yellow lines represent the results of our designed controller and the PI controller used in the simulation, respectively. For analyzing the results, the first case is assumed to be the adjustment of the pitch angle by the type-1 fuzzy controller, and the second case is considered to be that done by the default controller, i.e. the PI controller.

Fig. 7 shows that the wind speed increases to the predicted value of 15 m/s within the first 7 seconds, resulting in the monotonic increase of the rotor speed in both cases. This makes in both the situations the wind turbine transition from the "Park" state to the "Startup" mode, but is not sufficient to bring the turbine to "Generating" mode, and no power has been yet produced by the generator.

Therefore, the IT2FL controller adjusts the pitch angle more sensitively, and begins the adjustment with an angle relatively higher than that used by the default controller, and thus, applies a large force on the rotor to increase its speed; then, the IT2FL controller gradually reduces the rotor speed to a suitable value, making the power generation possible. Conversely, the default controller very irregularly adjusts the pitch angle staring from zero. This difference is due to the decision-making logic and the input parameters of the two controllers. In making decisions, unlike the default controller, the IT2FL controller takes also the output power of the generator into account, and owing to the zero value of the output power at this time, begins the adjustment of the pitch angle with a large value. It takes 24 and 10 seconds to reach to the "Generating" mode in the first and second situations, respectively. Since the wind speed is almost constant during power generation, the rotor speed and out power of the generator in the second situation is monotonic, but in comparison to the first situation, neither the rotor's nominal speed of 16.7 m/s nor the maximum output power of the generator, 220 kW, has been achieved. Taking the current conditions into account, the IT2FL controller tries to make a trade-off between the rotor speed and the output power, provided that both are maximized; however, these values do not exceed their predefined allowed values; therefore, we will have an acceptable output power with the use of the maximum output power of the generator while the wind turbine is kept in safe conditions with no wearing forces applied on its parts.

A point of note in Fig. 9 is the variation of the rotor speed for the controllers; the corresponding diagram shows dramatic changes in the first situation, while it is monotonic in the second case. This reflects that, the IT2FL controller more efficiently adjusts the rotor speed to bring the generator to its nominal output in comparison to the default controller.

3.2. Quantitative Comparison

In this section, the quantitative comparison between IT2FL controller and PI controller in theirs generator output powers and torques are presented. We will compare the significant attributes of diagrams like setting time, maximum overshoot and steady state error.

Some important values are specified in the generator output diagram of both PID controller and IT2FL controller (Fig. 11 and Fig. 12). Comparison of two diagrams based on mentioned attributes is presented in table 8. According to the result, IT2FL Controller has better results than PID Controller.

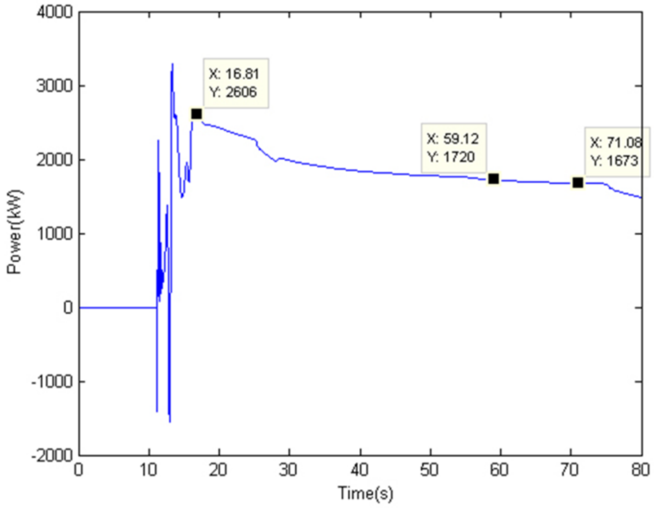

Fig. 11.Quantitative diagram of the generator output power (PI Controller)

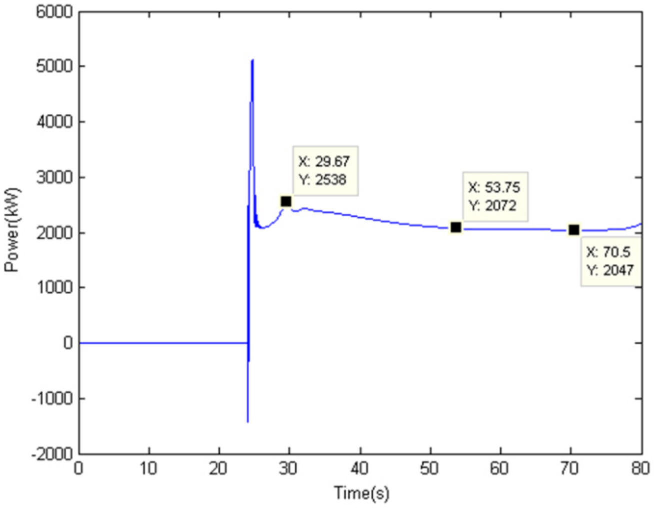

Fig. 12.Quantitative diagram of the generator output power (Interval Type-2 Fuzzy Logic Controller)

Table 8.PI Controller V.S. Interval Type-2 Fuzzy Logic Controller

	Setting Time	***Maximum Overshoot***	***Steady State Error***
PI Controller	42.31s	56%	16.35%
Interval Type-2 Fuzzy Logic Controller	24.08s	24%	2.35%

Conclusion

Maximizing the use of the power existing in wind's energy, and optimization of the generator output power along with taking the safety measures into account are of high significance in designing and implementation of a wind turbine, especially in large scales. Owing to the popularity of using the method of pitch control for different types of modern wind turbines having three blades with horizontal axis as an efficient method in harnessing wind energy, the controller designed for this structure should meet the performance. In the present study, we utilized the interval type-2 fuzzy logic theory in designing the aforementioned controller. Basically, the pitch control in wind turbines is better done with the use of fuzzy controllers as compared to other methods, proven by some general and specific advantages. The specific advantages include consideration of the highest possible number of input variables in designing the controller, and the observance of overlaps between adjacent fuzzy sets in designing. Applying a wide range of values for each linguistic variable, and therefore, the reduction of the length of their assigned intervals, leading to an increase in the number of the applied rules is another specific advantage. The highest number of fuzzy rules can be applied to consider all possible situations according to experiences of experts, and the suitable shapes for input membership functions can be considered. Finally, selecting a suitable inference engine compatible with the nature of the problem is possible. The Interval Type-2 Fuzzy Logic controller has all these advantages, and its performance has been proven in quantitative comparison with mentioned PI controller.

References

[1] L. Shuqin, "Magnetic Suspension and Self-pitch for Vertical-axis Wind Turbines," Fundamental and Advanced Topics in Wind Power, pp. 233-248, 2011.

[2] Vestas®Experts, "V80-2.0 MW Wind Turbine," in Vestas® Wind Systems, Vestas®, Ed., 1st ed. Denmark: Vestas® Company, 2011.

[3] O. Suvire, Wind Farm – Technical Regulations, Potential Estimation and Siting Assessment, 1st ed. Croatia: InTech Ltd, 2011.

[4] D. Parker, Microgeneration low energy strategies for larger buildings. United Kingdom: Elsevier Ltd., 2009.

[5] T. Burton, N. Jenkins, D. Sharpe, and E. Bossanyi, Wind Energy Handbook, 2nd ed. United Kingdom: A John Wiley and Sons, Ltd., Publication, 2011.

[6] Yen Kheng Tan and S. K. Panda, "Self-Autonomous Wireless Sensor Nodes With Wind Energy Harvesting for Remote Sensing of Wind-Driven Wildfire Spread," Instrumentation and Measurement, IEEE Transactions on, vol. 60, 2011.

[7] A. Abdelkafi and L. Krichen, "New strategy of pitch angle control for energy management of a wind farm," Energy, vol. 36, pp. 1470-1479, 2011.

[8] A. Hwas and R. Katebi, "Wind Turbine Control Using PI Pitch Angle Controller. IFAC Conference on Advances in PID Control," presented at the IFAC Conference on Advances in PID Control, Brescia, Italy, 2012.

[9] T. Li, A. J. Feng, and L. Zhao, "Neural Network Compensation Control for Output Power Optimization of Wind Energy Conversion System Based on Data-Driven Control," Journal of Control Science and Engineering, vol. 2012, pp. 1-8, 2012.

[10] A. S. Yilmaz and Z. Özer, "Pitch angle control in wind turbines above the rated wind speed by multi-layer perceptron and radial basis function neural networks," Expert Systems with Applications, vol. 36, pp. 9767-9775, 2009.

[11] M. Fard, R. Rahmani, and M. W. Mustafa, "Fuzzy Logic Based Pitch Angle Controller for Variable Speed Wind Turbine," presented at the IEEE Student Conference on Research and Development, Malaysia, 2011.

[12] B. Bahraminejad, M. R. Iranpour, and E. Esfandiari, "Pitch Control of Wind Turbines Using IT2FL Controller Versus T1FL Controller," International Journal of Renewable Energy Research (IJRER), vol. 4, pp. 1065-1077, 2014.

[13] M.-H. Chiang, "A novel pitch control system for a wind turbine driven by a variable-speed pump-controlled hydraulic servo system," Mechatronics, vol. 21, pp. 753-761, 2011.

[14] K. Das Sharma, A. Chatterjee, and A. Rakshit, "A Random Spatial lbest PSO-Based Hybrid Strategy for Designing Adaptive Fuzzy Controllers for a Class of Nonlinear Systems," Instrumentation and Measurement, IEEE Transactions on, vol. 61, 2012.

[15] O. Castillo, Type-2 Fuzzy Logic in Intelligent Control Applications. USA: Springer-Verlag Berlin Heidelberg, 2012.

[16] R. B. Gavino, J. Christpher Y.Ng, R. L. Ng, and B. L. Tan, "Development of an automated wind turbine using fuzzy logic," DLSU engineering e-journal, vol. 1, pp. 28-42, 2007.

[17] M. Zamani, H. Nejati, A. T. Jahromi, A. R. Partovi, S. H. Nobari, and G. N. Shirazi, "Toolbox for Interval Type-2 Fuzzy Logic Systems," Atlantis Press, 2008.

[18] O. Castillo and P. Melin, Type-2 Fuzzy Logic: Theory and Applications. USA: Verlag Berlin Heidelberg, 2008.

[19] D. Wu, "A Brief Tutorial on Interval Type-2 Fuzzy Sets and Systems," University of Southern California, USA2012.

[20] E. P. Dadios, Fuzzy Logic-Algorithms, Techniques and Implementations, 1st ed. Croatia: InTech Ltd., 2012.

[21] J. Jantzen, "Design Of Fuzzy Controllers," Technical University of Denmark, Department of Automation, Denmark1998.

[22] A. M. Fanelli, W. Pedrycz, and A. Petrosino, Fuzzy Logic and Applications, 1st. ed. USA: Springer-Verlag Berlin Heidelberg, 2011.

[23] O. Castillo and P. Melin, Recent Advances in Interval Type-2 Fuzzy Systems vol. 1. USA: Springer, 2012.

[24] J. R. Castro, O. Castillo, and L. G. Martínez, "Interval Type-2 Fuzzy Logic Toolbox," Engineering Letters, vol. 15, 2007.