Pitch Control of Wind Turbines Using IT2FL Controller versus T1FL Controller

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Abstract- Pitch control is one of the most important issues in modern wind turbines. It is vital to regulate the generator output power and reduce the fatigue load in related parts of wind turbine, also preventing from possible dangers due to an unpredicted increase of wind speed and output power. The most recent approach in pitch control is to use of fuzzy controllers. An important feature of fuzzy controllers is the ability to solve nonlinear problems. However, the Type-1 Fuzzy Logic (T1FL) controllers cannot show uncertainly of parameters in pitch control. In this study, Interval Type-2 Fuzzy Logic (IT2FL) is applied instead of the T1FL to include and represent high levels of uncertainties in problem parameters in order to increase the accuracy of the results. The results indicate that the IT2FL controller in compare with T1FL controller has better improvement in adjustment of pitch angle, controlling of rotor speed and optimizing output power to achieve rated power in the generator.

Keywords- Wind Turbine, Pitch Control, Interval Type-2 Fuzzy Logic, Type-1 Fuzzy Logic.

1. Introduction

Producing electricity from wind energy has been increased in recent years that shows the importance of wind energy among other renewable energies [1]. Wind turbines have been invented to generate electricity from wind energy and deployed fast [2].

As the capacity of electricity generation is increased, the control of wind turbines output power is noticed more in the world. Controlling output power will maximize the energy production. Also, guaranteed the safety of wind turbine that is an important issue in rotor [3] and generator functionality [4].

Horizontal axis wind turbine is the most modern wind turbine type that has three blades and usually mounted upwind at the top of the tower [5]. The power grid of wind turbines are installed entirely as a wind park or wind farm, to generate hundreds of Mega Watts. In recent types of wind turbines, Pitch Control method is used to increase the capacity of output power and preventing the generator from overloading or reducing the output power by optimizing it, which is the most effective factor for output power generation in the scale of wind farms [6]. In this method, rotor speed is changed through adjusting the rotor blades angle. The angle of the blades is changed around its longitudinal axis by using a pitch controller. This controller is mostly implemented through PID controllers with the use of functions like gain scheduling [7]. Neural networks [8] and artificial intelligence have also been used for this purpose [9]. According to nonlinear behavior of rotor blades and winds due to aerodynamic behavior of blades and irregular compression of wind (wind speed changes), there are simpler and more cost-effective methods to use. One approach is to adjust the pitch angle with the use of the fuzzy controllers [10], where type-1 fuzzy controller is applied, typically [11]. Also, fuzzy adaptive type of pitch controllers has been used to get better results [12].

A Type-1 fuzzy logic (T1FL) controller can bring about the desired change in the pitch angle without any ambiguity or complexity [13]. However, the T1FL controllers cannot show uncertainly of parameters in pitch control to get suitable results. In current work, Interval Type-2 Fuzzy Logic (IT2FL) is applied to replace the T1FL and includes high levels of uncertainties in problem parameters, and also to increase the accuracy of the results [14].

Type-2 fuzzy logic has been recently applied in different fields to design fuzzy controllers to get better results. For example, there are some discussions to optimize type-2 membership functions using Particle Swarm Optimization (PSO algorithm) for FPGA applications [15]. In the next sections, the effects of important parameters of the fuzzy controller like the wind speed and the rotor speed are discussed. Furthermore, the relation between blades functionality and amount of output power of the wind turbine on the change in blades angle will be illustrated. Then, linguistic variables, hedges and corresponding laws are defined. Finally, the controller obtained with this method will be simulated. The simulation results will

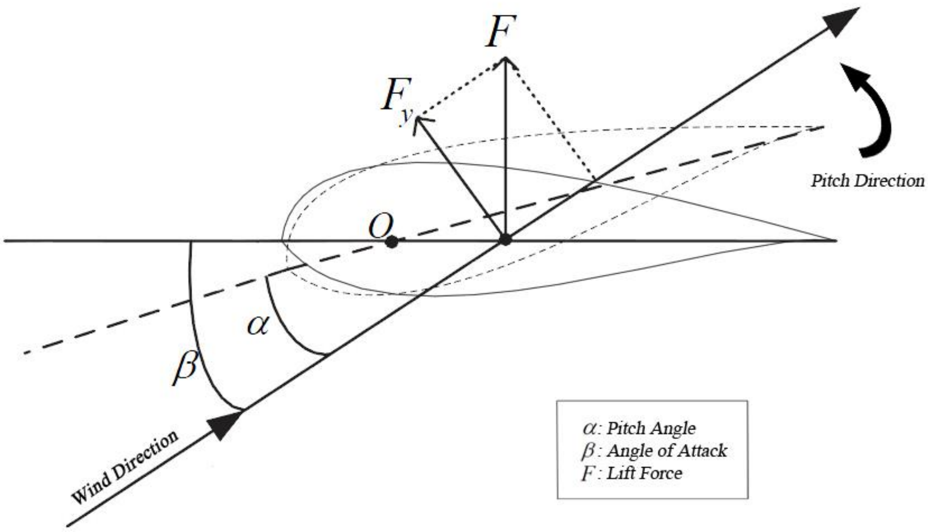


Figure 1. Pitch Angle and Angle of Attack [16].

evaluate the performance of designed IT2FL controller in comparison to a type-1 fuzzy logic controller.

2. Research Methodology

2.1. Pitch Control in Wind Turbines

The aim of the present study is to apply Interval Type-2 Fuzzy Logic controller to get the suitable pitch angle in order to produce optimal output power rather than previous similar works with Type-1 Fuzzy Logic controllers. Before proceeding to the next discussion, we need to know some concepts about pitch control in wind turbines. When the wind speed is less than the rated value, the pitch angle is reduced. Then, the angle between the wind direction and blade surface, called the angle of attack, is increased so that the lift force will be increased to hold output power about its nominal value (Fig. 1). On the other hand, when wind speed exceeds from its rated value, the pitch angle is increased, and therefore, the angle of attack is reduced. It will decrease the lift force and rotor speed to prevent possible dangers. Definition of the pitch angle is also dependent on the pitch design or the rotation direction of the pitch actuator. In this research, to understand the function of the pitch angle, the direction of increasing or decreasing for both pitch angle and angle of attack is considered to be at the same direction. The input variable parameters of the controller are wind speed, rotor speed and output power of the generator. The pitch angle is obtained from these parameters and considered as the output variable parameter. It will send to pitch actuators to adjust the rotor pitch angle. The blades will be rotated according to pitch angle value, and the required lift and drag force is applied to the rotor blades by the wind. Then, the torque required to move the blades is adjusted. It can be measured via specific sensors [17]. This torque is transferred to the generator through the gearbox so that the output power will be adjusted. Figure 2 presents the general scheme of Pitch Control System in the wind turbine.

2.2. Interval Type-2 Fuzzy Logic Controller

Modern turbines are divided into the three main parts: Mechanical, Electronic, and Software components, that making a whole Mechatronic system [18]. Fuzzy controllers are discussed in software scope. Functionality of these controllers is based on fuzzy logic rules, and a form of multi-value logic. It works with approximate, instead of exact and constant values. Type-2 fuzzy logic systems are more complicated and less understandable than 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 [19]. Therefore, the type-2 fuzzy logic is more general than the type-1. Generally, a fuzzy system is a function mapping input variables to output variables. This mapping is done with the use of a knowledge base that is included fuzzy rules. These rules represent general adjustments of type-2 fuzzy logic controller system. In type-2 fuzzy logic, each input variable is related to one or more sets called type-2 fuzzy sets. These sets are composed of different elements. When the membership degree of an element in a set cannot be identified based on 0 and 1, type-1 fuzzy sets are applied; 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 viewed as first- and second- order approximations to identify uncertainty [20]. These sets indicate the concept of uncertainty, but this uncertainty involves complicated calculations. To solve this problem, Interval type-2 fuzzy sets are used. Type-2 fuzzy sets are limited between maximum and minimum values of type-1 fuzzy sets, and represented as the

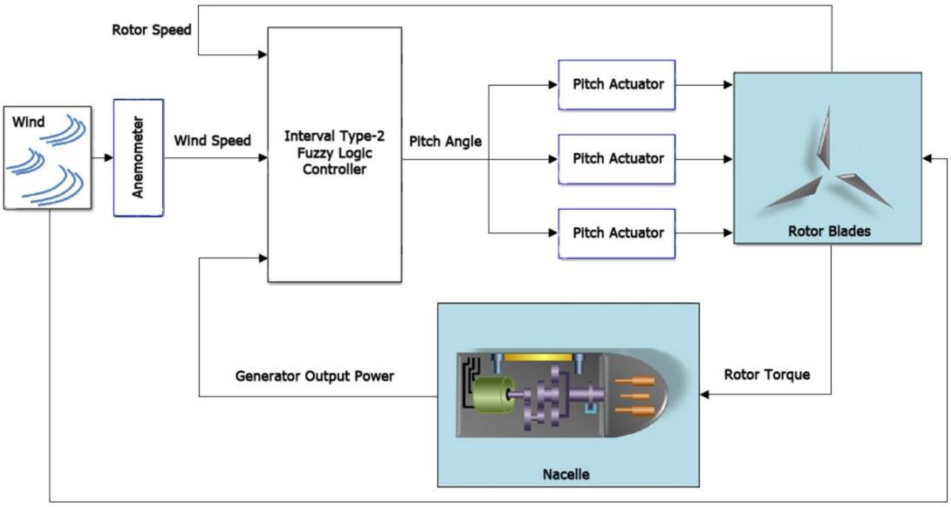


Figure 2. The scheme of Pitch Control System in the wind turbine.

maximum ($\overline{X}$) and minimum ($\underline{X}$) membership functions. The range between these two values is called Footprint Of Uncertainly (FOU) [21]. Linguistic variables are managed with the use of specific functions that are applied to input and output variables. Functions of input variables are mapped to the corresponding functions of output variables using some rules and base on the fuzzy inference system. Through type reduction and Defuzzification step, the results in output are converted into a crisp value for appropriate use [22]. In figure 3, the wind speed (V_w), the rotor speed (ω_r), and the current value of the output power (P_{out}) are specified as input variables, and the pitch angle (α_{final}) is defined as the output variable. In this section, complexity of the system is not considered; generally, a fuzzy controller is suitable when the dynamic of the system is complicated, or have some nonlinear characteristics.

2.3. *Wind Turbine Characteristics*

To design the controller, the 2-MW wind turbine with given characteristics in table 1 is 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 Rated Wind Speed are the speeds of the rotor and the wind, respectively, at which the wind turbine is working with nominal output power and safety. The wind speed above rated value which is unnecessary for the wind turbine is called the Cut-out Wind Speed. The maximum wind speed tolerable by the turbine, called the Survival Wind Speed, is the speed more than which bring damages to the turbine. The Nominal Output Power of the Generator is the proper output power defined for the wind turbine. The Maximum Output Power of the Generator is a power, more than which brings damage to Generator.

2.4. *Linguistic Variables, Values and Types*

Our fuzzy system has four main linguistic variables, three of them which are input variables, including the speed of the wind by applying an anemometer for measurement, the generator output power, and the rotor speed. The linguistic variable in the output is the pitch angle.

Tables 2 to 5 present the type and numerical range of linguistic variables. These ranges are obtained base on values in Table 1. The pitch actuators in simulated model, which will be introduced in “Results and Discussion”, have the ability to rotate rotor blades in 360 degree. It causes increasing or decreasing rotor speed depending on different circumstance according to controller output command to actuators to set suitable pitch angle and rotating rotor blades to desire direction. This is why the pitch angle numerical range covers all degrees between -90 and 90 in Table 5.

2.5. *Fuzzy Sets Definition*

The kind of variable and the expected results is important to determine the form of a fuzzy set. The most common form is triangular. However, to improve the system performance in tuning stages, functions types can be changed. The FOU range is also important in optimization of IT2FL controller design. In a similar case [23], optimal solution has been proposed for IT2FL problems based on the size of FUO. In this case, the range of the FOU for Interval Type-2 fuzzy sets is defined based on the degrees of freedom in each variable and suggested by the experts. Figures 4 show the fuzzy sets, based on Tables 2, 3, 4 and 5.

2.6. *Fuzzy Rules*

Fuzzy rules are obtained in four methods [24].

- The most common method is to use the knowledge of experts and control engineers. Fuzzy rules can be extracted through asking many on purposed questions from the experts. It can also be achieved through reading relevant books written by the experts.

Another method is to study on system work flow. The operator performs operations that relate

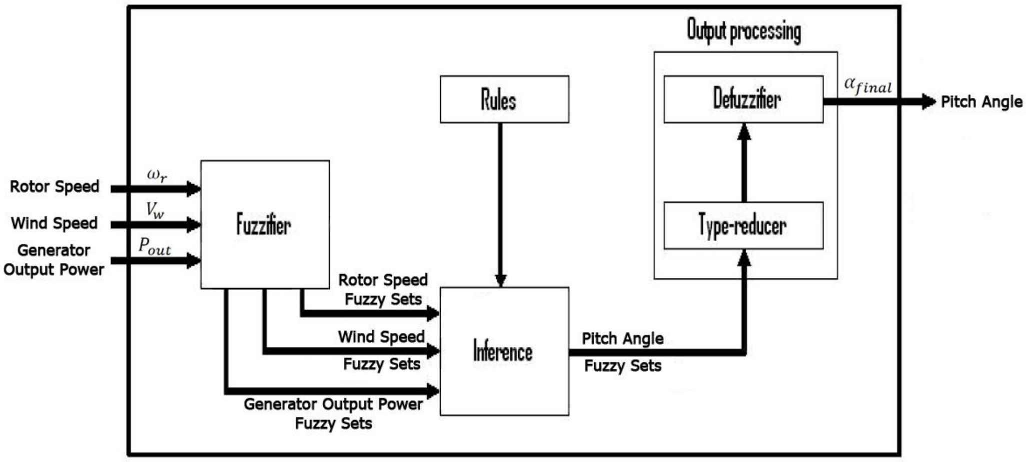


Figure 3. The Fuzzy Inference System.

- inputs to the output of the system; these relations give you required controlling rules. This can be either directly obtained from the operator or can be described in the form of flowcharts in books or system catalogs.
- Fuzzy model is important to extract the rules. The rules obtained from the model are known as linguistic rules, and 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 used for open- or closed-loop systems whose fuzzy models are available.
- Finally, learning methods can also be used to obtain fuzzy rules, as in neural networks, fuzzy rules can be obtained after learning stages.

In this research, experiences of experts and investigating on their operational procedures have been used to extract the following 125 fuzzy rules. These rules are in form of IF-THEN, and presented in structure of fuzzy rules table in table 6.

Two examples of the rules represented in this table 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

The Sugeno method is better than Mamdani method in dealing with nonlinear systems but Mamdani method is the most common approach to represent human experiences [25]. Therefore, both methods will be compared to choose the best one.

2.8. Type Reduction and Defuzzificaion

In this section, the crisp value is obtained from its fuzzy set. In Type Reduction step, type-2 fuzzy sets are converted into type-1 by the type reducer. The most common method for type reduction is the center-of-sets method [26]. Then, the desired crisp value in output is calculated by using the centroid method in Defuzzifiation step [20]. These steps have been illustrated in figure 5. The output crisp value is calculated by using following equation:

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

2.9. Implementing the IT2FL Controller

The interval type-2 fuzzy logic toolbox in MATLAB has been used to implement the fuzzy controller [27].
After defining all 125 rules in rule editor of the toolbox and declaring fuzzy sets, the Mamdani type inference engine is observed in the following surface diagrams (Fig.6).

2.10. System Tuning

The last and the most important step in designing a fuzzy controller is its tuning step. In this step, the designed fuzzy controller is evaluated to meet the expected controlling criteria. To this end, the above surface diagrams are used to analyze the performance of the system. These diagrams indicate reaction of the fuzzy controller to choose suitable values for the pitch angle. However, it can be improved by the following approaches. One approach for improving the system performance is to increase the number of values used for each linguistic variable, and consequently, reducing the range of these values. Through this approach, new sets are defined for each linguistic variable, and thus, the number of the rules is increased. This point was originally intended in this

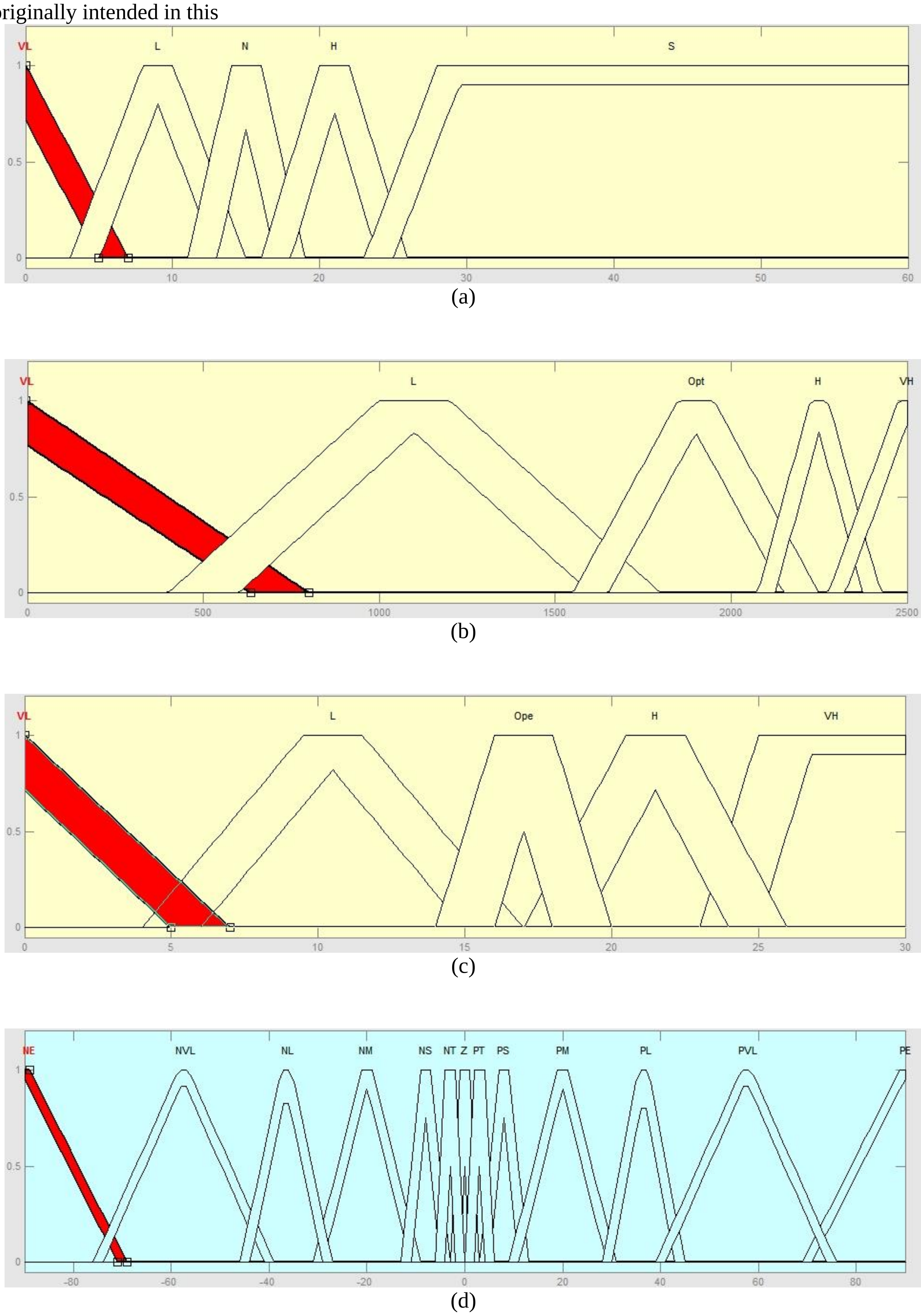


Figure 4. (a)The triangular functions of fuzzy sets for wind speed.(b)The triangular functions of fuzzy sets for output power.(c)The triangular functions of fuzzy sets for rotor speed.(d)The triangular functions of fuzzy sets for pitch angle.

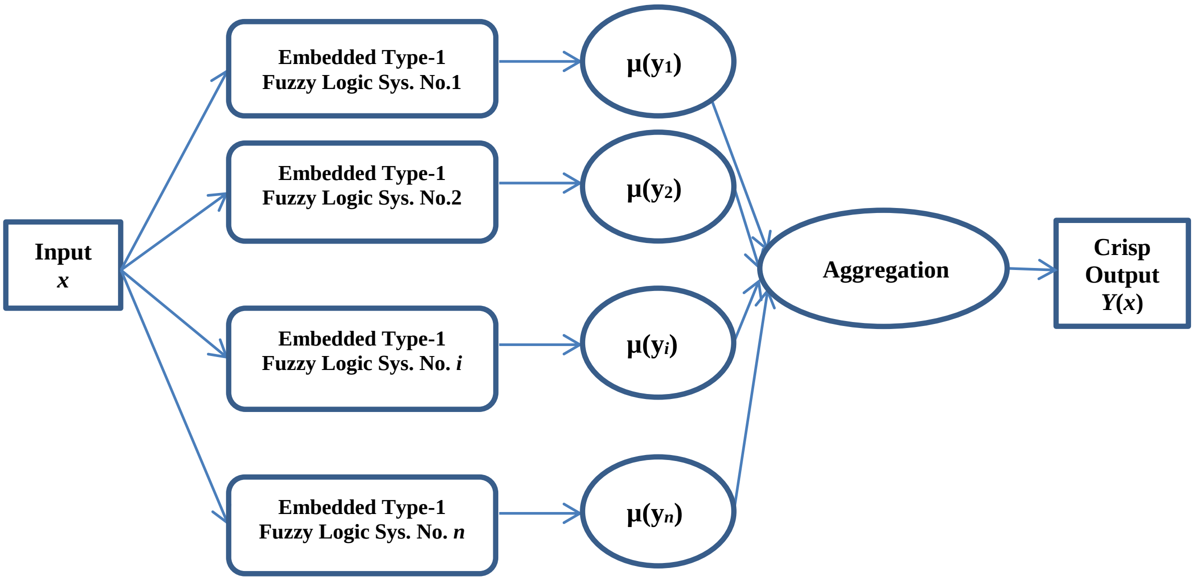


Figure 5. Type reduction and Defuzzificaion method.

Table 1. The wind turbine characteristics [28]

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 wind speed fuzzy sets

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 output power fuzzy sets

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]

Table 4. The rotor speed fuzzy sets

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 pitch angle fuzzy sets

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

V_w	VL					L					N					H					S				
P_{ou}	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

research, and linguistic variables were defined with the maximum number of suitable values. Another method is to study overlaps of adjacent fuzzy sets, which has been considered in designing system. Moreover, increase of the number of rules may also improve the performance of system. So, all possible rules have been defined. The membership functions of the fuzzy sets can also be changed. The Gaussian functions can help to prevent sudden variations of output values. As a result, the membership functions are shown in the following figures (Fig. 7). Furthermore, Sugeno method is suggested according to nonlinearity of the problem. It will increase the accuracy of the calculations. The zero-order type of Sugeno method will be applied, and then the values of the linguistic variables in output will be converted to the constant numbers (Table 7). It should be noted that the values in table 7 have been obtained from average of the numerical range in Table 5. Moreover, the center-of-sum method has been used in Defuzzification and Type Reduction steps to keep the highest compatibility of the method with selected inference. The diagrams in figures 8 obtained after applying all changes. The Diagrams show that tuning step has increased the ratio of the changes in pitch angle related to the other parameters. It will increase sensitivity of the controller on changes in input values to calculate a suitable output.

3. Results and Discussion

3.1. IT2FL Controller V.S. Type-1 Fuzzy Logic Controller

For assessment and evaluation of the designed controller, A wind turbine model of Simulink Software [29] has been altered and its controller has been substituted by the designed controller and performance of Interval Type-2 Fuzzy Logic Controller was studied in compare with result of Type-1 Fuzzy Logic Controller of another

similar work in this field [11]. This article proposed a new approach to pitch control of 2MW wind turbine with servo-hydraulic actuators similar to our model. The controller that is applied to adjust the pitch angle is a Type-1 fuzzy logic controller. In this research, the suitable performance of the controller in pitch control is evaluated by measuring the generator torque in the first 600 second of simulation. The relation between input generator power and generator torque is as follow:

$$P_{in} = \omega_g * T \quad (2)$$

P_{in} is the input generator power in watt, ω_g is the generator angular speed (2πN/60) and T is the generator torque in (Nm).

The generator output power is approximately 95 percent of input generator power. This constant value is considered as A.

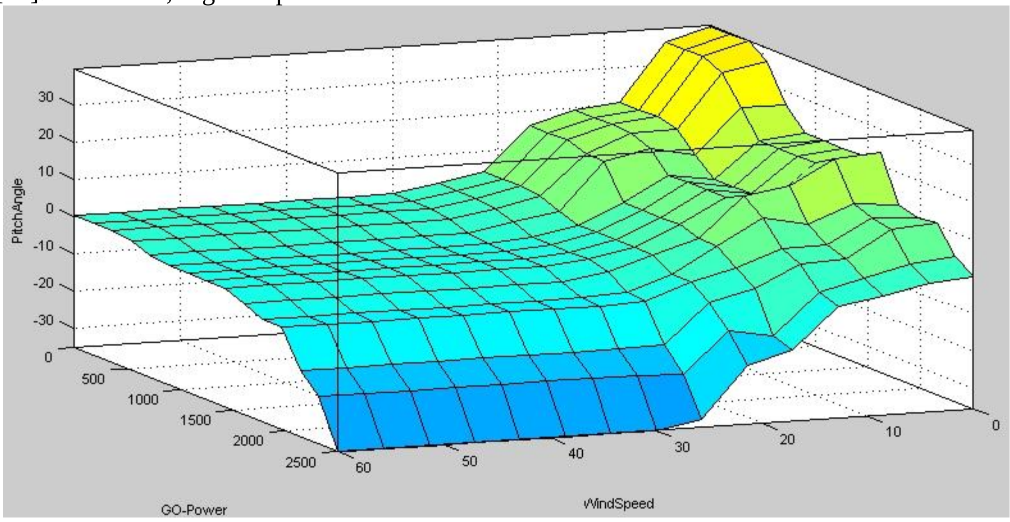
$$P_{out} = A * P_{in} \quad (3)$$

P_{out} is the generator output power in watt and A is a constant.

According to equations (2) and (3):

$$P_{out} = A * \omega_g * T \quad (4)$$

Notice that in both wind turbine models ω_g has a constant value so, according to equation (4), the generator torque diagram and generator output power diagram are same in their shapes. As a result, a comparison can be made between the generator torque diagram of current research and generator torque diagram of mentioned article to prove high performance of Interval Type-2 Fuzzy Logic controller in adjusting pitch angle and controlling generator output power. Wind speed values of mentioned article included random input of wind speed for 600 seconds have been used as a input wind speed set in our simulation to compare two controllers [11]. As a result, Figure 9 presents the



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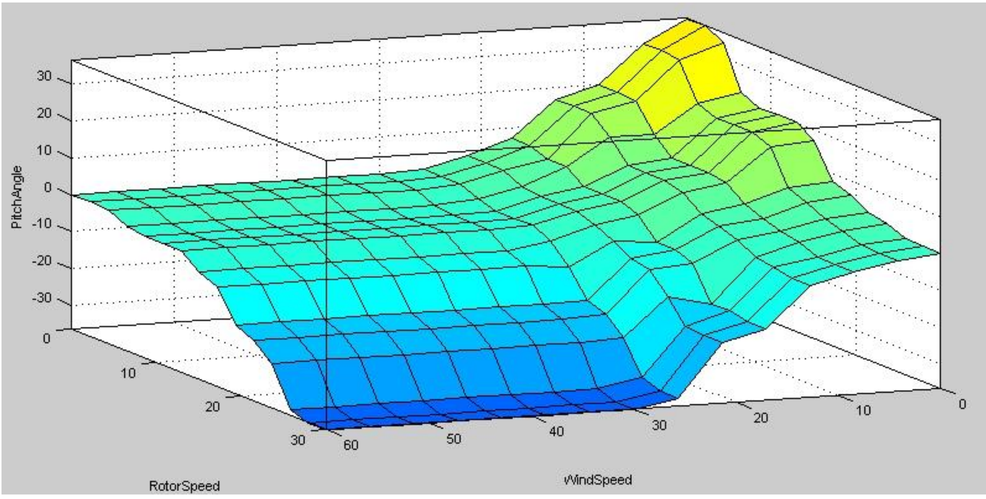

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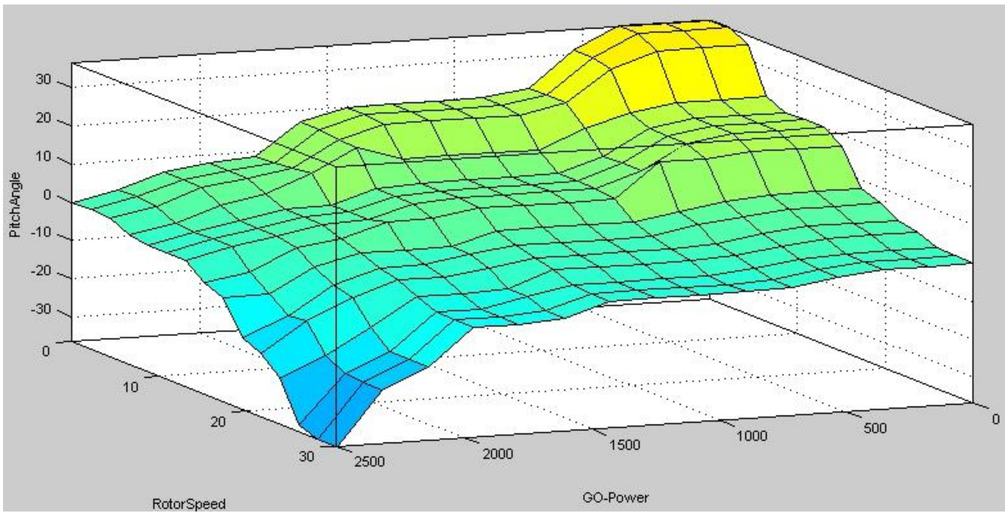
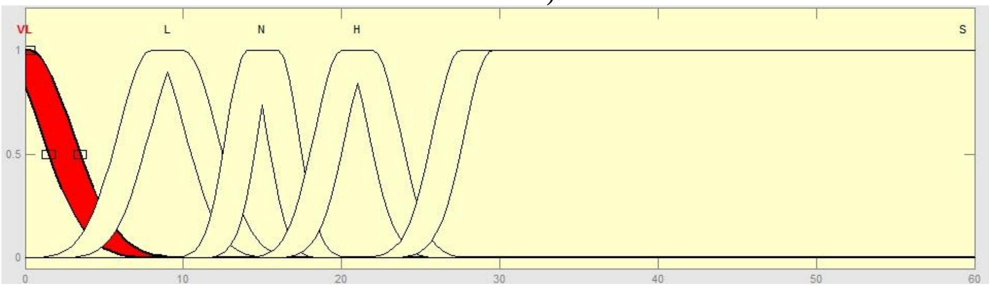


(c)

Figure 6. (a)Wind speed, output power and pitch angle (Nominal rotor speed is considered).(b)Wind speed, rotor speed and pitch angle (Nominal output power is considered).(c)Rotor speed, output power and pitch angle (Rated wind speed is considered).



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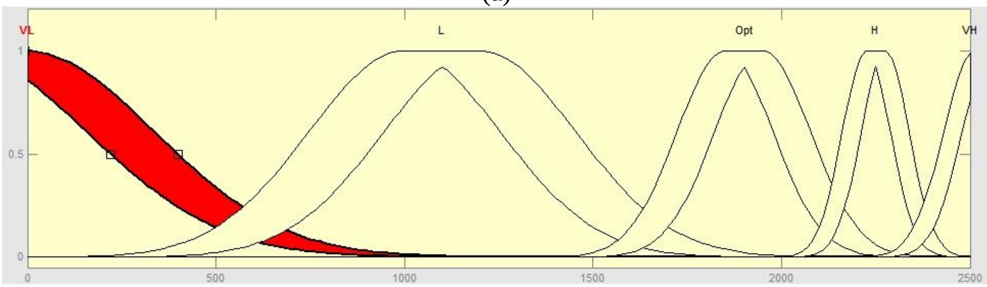

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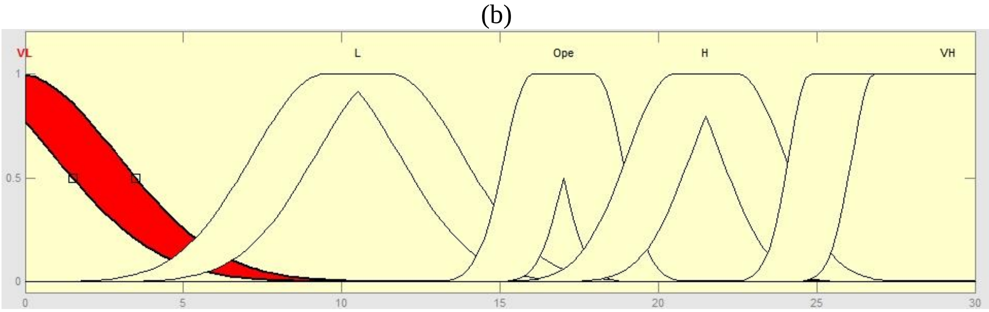


(c)

Figure 7. (a)The Gaussian functions of fuzzy sets for wind speed.(b)The Gaussian functions of fuzzy sets for output power.(c)The Gaussian functions of fuzzy sets for rotor speed.

Table 7. Pitch angles fuzzy sets of 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

generator torque diagram affected by IT2FL controller according to wind speed diagram.After 96 seconds, the turbine is in Generate state and the generator will be activated. Because of irregularity in wind speed, we have fluctuations in generator torque values but after 280 seconds, it will be controlled by IT2FL controller.

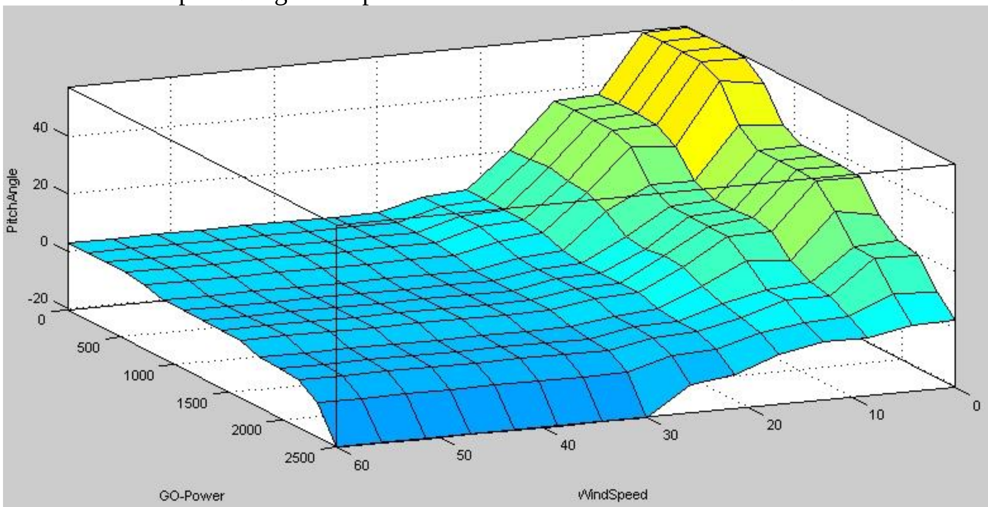
Table 8. Type-1 Fuzzy Logic Controller V.S. Interval Type-2 Fuzzy Logic Controller

	Rising Time	***Maximum Overshoot***	***Steady State Error***
Type-1 Fuzzy Logic Controller [11]	92s	53%	2.8%
Interval Type-2 Fuzzy Logic Controller	74s	65%	1.2%

It shows better functionality of IT2FL controller than Type-1 fuzzy controller, and according to equation (3-4), the generator output power is in nominate capacity value (Fig. 10).

3.2. Quantitative Comparison

Here, the quantitative comparison between IT2FL controller and Type-1 fuzzy controller is presented in theirs generator output powers and their torques. The significant attributes of diagrams like Rising time, maximum overshoot and steady state error will be compared. Figure 11 presents important values in generator Torque diagram. Final results are indicated in table 8.



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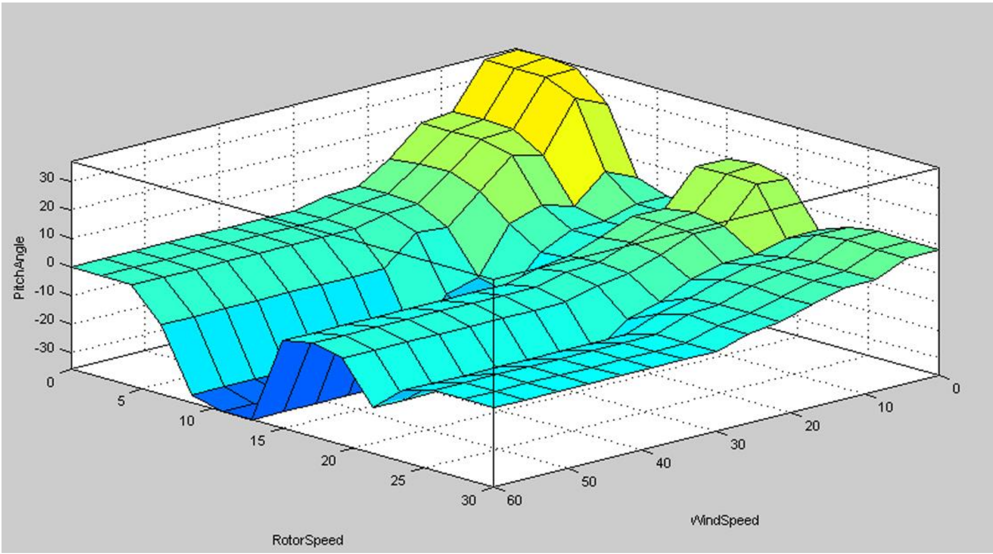

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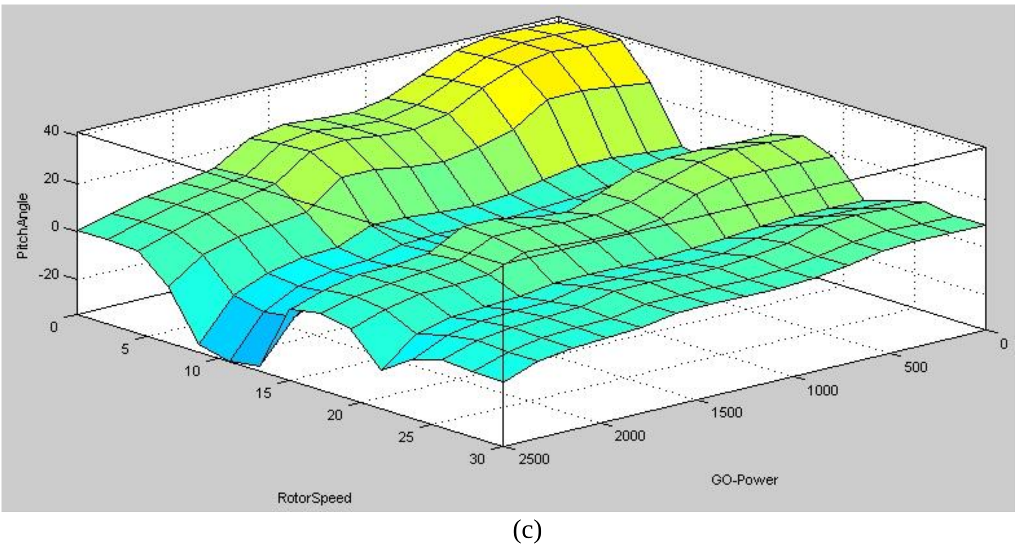

(c)

Figure 8. (a)Wind speed, output power and pitch angle (Nominal rotor speed is considered).(b)Wind speed, rotor speed and pitch angle (Nominal output power is considered).(c)Rotor speed, output power and pitch angle (Rated wind speed is considered).

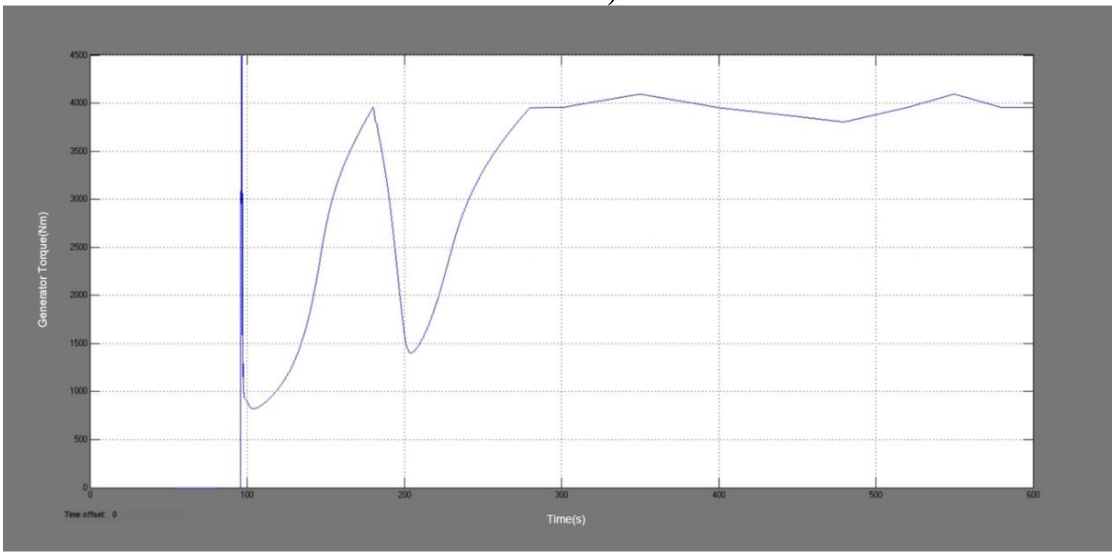

Fig.9. The generator torque (Interval Type-2 Fuzzy Logic controller).

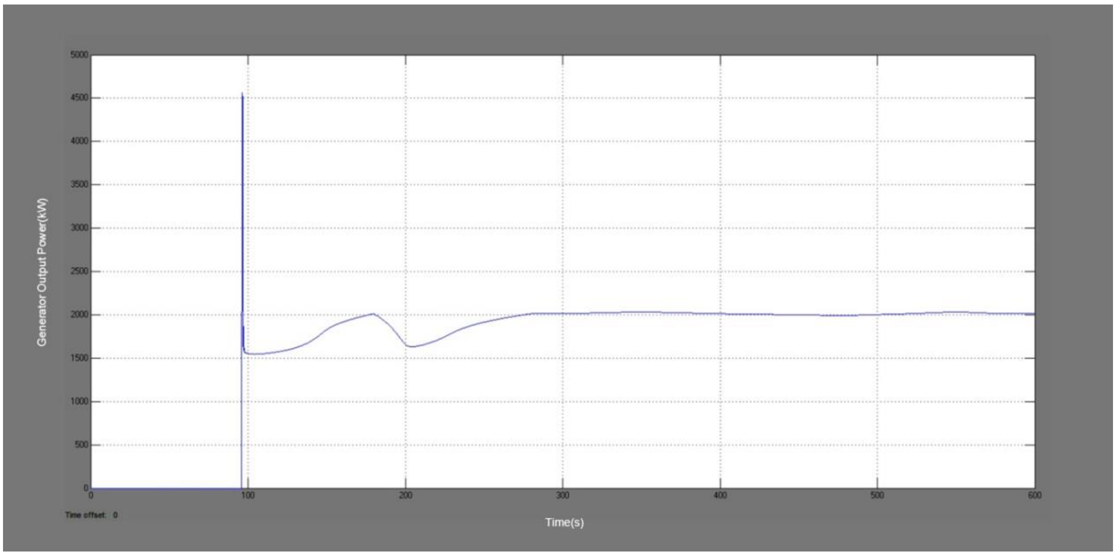

Fig. 10. The generator output power (Interval Type-2 Fuzzy Logic controller).

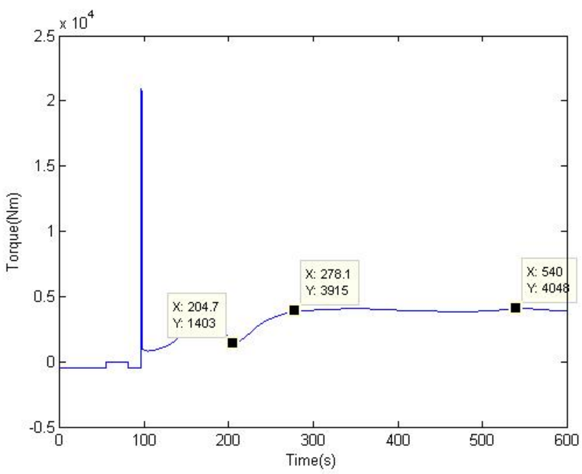

Fig. 11. Quantitative diagram of the generator torque (Interval Type-2 Fuzzy Logic Controller).

The Generator torque amplitude in IT2FL Controller is higher than Type-1 Fuzzy Logic Controller, rise time and error value in the steady state of the IT2FL controller diagram are lower than Type-1 Fuzzy Logic Controller.

4. Conclusion

Pitch Control will optimize output power and reduce fatigue loads in modern wind turbines. In the present study, the interval type-2 fuzzy logic theory was utilized in designing the pitch controller. In addition of fuzzy controller's common advantages, the fuzzy controller performance was better than other methods in pitch control, which is proven by some specific advantages. Results of this study indicated that applying interval type-2 fuzzy logic theory instead of the type-1 fuzzy logic theory, which is commonly applied in other works, resulted in more completed description of uncertainty concepts in existing parameters and more accuracy in result. Observance of the overlaps between adjacent fuzzy set functions was presented in designing fuzzy inference system. Applying wide range of values for each linguistic variable and therefore, reduction in length of their assigned intervals, led to increase the number of the generated rules. Using the highest number of fuzzy rules to consider all possible situations according to experiences of experts, consideration of suitable type for input membership functions, and finally, the possibility of selecting a proper inference engine compatible with nature of the problem are other specific advantages of present study, which has been proven in compare with the Type-1 Fuzzy Logic controller, quantitatively.

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