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BLADE PITCH ANGLE CONTROLLER IN WIND TURBINES

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IN
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BY

NOOR FAISAL SALIH AL-MAHDI

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March 2023

We certify that we have read this thesis and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science

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Noor Faisal Salih AL-MAHDI

ABSTRACT

BLADE PITCH ANGLE CONTROLLER IN WIND TURBINES

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Advisor: Prof. Dr. Halil Tanyer EYYUBOĞLU
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March 2023

Wind turbines have become the most important renewable energy source. When the speed of Wind turbines is above nominal, the blade pitch angle has to be controlled to ensure that the wind turbines operate safely and the output power is stable. The present research is an attempt to determine the type of control concerning the angle of inclination for blade pitch in wind turbines by applying the MATLAB (Simulink) program and modern control systems to obtain the best and highest output power. Firstly, the basic system of wind turbines is addressed, followed by the design of the proposed model and the basic mathematical equations by taking into account the external factors related to the wind turbine blades that affect the speed of rotation of the turbine. In this thesis, five types of control; PID, Fuzzy logic, Fuzzy logic with PID, Fuzzy Type- 2, and Fuzzy Type- 2 with PID have been applied and compared. The results showed that Fuzzy Type- 2 with PID provides the best controls. Finally, the ideal wind speed that works in wind turbines is determined along with the best blade pitch angle to generate electricity without any loss.

2023, 55 pages

Keywords: Pitch angle, PID control, Fuzzy logic control, Fuzzy-PID control, Fuzzy Type- 2, and Fuzzy Type 2-PID.

ÖZET

RÜZGAR TÜRBİNLERİNDE KANAT AÇISI KONTROL CİHAZİ

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Mart 2023

Rüzgar türbinleri en önemli yenilenebilir enerji kaynağı haline geldi. Rüzgar türbinlerinin hızı nominalin üzerinde olduğunda, rüzgar türbinlerinin güvenli bir şekilde çalışmasını ve çıkış gücünün kararlı olmasını sağlamak için kanat eğim açısının kontrol edilmesi gerekir. Bu araştırma, en iyi ve en yüksek çıkış gücünü elde etmek için Matlab (Simulink) programı ve modern kontrol sistemleri uygulanarak rüzgar türbinlerinde kanat eğim açısına ilişkin kontrol tipini belirleme girişimidir. İlk olarak rüzgar türbinlerinin temel sistemi ele alınmış, ardından rüzgar türbininin dönme hızına etki eden rüzgar türbini kanatları ile ilgili dış etkenler dikkate alınarak önerilen modelin tasarımı ve temel matematiksel denklemler verilmiştir. Bu tezde, beş tür kontrol; PID, Fuzzy logic, PID ile Fuzzy logic, Fuzzy Type- 2 ve PID ile Fuzzy Type- 2 uygulandı ve karşılaştırıldı. Sonuçlar, PID'li Fuzzy Type-2'nin en iyi kontrolleri sağladığını gösterdi. Son olarak, kayıpsız elektrik üretebilmek için rüzgar türbinlerinde çalışacak ideal rüzgar hızı ve en iyi kanat hatve açısı belirlenir.

2023, 55 sayfa

Anahtar Kelimeler: Adım açısı, PID kontrolü, Fuzzy logic kontrolü, PID ile Fuzzy logic kontrolü, Fuzzy Type- 2, ve PID ile Fuzzy Type- 2.

PREFACE AND ACKNOWLEDGEMENTS

Throughout time, although of difficulties in life and finding enough time to study and enhance my knowledge in my academic specialization, we could achieve one of my important ambitions, I became aware that we can achieve the goal anywhere and anytime just we need to not giving up on lofty goals, no matter how long just need to seize the opportunities and be brave and begin your adventure. On this occasion, I would like firstly to thank my supervisor Prof. Dr. Halil Tanyer EYYUBOĞLU, and co-Advisor Asst. Prof. Dr. Zafer CİVELEK, for his patience, guidance, and understanding. Also, thank my family and particularly my wife for supporting me all the time.

Noor Faisal Salih AL-MAHDI
Çankırı-2023

CONTENTS

LIST OF SYMBOLS

P	Output power
ρ	Air density
A	Area swept by the blades
v	Wind speed
C_p	Power factor
β	Blade Pitch angle
λ	Blade tip speed ratio
P_{wt}	Mechanical power of a Wind Turbine
$C_p(\beta,\lambda)$	Power parameter of wind turbine
W_{wt}	Wind turbine rotor angle speed
R	Wind turbine blade radius
P_r	Rotor power
r(t)	Input variable
e(t)	Error signal
u(t)	Output from the control
n(t)	Actual output
T	Controlled target
c(t)	Crisp output
K_p	Proportional parameter
K_i	Integral parameter
K_d	Differential parameter
x,y	Set of elements x,y
μ_x	Represents the expected value of some random variable x
∩	Union of fuzzy sets
U	The intersection of fuzzy sets

LIST OF ABBREVIATIONS

AC	Alternating current
DC	Direct current
FLC	Fuzzy logic control
FLCs	Fuzzy logic control system
FOU	Footprint of uncertainty
HAWT	Horizontal axis wind turbine
LMF	Lower membership function
MF	Membership function
PID	PID control
PMSG	Permanent magnet synchronous generator
TS	Takagi sugeno
TSK	Takagi sugeno kang
TSR	Tip speed ratio
Type-1 FLC	Type 1 fuzzy logic control
Type-1 FLC-PID	Fuzzy-PID control
Type-2 FLC	Type 2 fuzzy logic control
Type-2 FLC-PID	Fuzzy type 2 – PID control
UMF	Upper membership function
VAWT	Vertical axis wind turbine
WTs	Wind turbine system

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1 INTRODUCTION

Speed is arguably the most fundamental feature of wind in today's non-fossil-based energy production initiatives. In essence, wind speed differs in accordance with geography and atmospheric conditions around the globe. Since wind speed can be irregular, the related information is generally obtained by means of measurable techniques (Tong 2010).

The year-to-year variety of the mean wind speed depends exclusively on the region in point and, as a result, there is no easy way to predict it. Wind changes with the topographical areas, time of day, season, altitude, climate, and surroundings. For this reason, understanding wind characteristics will assist in enhancing wind turbine configuration, improving wind measurement, and selecting wind destinations (Tong 2010).

As a result, the theoretical maximum efficiency has not yet been reached (Liang and Mendel 2000).

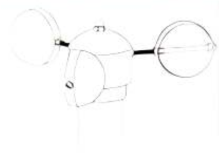
Many different design styles have developed over the year some of the more distinctive ones are included in Specify.

As an example of the earliest models of wind use, Persian windmills used the drag created by sails made of fabric and wood. These windmills still share many characteristics with their contemporary equivalent, the Savonius rotor, which is in use today to rotate advertising signs and ventilation cowls (Schubel and Crossley 2012).

The cup-type differential drag rotor operates similarly owing to its simplicity in calibration paired with the ease to operate in multiple directions. Today's anemometers use them to calculate airspeed. Another example is the old farm windmill in the United States as an antique illustration of a distinctly solid, excessive torque-raise pushed rotor that is nevertheless in use even today for water pumping functions. Another early lift-type apparatus used for grinding maize is the Dutch windmill, which has since fallen out of common use, though a few still remain as tourist attractions (Schubel and Crossley 2012).

The Darrieus VAWT, despite major improvements, is an aerodynamic aerofoil blade design that has not been able to compete with the modern-day HAWT diagram. However, new advancements may herald a comeback for this rotor type. The airfoil three-bladed HAWT is exceptionally easy to manipulate, an ideal alternative for use in wind turbines, and, as such, continues its dominance in this field for the foreseeable future. However, in terms of the theory, the best efficiency is yet to be obtained. Over the past decades, many different plans and designs have emerged, the most outstanding of which are listed in Table 1.1 (Schubel and Crossley 2012).

Table 1.1 Modern and historical rotor designs (Schubel and Crossley 2012)

No.	Design	Orientation	Use	Propulsion	Efficiency %	Diagram
1	Savonius rotor	VAWT	Historic Persian windmill to modern-day ventilation	Drag	16	
2	Cup	VAWT	Modern-day cup anemometer	Drag	8	
3	American farm windmill	HAWT	18th century to present-day, farm use for Pumping water, grinding wheat, generating electricity	Lift	31	
4	Dutch Windmill	HAWT	16th Century, used for grinding wheat	Lift	27	
5	Darrieus Rotor	VAWT	20th century electricity generation	Lift	40	
6	Modern Wind Turbine	HAWT	20th century electricity generation	Lift	QTY of Blade: Efficiency 1: 43% 2: 47% 3: 50%	

The sector related to large-scale wind turbines is currently dominated by the three-blade design in wind turbines Figure 1.1 which has been widely adopted as the most effective approach to address environmental, commercial, and cost-related concerns. The modern wind turbines that are available for sale have sophisticated safety and control systems, remote monitoring, and lightning protection (Schubel and Crossley 2012).

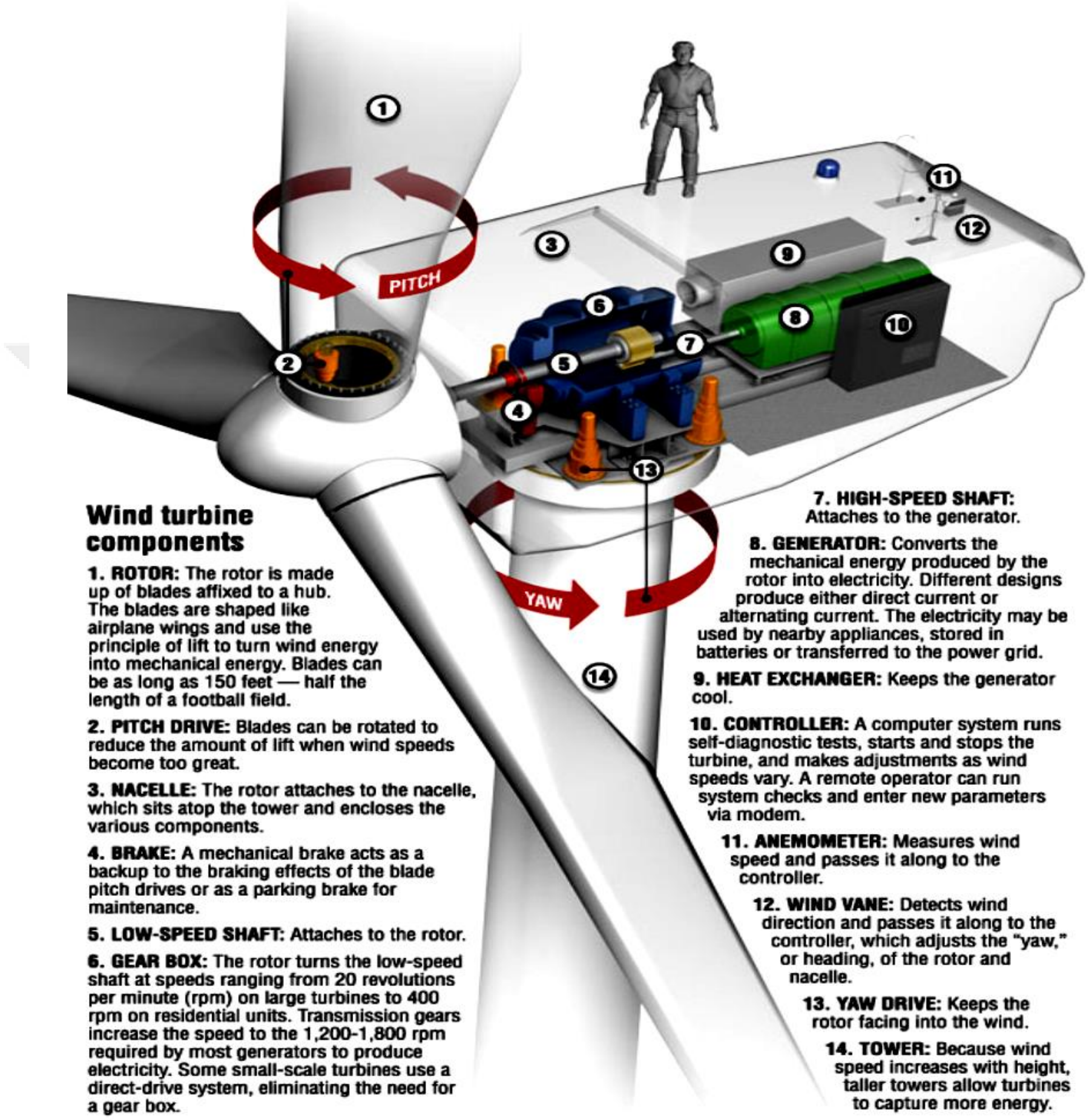


Figure 1.1 A modern, large-scale wind turbine, in its typical configuration (Schubel and Crossley 2012).

Pitch control, as an important property, is required in a number of unique operating circumstances.

Low-rated wind speeds must be controlled, the power grid must be injected into inertia, and low-voltage crossings must be avoided with contained energy. It is crucial to keep in mind, however, that the present research on pitch control over the rated wind speed aims to balance the power. Figures 1.2 and 1.3 show how the blades respond to changes in pitch and the variable-pitch drive mechanism, respectively (Zhou and Liu 2018).

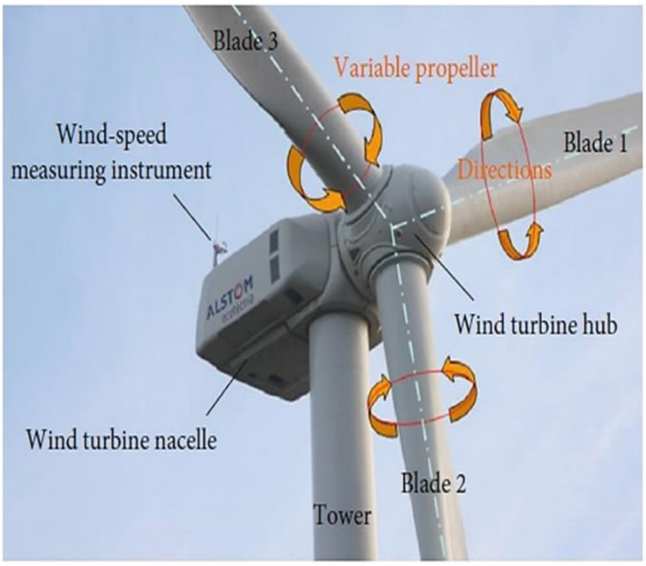


Figure 1.2 Hub wind turbine driving system with variable pitch (Zhou and Liu 2018)

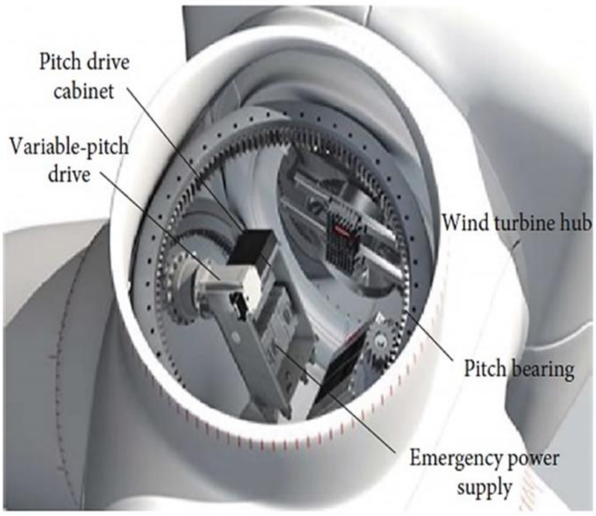


Figure 1.3 Blades action under pitch-controlled (Zhou and Liu 2018)

2 MATHEMATICAL MODEL OF WIND TURBINE

A conventional horizontal-axis, three-blade wind turbine was depicted in Figure 2.1. The hub, the nacelle, the tower, and the blades were the main parts of the wind turbine system. According to (Saravanakumar and Jena 2015), several actuators and sensors may be used to regulate activity processing and monitoring in a contemporary megawatt turbine.

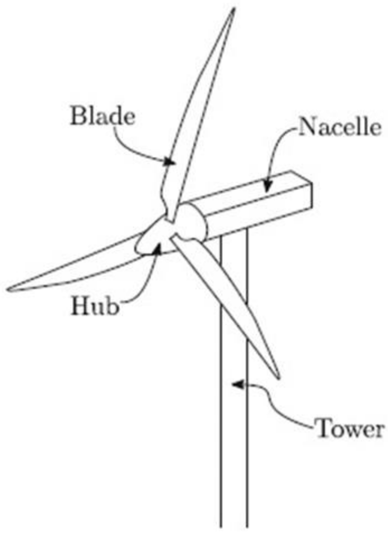


Figure 2.1 A horizontal-axis wind turbine, often consisting of three blades whose rotational speeds may vary (Saravanakumar and Jena 2015)

Briefly discussing actuators and sensors. Blade load sensors, such as pressure gauges or fiber optics, were put at the base of the blades to detect the bending moments at the flaps and edges, and pitch actuators were utilized to adjust the pitch angles inside the turbine blades. Also, the nacelle's rotating velocity was calculated using a generator and rotational speed sensors, and wind speed at hub height was measured and shown using an anemometer mounted on top of the nacelle (Lio 2017).

One of the most significant and advanced technologies utilized to generate power today is the wind turbine. This method produces electricity in a sustainable and safe manner. This process works by first converting the wind's potential energy into mechanical energy, which is subsequently converted into electricity. Since wind energy is being absorbed into the power grid, it is vital to understand how wind turbine technologies impact frequency and voltage stability (Lio 2017).

The system works according to the basic Equation (2.1) which are:

$$P = 0.5\ \rho\ A\ v^3 \tag{2.1}$$

Wind speed and power fluctuations are graphically illustrated in Figure 2.2.

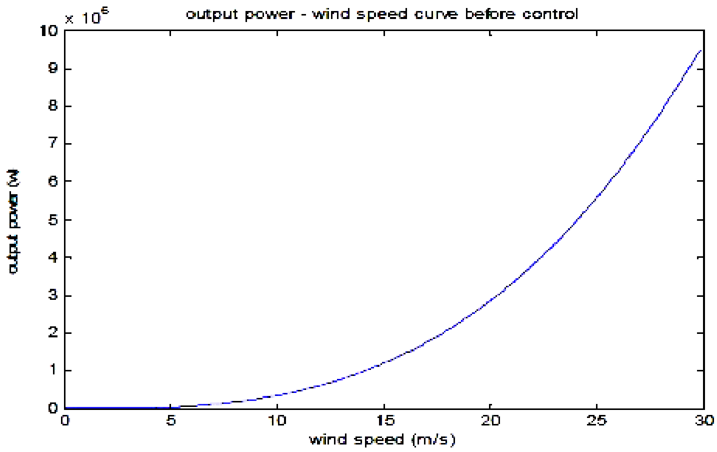


Figure 2.2 Changes in wind speed and power

Previous research has shown that the mechanical power, Pwt, of a wind turbine can be calculated by solving Equations (2.2) and (2.3). This calculation is based on the connection between the Cp power factor and the position of the blade tip, which is graphically shown in Figure 2.3. It is noted that two factors can impact the turbine's rotational speed: the blade pitch angle and the blade tip speed ratio. This is because wind turbines rotate in order to produce electricity using the kinetic energy of the wind.

$$P_{wt} = P\ C_p\ (\beta, \lambda) \tag{2.2}$$

$$P_{wt} = 0.5\ \rho A v^3 C_p(\beta, \lambda) \tag{2.3}$$

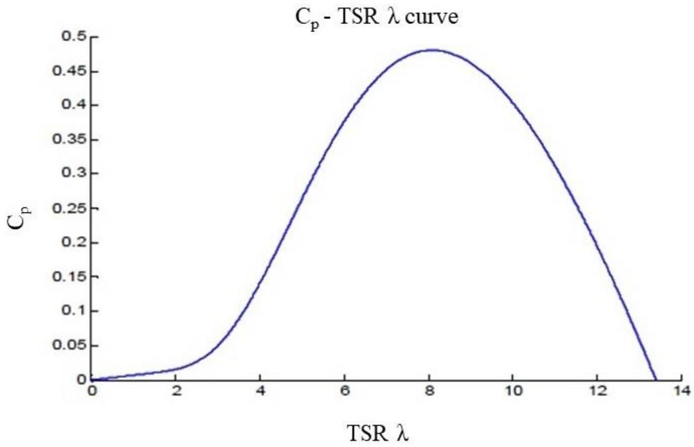


Figure 2.3 Power Parameter C_p - Blade Tip Speed Ratio λ relationship

The relationship between the power parameter C_p and the blade tip speed ratio λ when the blade angle β is 0 degrees is represented by Figure 2.3.

The power parameter C_p is nonlinear at most and it can change according to wind speed variations in the system, as shown in Equation (2.4) (Xu *et al.* 2020).

$$C_p = 0.5176(\frac{116}{\lambda_i} - 0.4\beta - 5)e^{\frac{-21}{\lambda_i}} + 0.0068\lambda \tag{2.4}$$

A replacement of λi in Equation (2.4) and Equation (2.5) with the tip speed ratio λ, as defined by the change in the angle inclination velocity and the average wind speed, was reported to result in Equation (2.6) (Civelek et al. 2016).

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{3\beta + 1} \tag{2.5}$$

$$\lambda = \frac{W_{wt}R}{v} \tag{2.6}$$

In Figure 2.4, the C_p - blade tip speed ratio λ curves for different blade pitch angles β are shown (Civelek 2020).

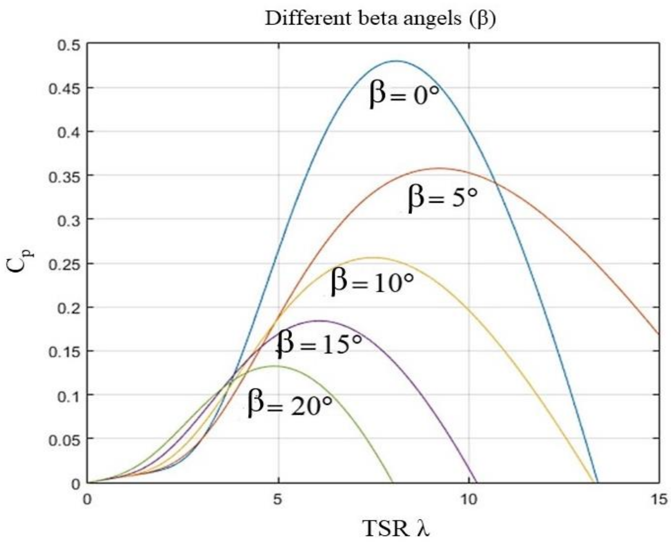


Figure 2.4 Curves for different beta angels (β) (Civelek 2020)

Table 2.1 lists the effects of an increase or decrease in tip speed ratio.

Table 2.1 Tip speed ratio design considerations (Schubel and Crossley 2012)

Tip speed ratio	High	Low
Value	Tip Speeds higher than 10 are considered high	Tip speeds of one to two are considered low
Utilization	Mainly single or two bladed prototypes	Traditional windmills and water pumps
Togue	Decreases	Increases
Efficiency	Insignificant increases after eight	Decreases significantly below five due to rotational wake created by high torque
Centrifugal Stress	Increases as a square of rotational velocity	Decreases
Aerodynamic Stress	Increases proportionally with rotational velocity	Decreases
Area of Solidity	Decreases significantly	Increases, multiple 20+ blades required
Blade Profile	Significantly Narrow	Large
Aerodynamics	Critical	Simple

Here, we see, shown by Equation (2.7), the connection between wind velocity, blade pitch angle, and rotor power (mechanical power) (Baburajan 2017) Figure 2.5 shows a diagram that illustrates this.

$$P_r = C_p\,(\beta,\lambda)P = C_p\,(\beta,\lambda)0.5\,\rho\,A\,v^3 \qquad (2.7)$$

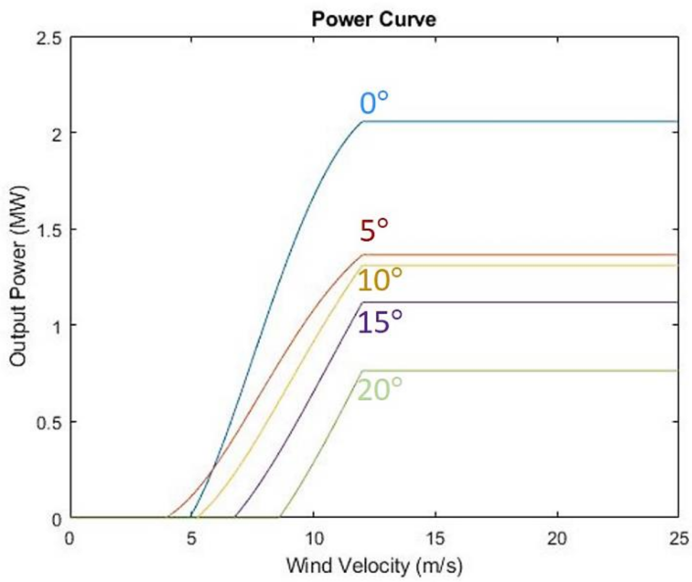


Figure 2.5 Power loss due to change in pitch angle (Lara *et al.* 2021)

The relationship between wind speeds and the amount of electricity produced by a wind turbine was illustrated by the energy curve of a wind turbine in Figure 2.6. (Lara *et al.* 2021).

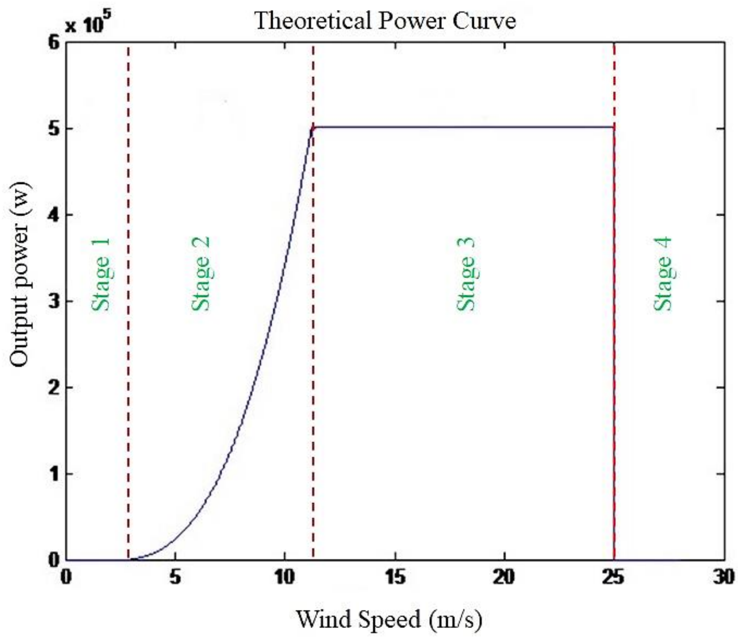


Figure 2.6 Wind turbine power curve characteristics (Lara *et al.* 2021)

The mechanical output power in wind turbines varies throughout four stages:

First: The output power is zero because of slow wind turbine rotation.
Second: The output power is between the cut-in and normal speed (partial load regime).
Third: The output power is normal between cut-in and cut-off (Full-load regime).
Fourth: The output power is cut off due to exceeding the speed limit to protect the system.

In Figure 2.6, the energy properties of a wind turbine are illustrated, showing that the output power generated quickly decreases as wind speed rises. This phenomenon is explained by the solution of Equation 2.1, while the output power is seen to double with every doubling and half of the wind speed (Baburajan 2017).

3 WIND TURBINE CONTROL

3.1 Wind Turbine Simplifications

As mentioned early in chapter one, the wind turbine contains several mechanical components. These components are connected in series in order to convert wind energy into electrical energy. In order to simulate the wind turbine components mechanisms and design the best controller, the wind turbine components have been simplified as shown in the structure diagram in Figure 3.1

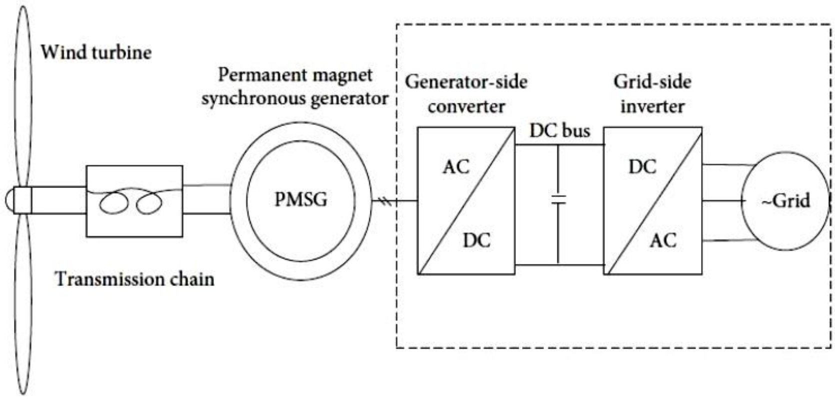


Figure 3.1 Wind turbine whole structure diagram

Because of the system's reliance on wind energy, any variations in the turbines' rotational speed or output power must be kept to a minimum. To solve this problem, engineers have turned to the permanent magnet synchronous generator PMSG. Two stages of fully controlled frequency converters connect the PMSG to the grid.

- In order to achieve high performance, the PMSG relies on the rectifier AC/DC converter, which, unlike diode and thyristor rectifiers, can provide sinusoidal currents.
- The DC-to-AC inverter regulates the DC-LINK, guarantees a constant output voltage, and feeds only active power into the grid.

A DC bus was connected to the rectifier and inverter and the performance of the Permanent Magnet Synchronous Generator (PMSG) was evaluated in terms of its compact design, low weight, high air-gap flux density, power density, torque-to-inertia ratio, torque capabilities, and overall performance. A novel method of pitch angle control based on fuzzy logic control was proposed to address the nonlinear features of wind turbines and reduce the stresses on the blades. Five controllers were used to verify the mathematical model of the wind turbine (pitch control system) which included the PID, the Fuzzy logic, the Fuzzy-PID, the Fuzzy Type-2, and the Fuzzy Type 2-PID. Simulation results showed that the Fuzzy Type 2-PID was capable of governing the pitch system, the disturbances, and unpredictable elements. This controller showed the best performance of the simplified wind turbine system WTs as shown in Figure 3.1.

3.2 PID Control

The most common and widely used mechanism for controlling the pitch angle change in wind turbines is PID. When the wind speed increases, the speed of rotation of the wind turbine also increases, necessitating a change in the angle of the blades to control the speed of the turbine.

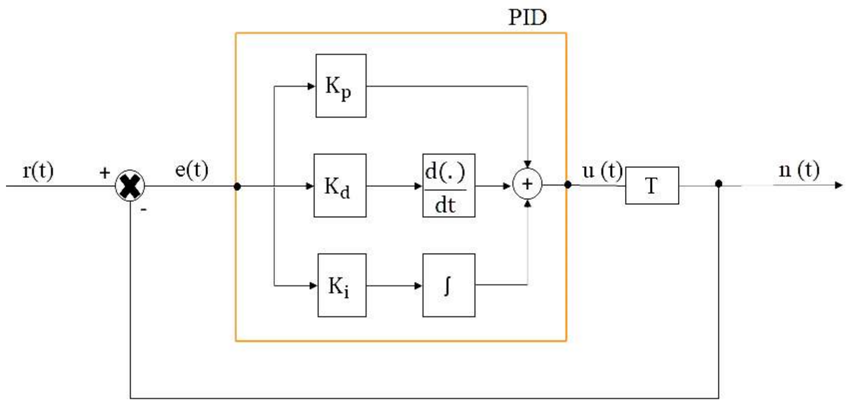


Figure 3.2 Basic components of a PID controller

It was illustrated that PID is composed of three variables, P percentage, I integration and D differential, which act as the input variables for the control function and the output that is acted upon by the controlled target T. (Baburajan 2017)

Concerning the PID control variables; e (t) define the tracking error which is the deviation between r (t) the desire input and n (t) the controlled target output. The PID controller uses e (t) the tracking error as input data. The PID computes it by means of the derivative and integral methods. u (t) defined as the PID controller output signal as defined in Equation (3.1) (Civelek *et al.* 2016).

$$u(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{de}{dt} \tag{3.1}$$

The PID controllers have a simple structure, high dependability, and good stability; yet, it relies too heavily on the model parameters of the controlled objects. However, The PID controller has poor resilience. Variable pitch control has drawbacks, such as the inability to precisely obtain the model structure and parameters and the presence of severe nonlinearity. Thus, making it difficult to achieve good control performance using a PID controller (Baburajan 2017).

Mode of Sliding Variable shape manage, additionally referred to as discrete transfer manage, can conquer the nonlinear consequences of a manage machine, making it acceptable for nonlinear, strong-coupling, and insensitive to adjustments in machine parameters variable pitch manage structures of wind turbines (Baburajan 2017).

Adaptive manage is a manage technique that could understand a manage version as a reference. When dynamic changes occur throughout the operation process, the adaptive management device detects those changes and adjusts the controller's parameters or manage algorithms in actual time to convey the given overall performance index to the maximum possible level while maintaining overall performance. As far as the modeling uncertainty of the variable pitch management of wind turbines is concerned, adaptive management has major benefits. The manage shape of conventional PID controllers consists of remarks manage. After passing device mistakes from proportional, integral, and by-product processes, the mistake is implemented to the device again (Baburajan 2017).

3.3 Fuzzy Logic Control

In MATLAB, fuzzy logic controller FLC is a very important application in the field of control, and it is used in a wide range and often credited with finding appropriate solutions due to its efficiency in designing control units. Using fuzzy, one can obtain good and fast results in the face of ambiguity and inaccuracy. What is more, those with little background in algorithms can find appropriate solutions and develop algorithms in a far less complicated manner that is both clear and understandable.

At times, FLC outperforms common manage structures (management systems) such as PID system, and even human operators (Mendel *et al.* 2014).

A non-linear system is notoriously difficult to model and control. In terms of dampening and regulation, the traditional controller falls short. As a result, to resolve this nonlinearity, an enhanced fuzzy controller is employed to solve the problem (Suganthi *et al.* 2015).

The two main algorithm classes in FLC may be identified principally by the sets of regulating parameters that each class uses to be identified. Linguistic ideas were used for their antecedents and consequents by Mamdani FLC rules, which were developed in 1975 by Mamdani and Assilian. Type-1 FLC sets were used to express the linguistic labels by a Mamdani FLC. Type-1 FLC sets were treated as the antecedents of the rules and the results of each rule were described as a mathematical function of the input variables by Takagi and Sugeno's TS FLC/TSK FLC (Mendel *et al.* 2014). FLCs are fundamentally constructed on fuzzy set conceptions, the presentation and reasoning of fuzzy linguistic information, and fuzzy good judgment criteria in order to emulate human questioning and reasoning. Figure 3.3 shows how a Type-1 FLC is built overall (Didier and Henri 1982).

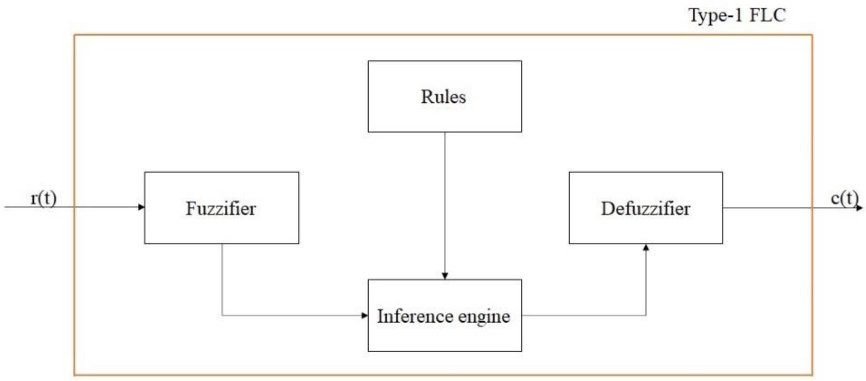


Figure 3.3 General structure of a Type-1 FLC (Baburajan 2017)

- Each r-valued input variable be. Noise or a lack of clarity was the reason why this was done, so that the uncertainty of a specific temperature measurement could be demonstrated by a Type-1 fuzzy set in the shape of a triangle with the recorded value of 25 degrees Celsius as its point. Discrete sets could be shown if it were assumed that all measurements were exact.
- The rule says that the fan speed should be low if both the pressure and the temperature are low. For each rule's IF condition, we have an antecedent, and for each rule's THEN condition, we have a consequence. Fuzzy input sets are linked to fuzzy output sets that are based on rules. A rule base is all the rules put together.
- The Fuzzifier was given to the Inference engine and the Defuzzifier was sent the degree of firing for each rule. The rule's output fuzzy set was then made by combining the rule's subsequent fuzzy set with the degree of firing and the aggregated fuzzy output set was made by combining all of these sets using fuzzy set mathematics.

3.3.1 Fuzzy set

The classical crisp set theory employs a more subtle logic to decide whether or not an item belongs to the set in contrast to the fuzzy set, a subset of the classical set. It can only contain parts under the theory of fuzzy sets, however each membership level is along a continuum between total inclusion and total exclusion (Hemeyine *et al.* 2020). Since objects may have membership degrees ranging from 0 to 1, membership functions are used to characterize the boundary of fuzzy logic sets (Wang 2015). Determining the most practical membership value or degree for each element yields the membership function MF, which is a curve that precisely specifies the nature of a fuzzy set. Figure 3.4 illustrates the translation of an input space point and a generic membership function curve to calculate a membership value within the closed unit interval [0, 1]. (Bogdan and Kovacic 2006). The membership value is shown on the vertical axis, indicated by x, while an input variable x is represented on the horizontal axis. The Support-of-Membership Function curve explains input variables having membership values other than zero. The region that supports the value x, where x is any point in the range [a, d].

The domain in which the input variable x has full membership is represented by a Core-of-Membership Function curve with x = 1. In other words, any point in the range [b, c] Core region is included in the fuzzy set produced by this membership function (Wang 2015).

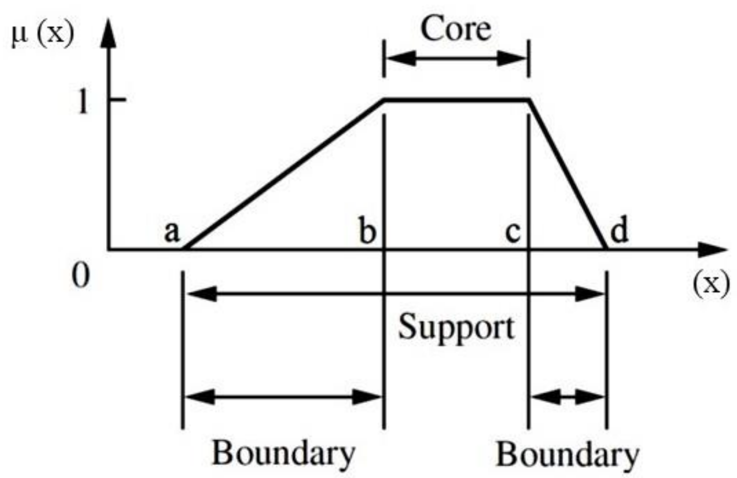


Figure 3.4 Representative membership function (Bogdan and Kovacic 2006)

3.3.2 Logical operation

The logic in fuzzy control is a particular case because the membership function is either 1, which represents TRUE, or 0, which represents FALSE. Therefore, consistent logical operations must be treated as equivalent to conventional logical operations.

Although NOT is the normal logical operation, AND and OR are the two most used logical operations.

In a fuzzy logic operation, the lowest value of "A" and "B" is equal to the expression "A AND B", while the maximum value of "A" and "B" is equivalent to the expression "A OR B". The logical NOT make operation is represented by NOT A, which can be written as 1 - A (Wang 2015).

3.3.3 IF-THEN rules

The parallel IF and THEN rules that make up FLC's inference process also help to describe how the output is produced using the input. Each IF-THEN fuzzy logic rule takes the form IF (x is A) THEN (y is B).

An input variable known as the Prior is the initial branch of an IF statement. The second THEN clause is known as the Resulting THEN clause, where y is an output variable (El-Fahham *et al.* 2021).

IF-THEN conditional expressions are practical and beneficial because, in the majority of situations, both A and B may be understood as linguistic values or adjectives. This if-then clause works similarly to how people make decisions. For instance, the cutting speed should be decreased if the material is very hard.

The intended result of determining the membership value of x inside fuzzy set A and assigning a sharp value to the output variable y, representing the fuzzy set B, was produced by the IF section (Wang 2015).

3.4 Fuzzy-PID Control

The combined Type-1 FLC-PID control will maintain and protect the linear structure of the output wave in a steady form by a procedure called ‘tuning’ – more accurately put, either self-tuning or non-self-tuning - where one can adjust the parameters related to PID (Tang *et al.* 2001).

The adaptive Type-1 FLC-PID controller has smoother outputs than the conventional PID method. The Type-1 FLC-PID controller in the wind turbine allows for a continuous motion of the pitch angle of the blades as an output. Fuzzy adjustments to PID parameters boost wind turbine speed responsiveness over just using a PID controller (Hamoodi *et al.* 2020).

The three parameters of PID control, Kp, Ki, and Kd, are adjusted by the FLC using the pitch error values as input. The primary basis for adjusting the PID controller's three settings is the most recent pitch variation. A Type-1 FLC-PID controller is illustrated in Figure 3.5 (Baburajan 2017).

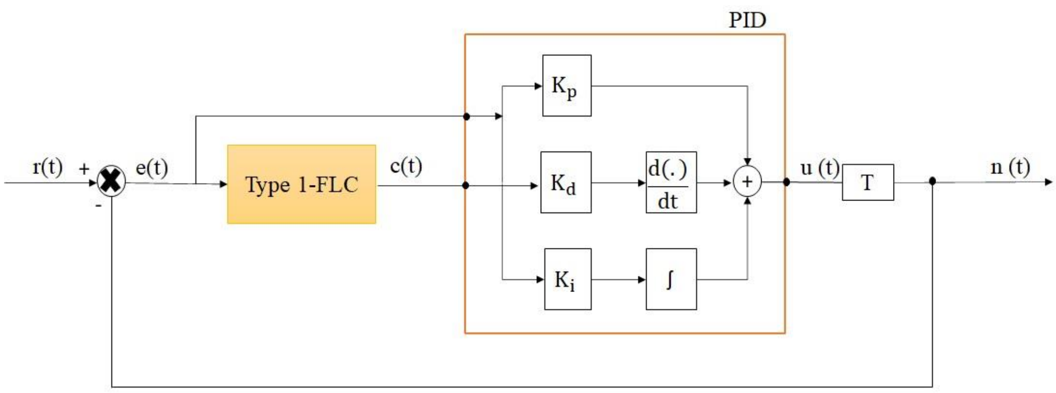


Figure 3.5 Type-1 FLC-PID structure (Baburajan 2017)

It can be stated that intelligent strategies outperform standard control methods in terms of achieving pitch angle control and ensuring wind turbine output power stabilization.

3.5 Fuzzy Type-2 Control

Type-2 FLC and Type-1 FLC have been found to be similar on the inside, with the most notable similarity being that the Type-2 FLC set has great sensitivity. This has been found to be helpful and broadly applicable when the conditions are unknown, allowing for more accurate findings to be obtained. Type-2 FLC has also been found to provide superior control performance over Type-1 FLC due to the extra degree of freedom afforded by the Footprint of Uncertainty FOU in the membership functions. However, the Span Type-2 FLC's control surfaces are more refined, making the Type-2 FLC rational regulators difficult to dissect and design for due to their more complex internal architecture. (Karnik and Mendel 1999, Liang and Mendel 2000, Kumbasar *et al.* 2012).

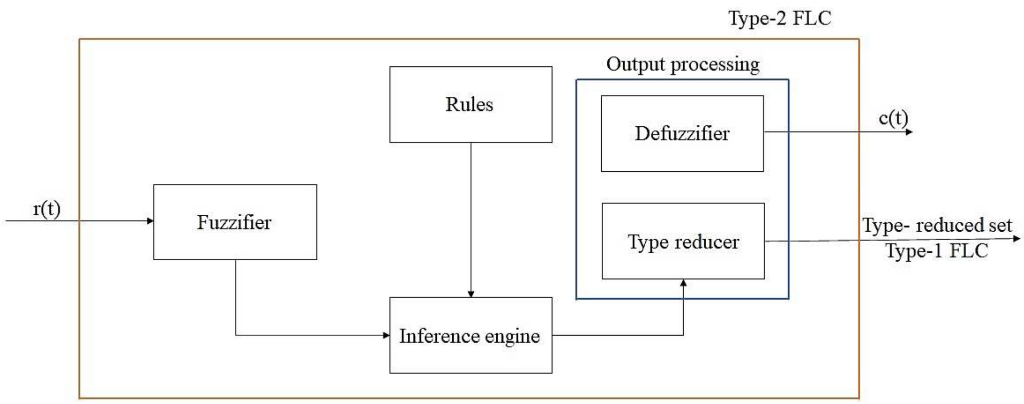


Figure 3.6 General structure of a Type-2 FLC (Kumbasar *et al.* 2012)

The process of output processing with a Type-2 FLC is achieved by using the five basic components shown in Figure 3.6: the Fuzzifier, the Rules, the Inference engine, the Type reduction, and the Defuzzifier. The input sensors provide clean data to the Fuzzifier which then fuzzes it up in the Type-2 FLC. The Inference engine is then used with the input and the same rules as a Type-1 FLC. The resulting Type-1 FLC is then fed into a Defuzzifier to provide a clean output which can be used as a command to an actuator in the control system. This output processing process often entails type reduction followed by defuzzification, thus making the Type-2 FLC an efficient tool for output processing (Mendel *et al.* 2014; Vi Ngo, Q *et al.* 2020).

3.5.1 Fuzzy Type-2 set

The development of the Membership functions of fuzzy sets has been done in order to describe the numerous sources of uncertainty, which Type-1 FLC sets are unable to properly depict due to their fully crisp Membership functions (Castillo and Melin 2008). However, Type-2 FLC sets have fuzzy Membership functions.

Studies of Type-1 FLC sets demonstrate that they have a two-dimensional Membership function, whereas the addition of a single dimension to a Type-2 FLC set produces three-dimensional Membership functions (Al Shnaikat 2013).

3.5.2 Fuzzy Type-2 membership functions

Type-2 FLC systems with their Upper Membership Function (UMF) and Lower Membership Function (LMF) are reported to be more complex than Type-1 FLC systems. The uncertainty or Footprint of Uncertainty (FOU) between the boundaries of the Type-2 FLC curve is illustrated in Figure 3.7 and is represented by the thickness of the curve. (Al Shnaikat 2013).

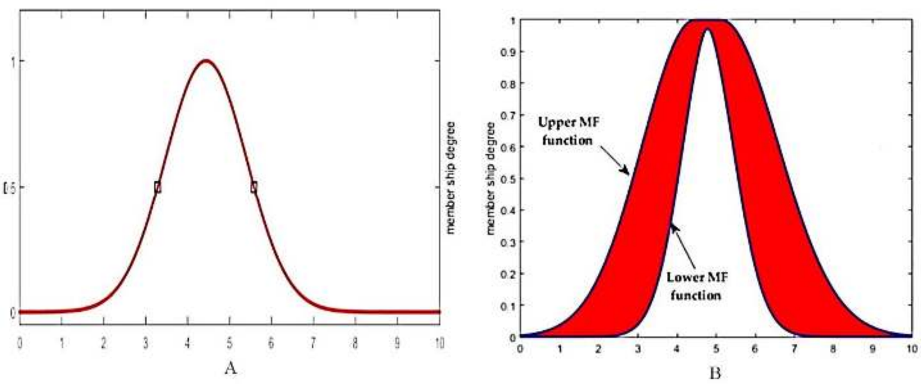


Figure 3.7 (A) Type-1 FLC (B) Type-2 FLC membership (Al Shnaikat 2013)

3.5.3 Fuzzy Type-2 IF-THEN rules

Type-2 FLC sets, type-2 FLC reduction and defuzzification, and type-2 FLC relations and composition are all carried out in order to manage the noise and lack of control in the Type-1 FLC control more accurately when modeling uncertainties using Type-2 FLC in both fuzzy sets and fuzzy logic systems, as was mentioned earlier (Tao Zhao et al. 2019).

The following formula was used to design a number of these operations, including Complement (negation), Intersection, and Union, for Type-2 FLC sets:

Complement Equation (3.2)

$$\mu_{A^c}(x) = 1 - \mu_A(x) \tag{3.2}$$

Intersection Equation (3.3):

$$\mu_{A \cap B}(x) = \min\left(\mu_A(x), \mu_B(x)\right) \tag{3.3}$$

Union Equation (3.4)

$$\mu_{A \cup B}(x) = \max\left(\mu_A(x), \mu_B(x)\right) \tag{3.4}$$

The aforementioned formulae were therefore applied to Type-2 FLC groups A and B, which stand in for well-known union and intersection when the evaluation set is reduced to [0, 1].

3.6 Fuzzy Type 2 – PID Control

The one-to-one derivative Type-2 FLC-PID controller that is suggested for usage with a single input interval is given a high-level overview in this section. The suggested architecture is shown in Figure 3.8.

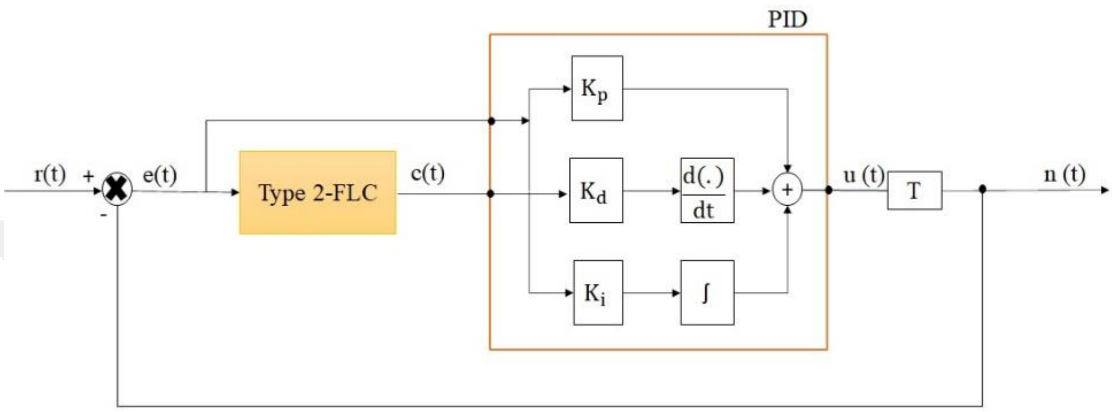


Figure 3.8 Type-2 FLC-PID control structure

When PID control is added to the traditional Type-2 FLC structure, the entire system works in the same way as Type-1 FLC plus gaining time.

The defining characteristics of PID controllers, including simplicity and ease of building, have been preserved by the previously suggested model. The most notable advantage of this model is its single-entry Type-2 FLC interior, which provides the opportunity to acquire the output in a closed shape in terms of the tuning parameters provided. More degrees of freedom were offered before Type-2 FLC interval settings. Therefore, the output of the Type-2 FLC controller in the error domain may be correctly represented using the derived closed structure (Kumbasar 2014).

4 RESULTS AND DISCUSSION

As mentioned earlier, this thesis aims to design a controller for a wind turbine to obtain the optimum output power by controlling the wind turbine blade pitch angle for various wind speeds. Figure 4.1 shows the wind speed data set used as input data in this thesis. This thesis carried out several control methods as explained in chapter 3 previously. Namely:

A- PID control (section 3.2)
B- Fuzzy Logic control (section 3.3)
C- Fuzzy-PID control (section 3.4)
D- Fuzzy Type 2 control (section 3.5)
E- Fuzzy Type 2-PID control (section 3.6)

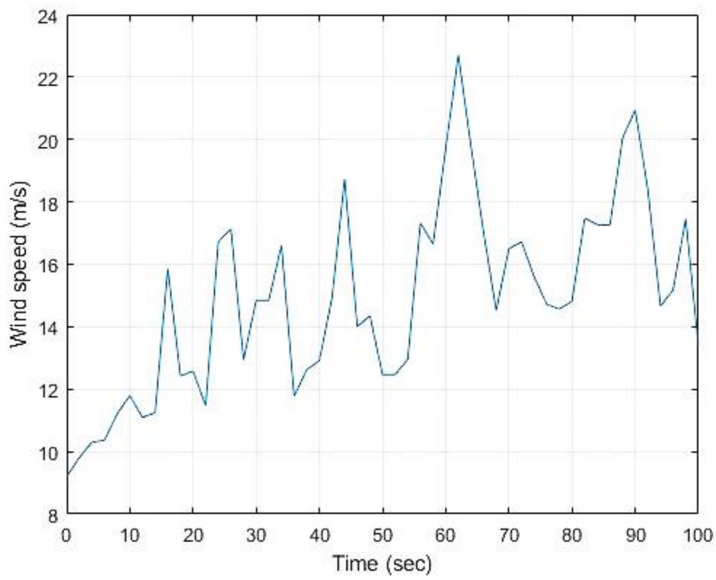


Figure 4.1 Wind speed dataset

4.1 Wind Turbine Modeling

The thesis work uses some basic equations and parameters that are applied in all different types of controllers as follows:

4.1.1 Model of the wind turbine

The thesis uses the most common wind turbine that has been used in other related research and scientific reports (considering some differences depending on the author or research needs).

Figure 4.2 show the modeling (MATLAB Simulink) of the power equation P from Equation (2.1) and the power parameter equation Cp from Equation (2.4) and Equation (2.5) as explained in chapter 2.

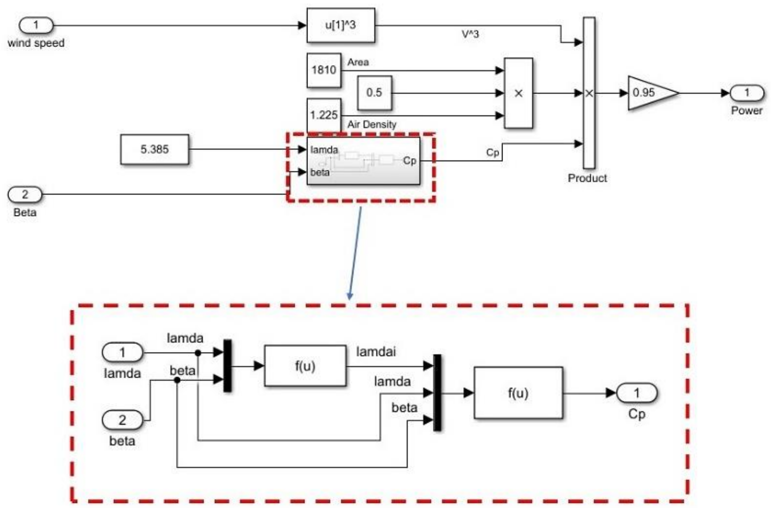


Figure 4.2 General structure of the model in WTs

4.1.2 Servo motor

What is meant by the servo motor is the electric or hydraulic motor that controls the angle of inclination of the blade in a wind turbine. The servo motor is controlled by one controller based on one type to obtain the appropriate angle of inclination with the wind speed.

Most wind turbine suppliers employ electric pitch angle control systems. Here, a DC servo motor serves as the actuator. The position control transfer function is represented in Equation (4.1) while Figure 4.3 shows the MATLAB program of the servo motor.

$$G(S) = 1/s(s + 1) \tag{4.1}$$

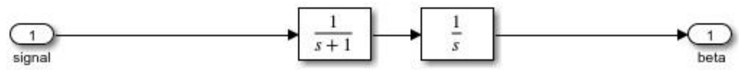


Figure 4.3 Servo Motor model

4.1.3 Wind speed – Beta angle (β) function

The wind speed – beta angle β relationship has been written as MATLAB code. The IF-ELSE function has been used to determine the optimum output of the wind turbine against the wind speed between 12 to 25 m/s.

```
function y = fcn(u,r)
%#codegen
if r>=25
y = 90;
end

if r<=12
    y=0;
else
    y=u;
end
```

4.1.4 Main system parameters

Table 4.1 lists the main simulation system parameters used in this thesis

Table 4.1 Simulated system parameters

Simulated System Parameters	
Nominal output power	500 kW
Working mode	Network connection
Cut in wind speed	3 m/s
Nominal wind speed	12 m/s
Cut out wind speed	25 m/s
Rotor diameter	48 m
Sweep area	1810 m
Blade number	3
Nominal rotor speed	30 RPM
Rotor speed range	10-30 RPM
Gearbox rate	01:50
Generator number	2
Generator type	PMSG
Generator nominal output	250 kW
Generator nominal cycle	1.500 RPM
Generator voltage	690 V

4.2 Controller Modeling

This section explains the modeling and the results of applying all types of controller methods in the wind turbine plant.

4.2.1 PID control modeling

In PID control, the system input and the system output are in accordance with controlled in the manner deemed necessary. The modeling of the PID controller is shown in Figure 4.4 below. And the PID parameters lists in Table 4.2.

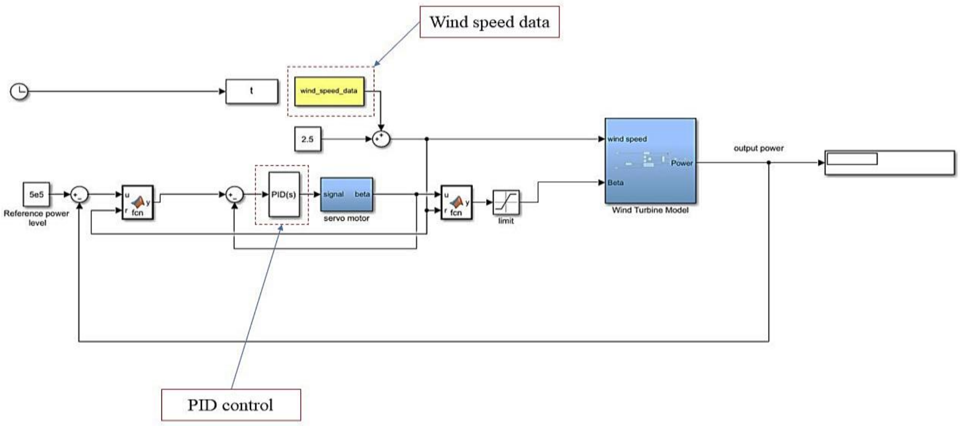


Figure 4.4 The PID control block in the wind turbine system

Table 4.2 PID control parameter

Proportional (P)	-0.008927661299092
Integral (I)	0.0110306888469848
Derivative (D)	1.149549482459326

The PID uses the wind speed dataset as an input to the planet. The PID controls the pitch angle and drives the output power are depicted in Figure 4.5 and Figure 4.6 respectively.

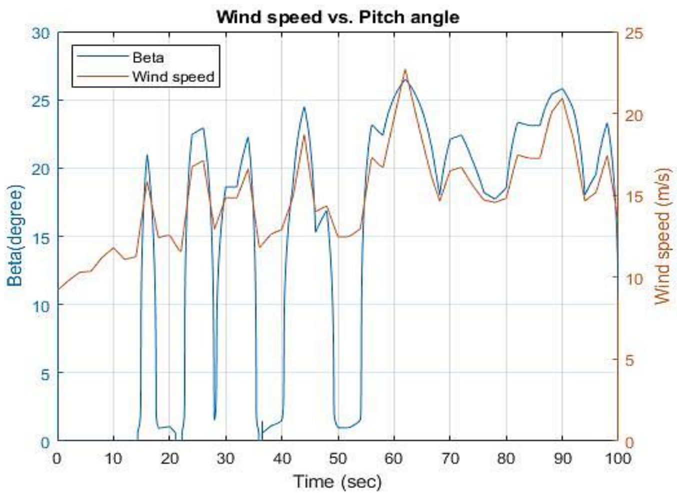


Figure 4.5 PID Pitch angle control output (degree)

As shown in Figure 4.5 above, the PID controller was able to predict the wind speed changes and control the wind turbine blade pitch angle accordingly. It can be noticed that the PID recognizes the wind speed value which is less than the minimum controlled limit

0-12 m/s. At low wind speeds, the PID control does not respond to changing the pitch angle.

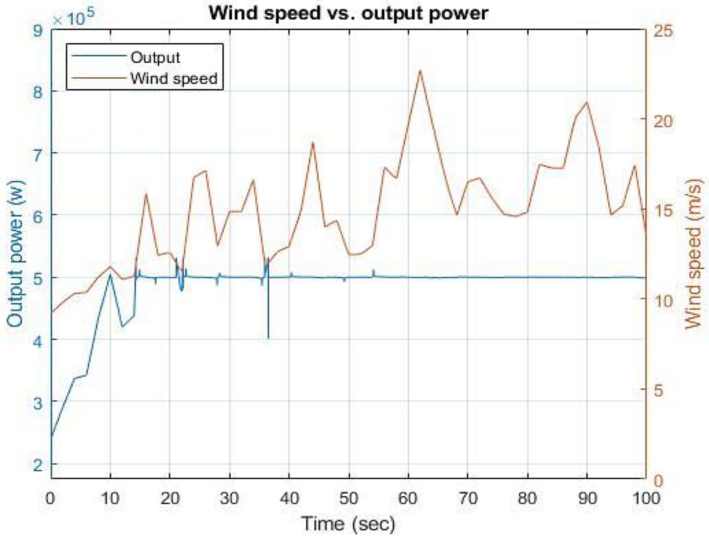


Figure 4.6 PID control output power (w)

Figure 4.6 above shows the wind turbine output power related to the controlled pitch angle. The controller pitch angle protects the wind turbine from generating high output power more than the nominal value with a high overshot. In the presence of outgoing energy without control, the system can be exposed to damage and cause major electrical energy losses when the loads are high; whereas, in the presence of a PID control, the output energy can be managed and the system is protected from such unanticipated damage.

4.2.2 Fuzzy logic control modeling

The PID controller has been placed by Type-1 FLC. The system performance was improved by using Type-1 FLC parameters for the pitch angle control. Figure 4.7 shows Type-1 FLC control modeling.

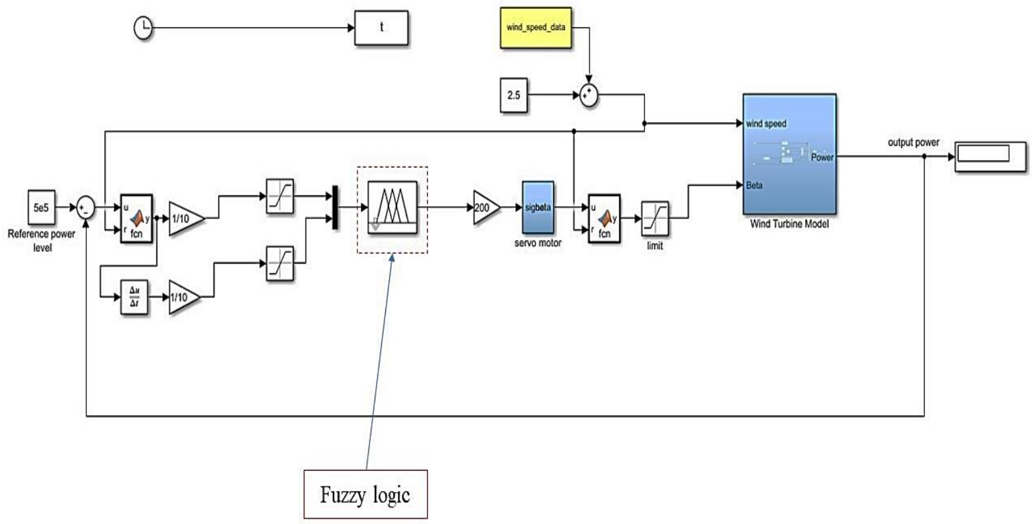


Figure 4.7 Type-1 FLC control block in wind turbine system

For the Type-1 FLC in the present study, two inputs are applied: (1) error data, as shown in Figure 4.8 and (2) change of error data Figure 4.9. The surface graph is shown in Figure 4.10, and Figures 4.11 and 4.12 show one output and associated rules, respectively. Relationship between inputs and outputs is shown graphically on a surface.

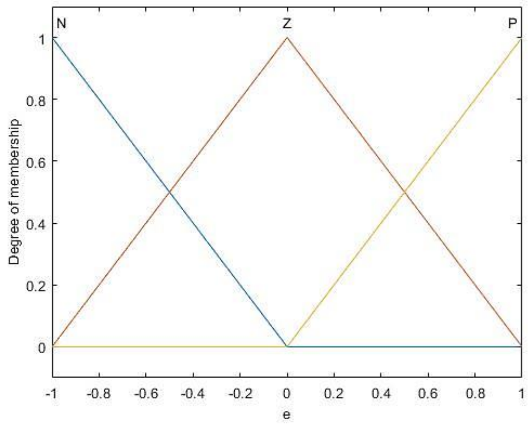


Figure 4.8 Error data input variable (e)

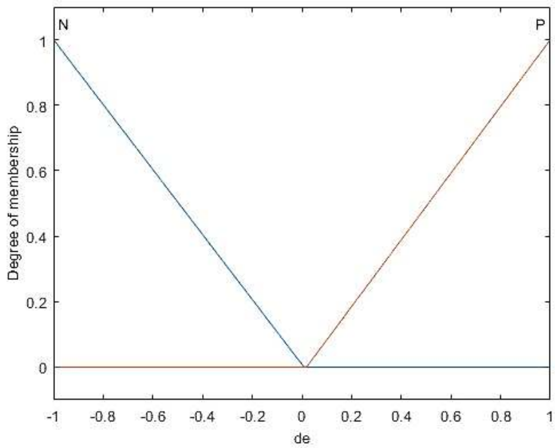


Figure 4.9 Change off error input variable (de)

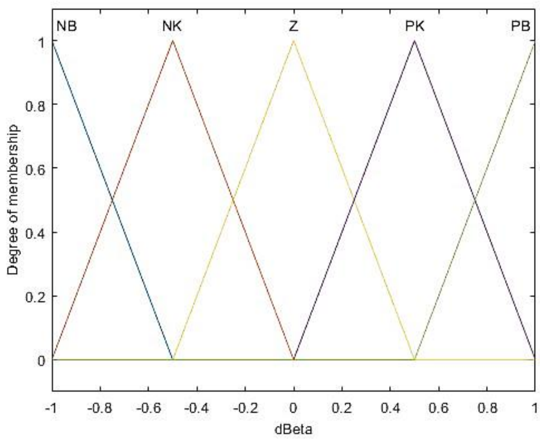


Figure 4.10 Output variable of Type-1 FLC (dBeta)

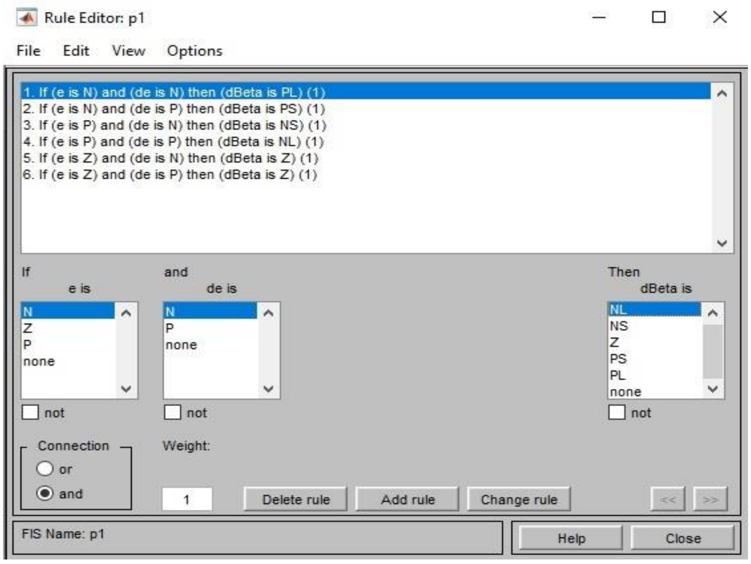


Figure 4.11 Rules of Type-1 FLC

Table 4.3 below show a Type-1 FLC rules matrix

Table 4.3 Type-1 FLC rules matrix

DE \ E	N	Z	P
N	PB	Z	NK
P	PK	Z	NB

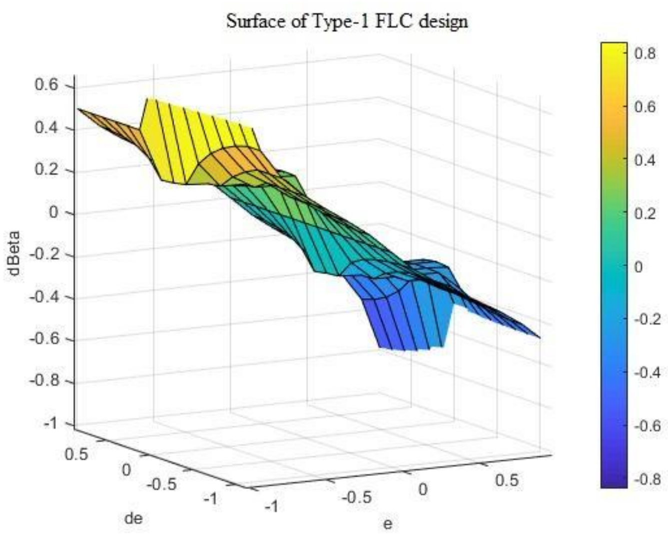


Figure 4.12 Surface graph of Type-1 FLC

The recommended control method produces great results when the wind turbine's blade pitch is altered in response to changes in wind speed, blade angle, and output power, as shown in Figures 4.13 and 4.14.

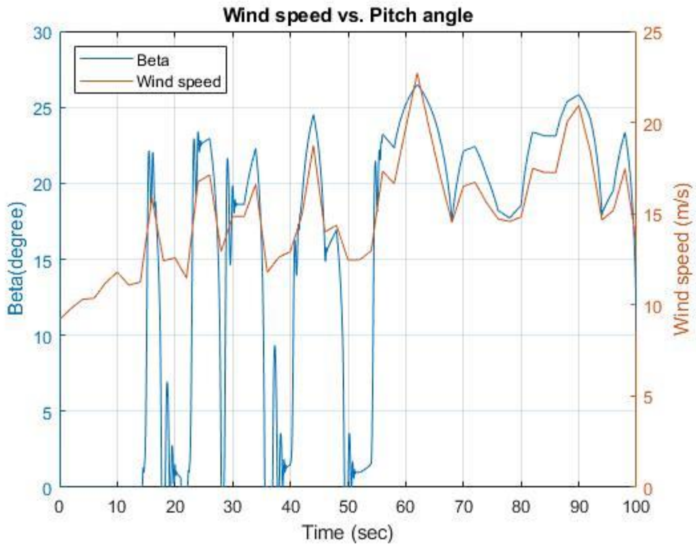


Figure 4.13 Type-1 FLC Pitch angle control output (degree)

Figure 4.13 shows the Type-1 FLC control can change the pitch angle related to the input wind speed. However, the Type-1 FLC seems more sensitive to the input data than the generic PID controller.

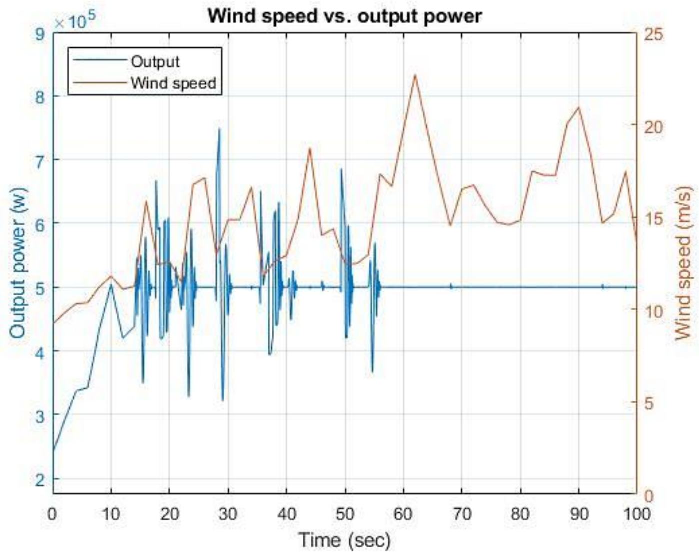


Figure 4.14 Type-1 FLC control output power (w)

Figure 4.14 shows the wind turbine model can generate the output power according to the pitch angle change. However, the output power shows high output than the nominal value. This leads to the system being exposed to damage and the system will not be stable when the outputs are too high. Therefore, an additional PID controller is needed to solve this problem.

4.2.3 Fuzzy-PID control modeling

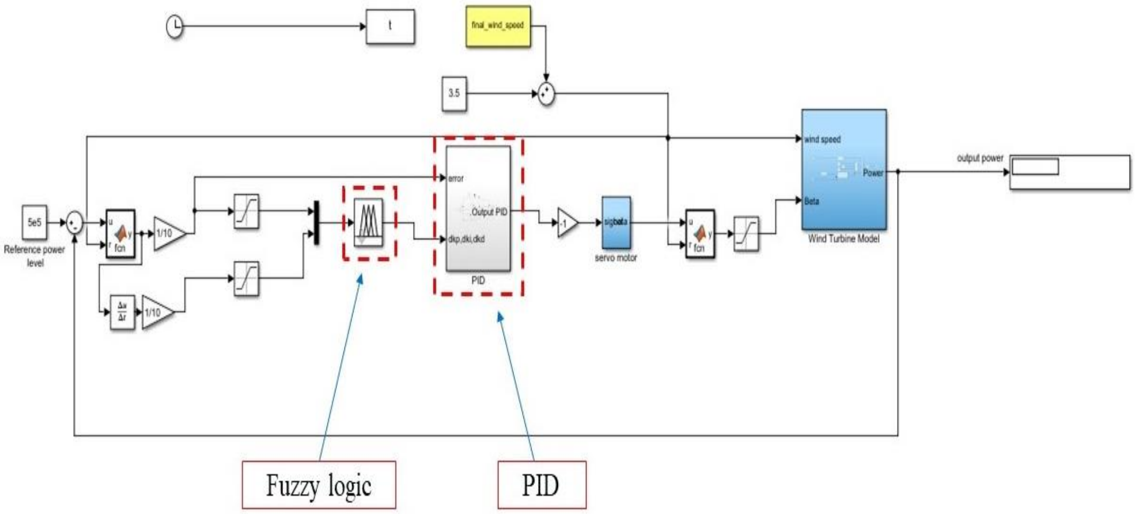


Figure 4.15 Type-1 FLC-PID control block in the wind turbine system

As explained in section 4.2.2, the Type-1 FLC was too sensitive to the input wind speed which reflects too high generated output power. An additional PID controller is added to control it. Figure 4.15 below shows the Type-1 FLC-PID controller modeling. Table 4.4 lists the PID controller tuning parameters.

Table 4.4 Type-1 FLC-PID control parameter

Proportional (P)	10
Integral (I)	0.25
Derivative (D)	1

For the Type-1 FLC-PID in the present study, two inputs are applied: (1) error data and (2) change of error data, as shown in Figure 4.16. Apart from this, three output (DKp, DKi, Dkd) and related rules appear in and Figure 4.17, respectively.

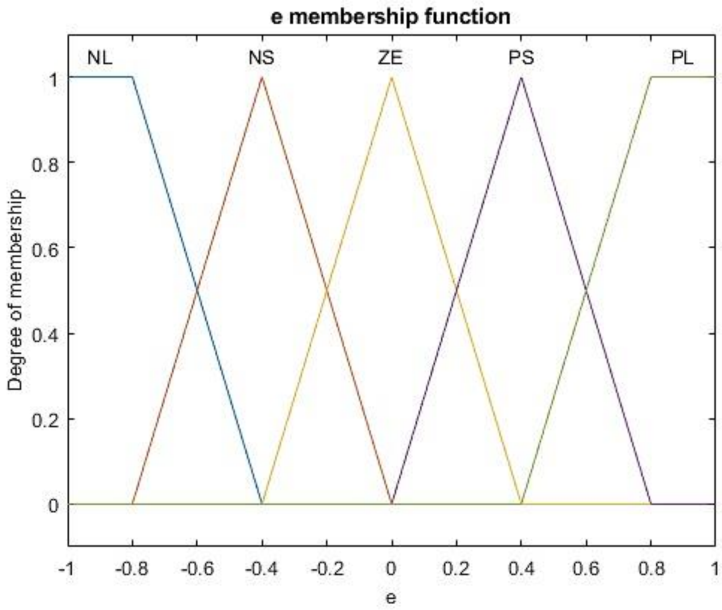


Figure 4.16 Error data input variable (e)

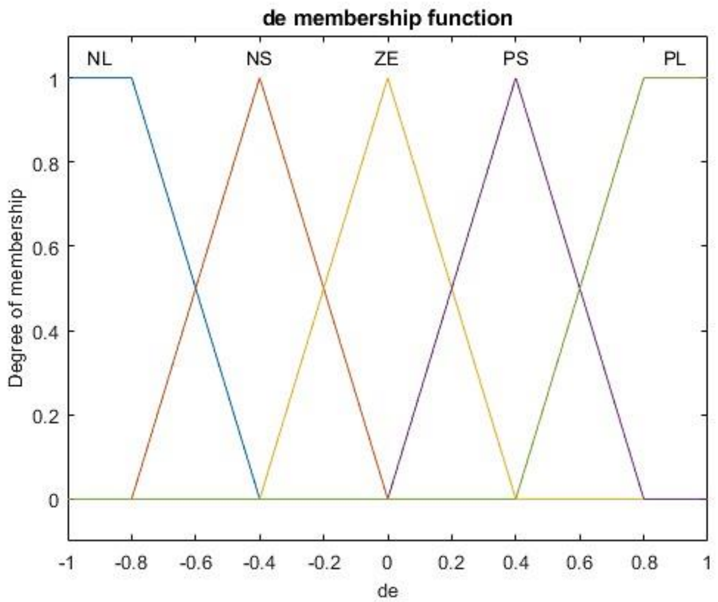


Figure 4.17 Change off error input variable (de)

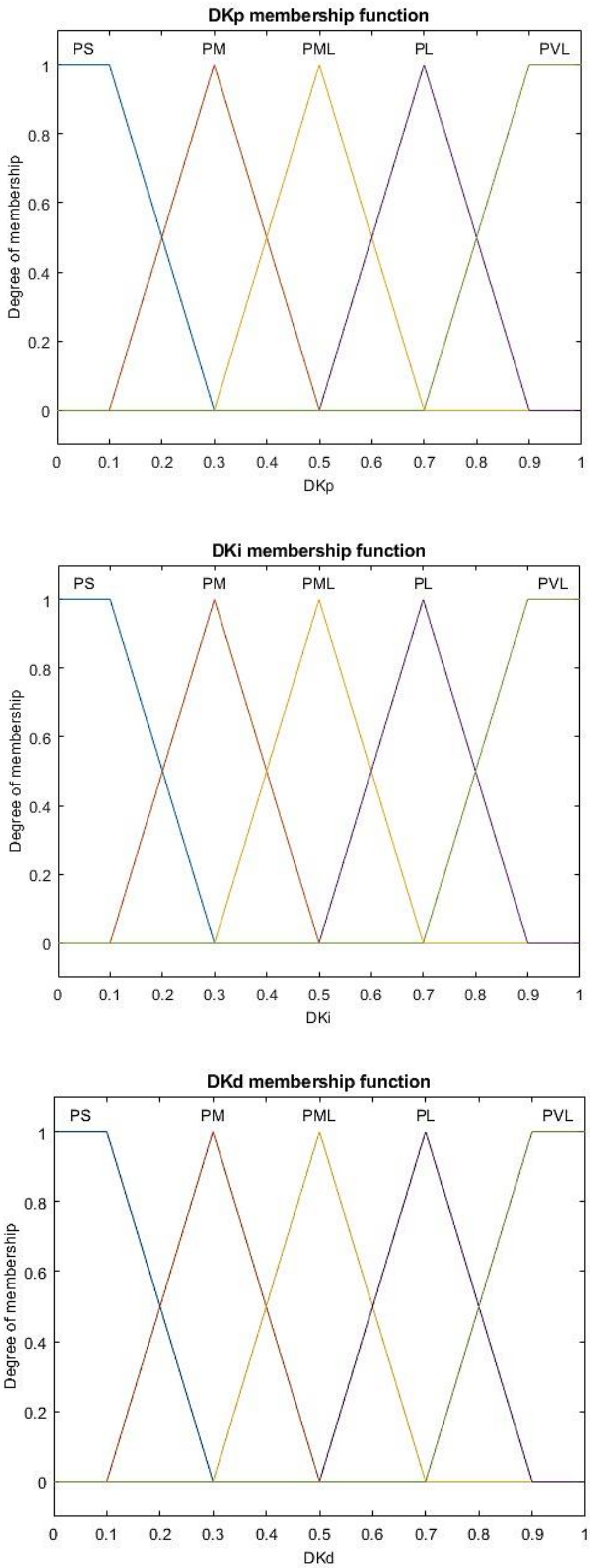


Figure 4.18 Output variable of Type-1 FLC-PID (DKp, DKi, DKd)

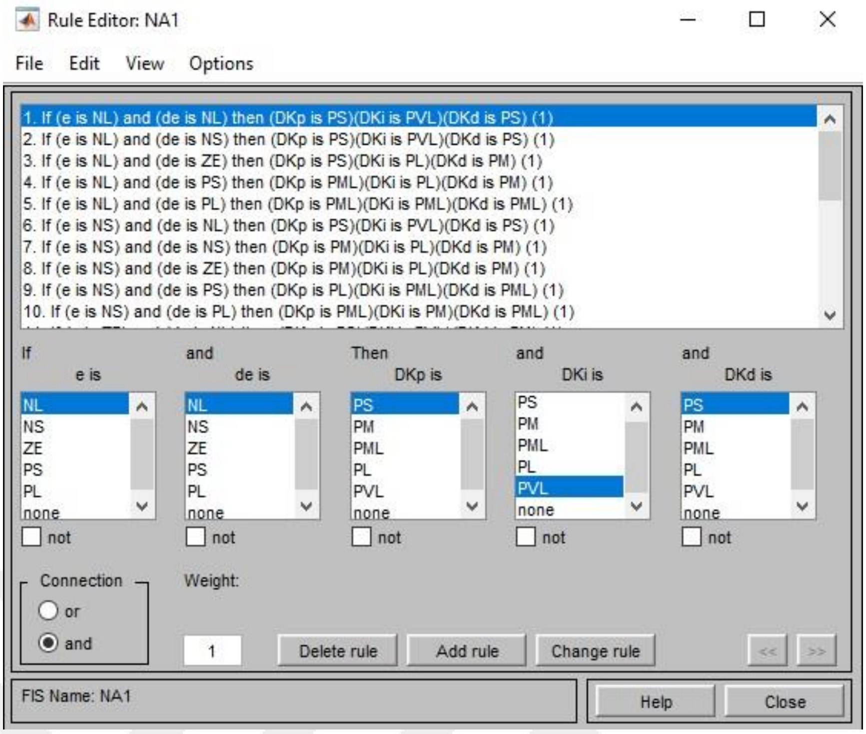


Figure 4.19 Rules of Type-1 FLC-PID

A Type-1 FLC-PID rule matrix is shown in Table 4.5.

Table 4.5 Type-1 FLC-PID rules matrix

DKp					
E / DE	NL	NS	ZE	PS	PL
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
DKi					
E / DE	NL	NS	ZE	PS	PL
NL	PVL	PVL	PVL	PM	PS
NS	PVL	PL	PL	PML	PM

Table 4.5 Type-1 FLC-PID rules matrix (Continued)

ZE	PVL	PML	PML	PL	PS
PS	PM	PML	PS	PL	PS
PS	PS	PML	PS	PVL	PS
DKd					
E / DE	NL	NS	ZE	PS	PL
NL	PS	PS	PM	PM	PML
NS	PS	PM	PM	PML	PML
ZE	PS	PM	PML	PL	PVL
PS	PM	PML	PL	PL	PVL
PL	PML	PVL	PL	PVL	PVL

Upon combining the two controls, the obtained results improved with stable output power and good pitch angle control without the presence of any fluctuating output power as was the case in the Type-1 FLC-PID control. These results are shown in Figure 4.20 and 4.21.

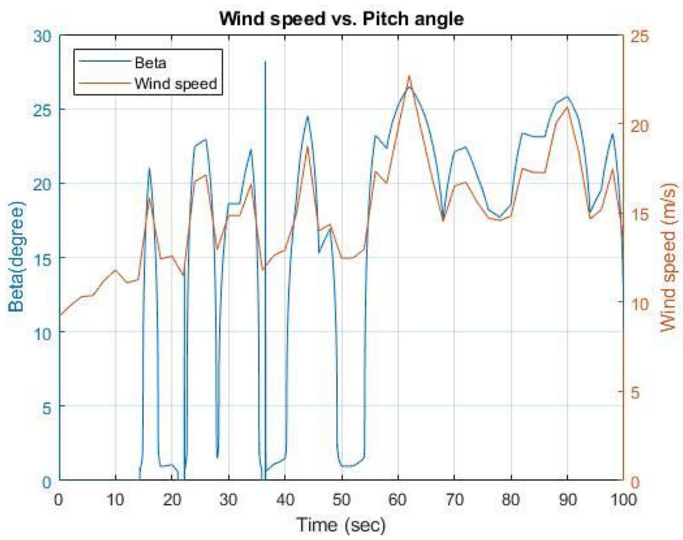


Figure 4.20 Type-1 FLC-PID Pitch angle control output (degree)

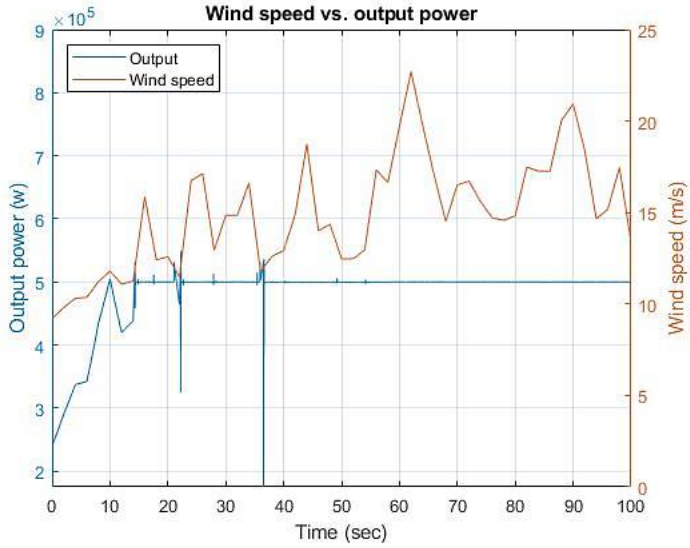


Figure 4.21 Type-1 FLC-PID control output power (w)

4.2.4 Fuzzy Type-2 control modeling

In this section, the Type-2 FLC is introduced to the wind turbine model to examine the control sensitivity. Figure 4.22 below shows the Type-2 FLC implementation in the model. Note that, the MATLAB Simulink library does not contain the Type-2 FLC codes. The Type-2 FLC codes have been added manually.

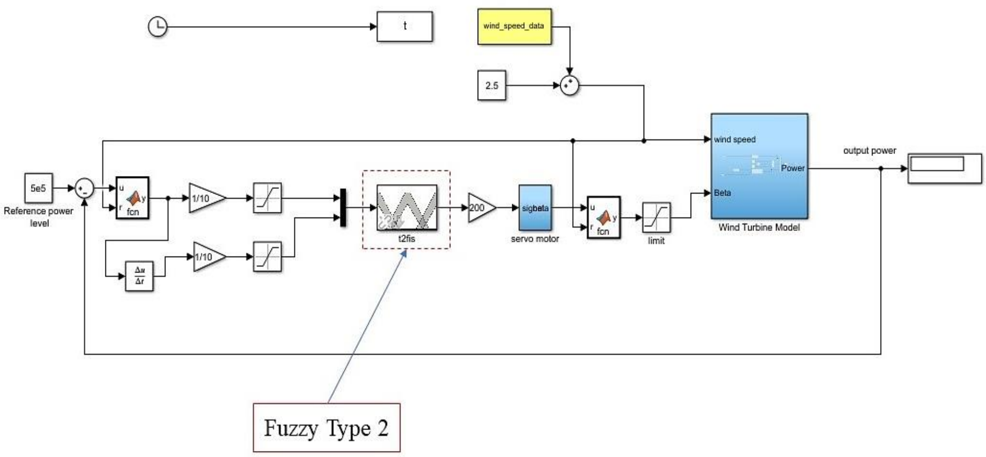


Figure 4.22 Type-2 FLC control block in the wind turbine system

In this research, the Type-2 FLC Takagi–Sugeno–Kang TSK algorithm has been used which is different than the Type-1 FLC used in section 4.2.2 previously. This leads to input 1 and input 2 shown in Figure 4.23, and Figure 4.24. In Type-2 FLC, the output parameters cannot be added because it is registered automatically as shown in Figure 4.25, which is different from Type-1 FLC though the rules are the same, as shown in Figure 4.26 along with the surface graph in Figure 4.27 for Type-2 FLC. Surface showing the relationship between input and output variables.

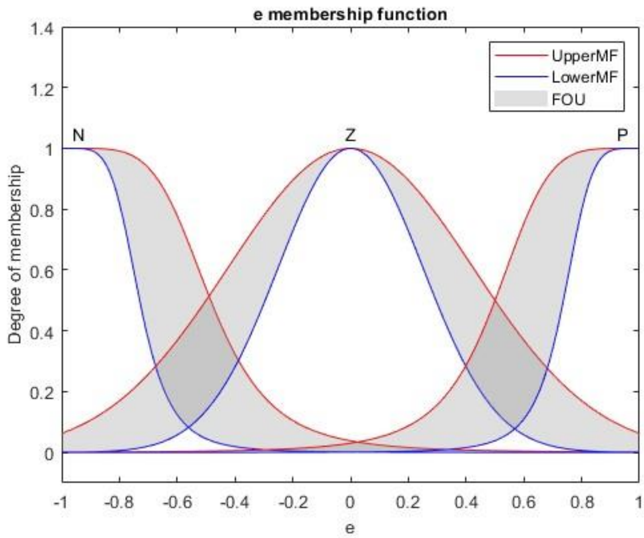


Figure 4.23 Type-2 FLC input 1 variable (e)

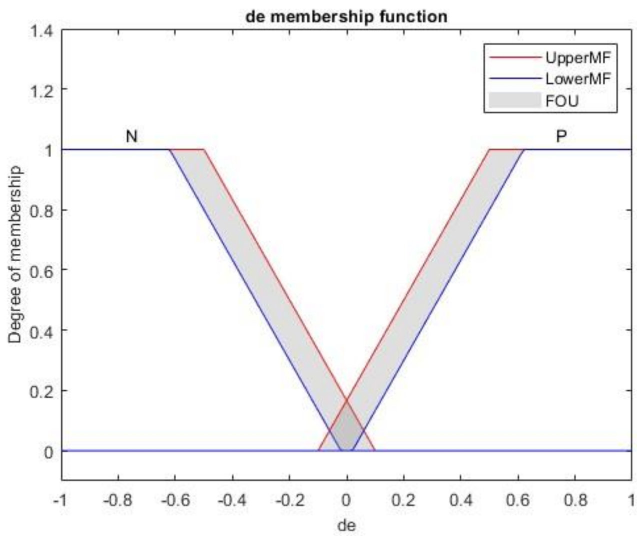


Figure 4.24 Type-2 FLC input 2 variable (de)

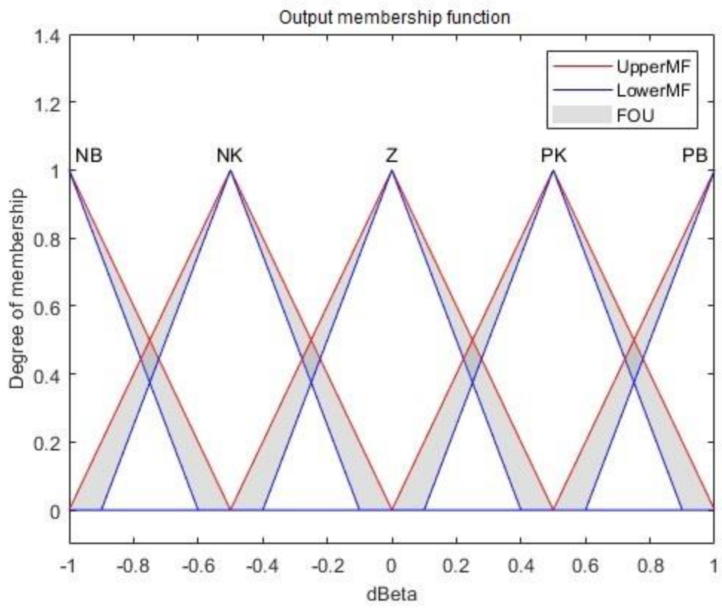


Figure 4.25 Type-2 FLC output variable (dBeta)

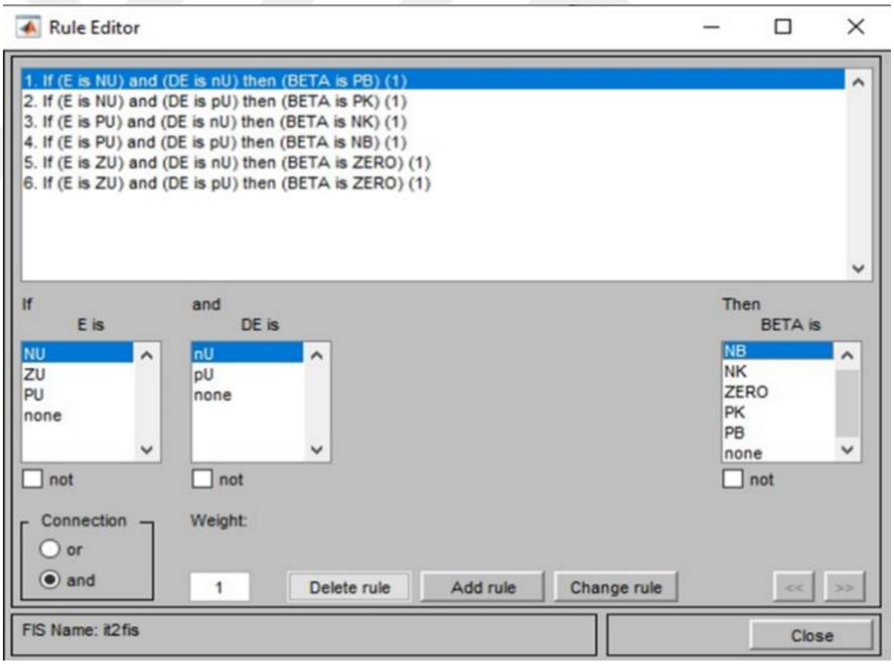


Figure 4.26 Rules of Type-2 FLC

Table 4.6 below show a Type-2 FLC rules matrix

Table 4.6 Type-2 FLC rules matrix

E / DE	N	Z	P
N	PB	Z	NK
P	PK	Z	NB

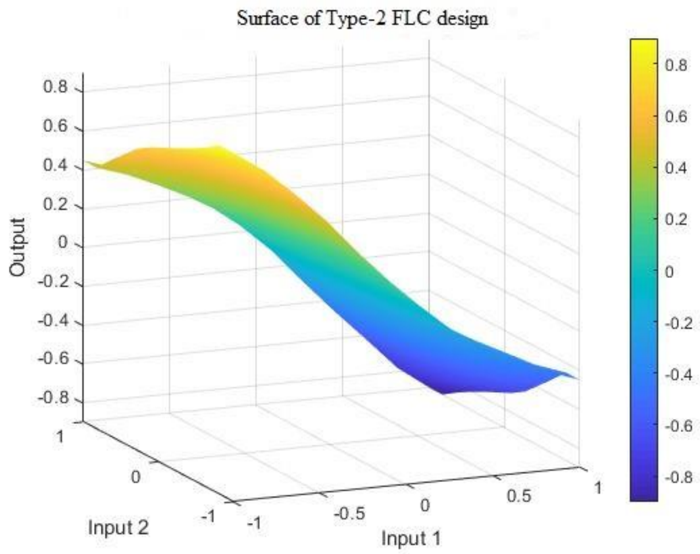


Figure 4.27 Surface graph of Type-2 FLC

Figures 4.28 and 4.29 illustrate the beneficial effects of the recommended control system on the wind turbine's output power and blade pitch angle, respectively.

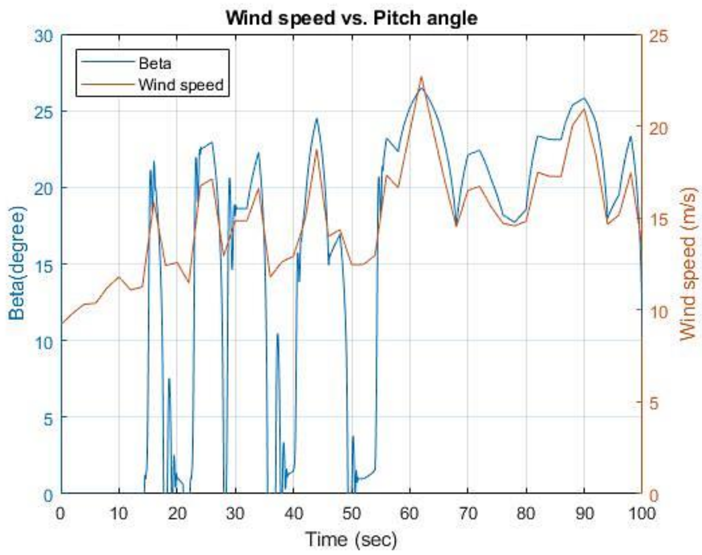


Figure 4.28 Type-2 FLC Pitch angle control output (degree)

Figure 4.29 shows the Type-2 FLC control can change the pitch angle related to the input wind speed. However, the Type-2 FLC seems more sensitive to the input data than the generic PID controller same as the Type-1 FLC.

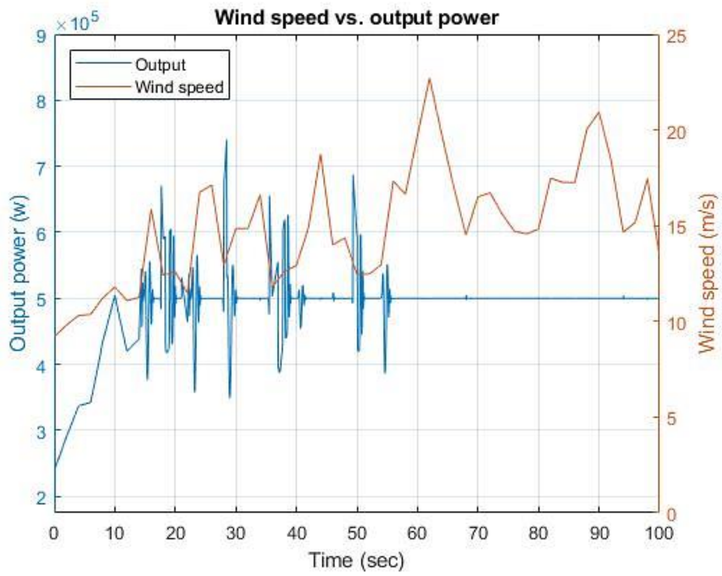


Figure 4.29 Type-2 FLC control output power (w)

The wind turbine model can generate the output power according to the pitch angle change using Type-2 FLC only. However, the output power shows high output than the nominal value. This leads to the system being exposed to damage and the system will not be stable when the outputs are too high. Therefore, an additional PID controller is needed to solve this problem.

4.2.5 Fuzzy Type 2-PID control modeling

As explained in section 4.2.4, the Type-2 FLC was too sensitive to the input wind speed which reflects too high generated output power. An additional PID controller is added to control it. Figure 4.30 below shows the Type-2 FLC-PID controller modeling. Table 4.7 lists the PID controller tuning parameters.

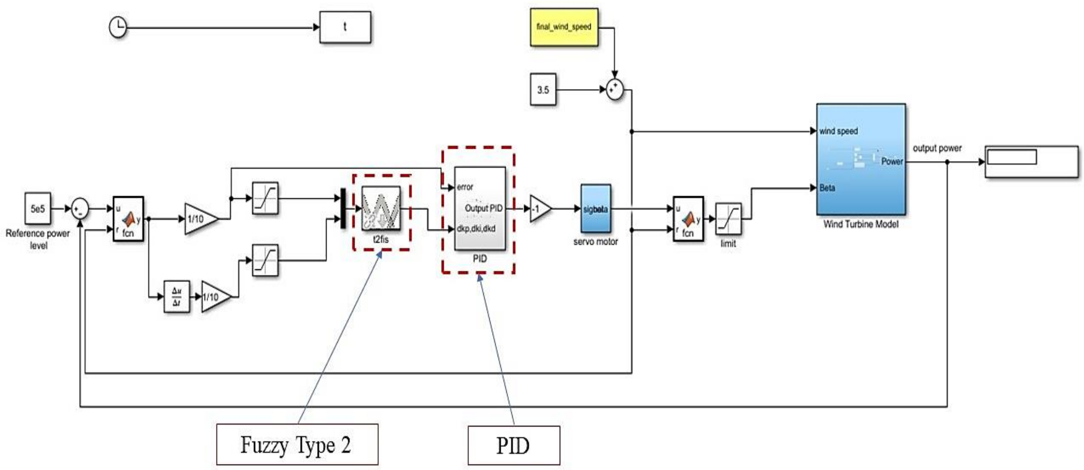


Figure 4.30 Fuzzy Type 2-PID control block in the wind turbine system

Table 4.7 Type-2 FLC-PID control parameter

Proportional (P)	10
Integral (I)	0.25
Derivative (D)	1

For the Type-2 FLC-PID in the present study, two inputs are applied: (1) error data, as shown in Figure 4.31 and (2) change of error data, as shown in Figure 4.32. Apart from this, three output (DKp, DKi, Dkd) in Figure 4.33, which is different from Type-1 FLC-PID though the rules are the same, as shown in Figure 4.34.

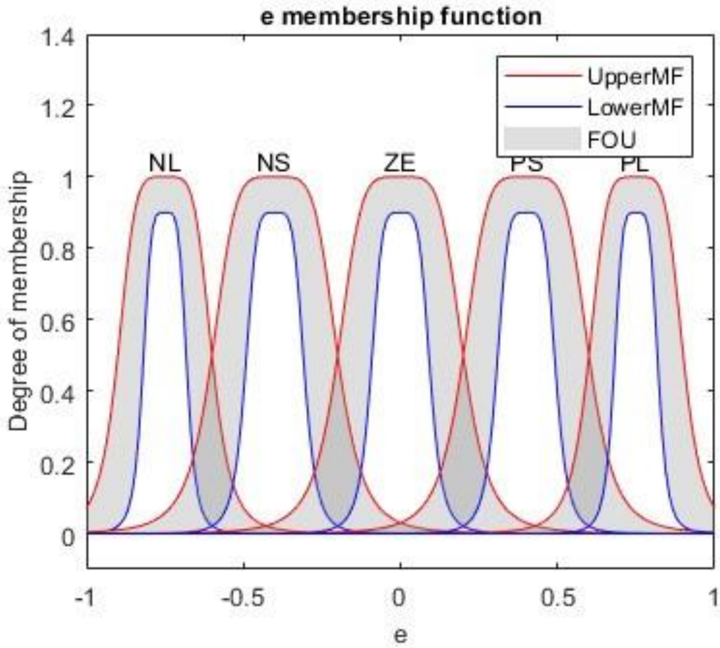


Figure 4.31 Type-2 FLC-PID input 1 variable (e)

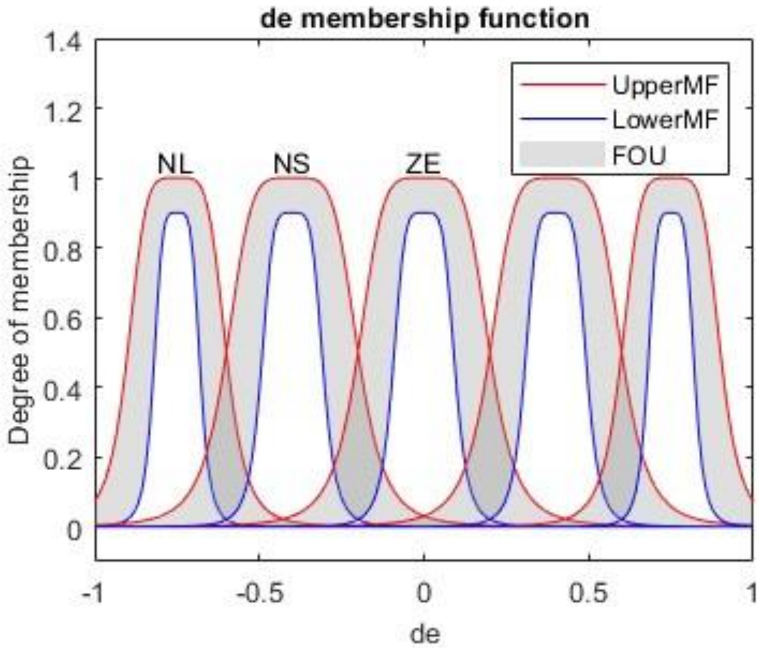


Figure 4.32 Type-2 FLC-PID input 2 variable (de)

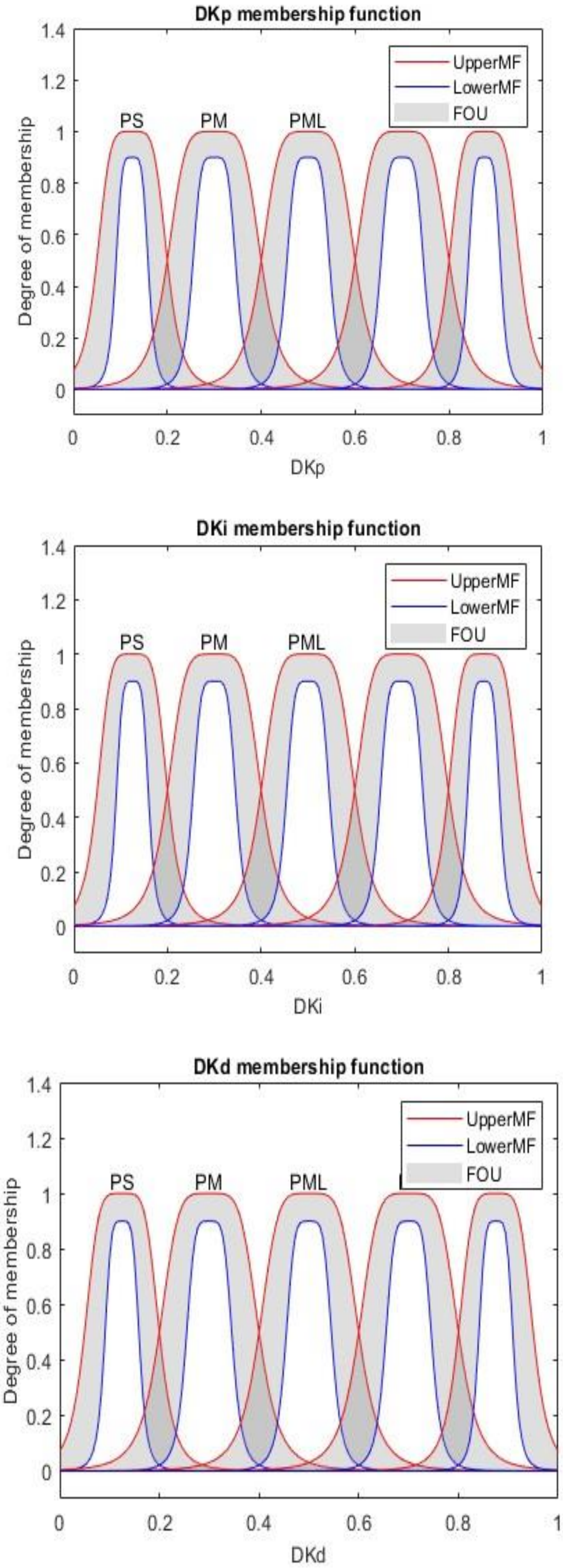


Figure 4.33 Output variable of Type-2 FLC-PID (DKp, DKd, and DKi)

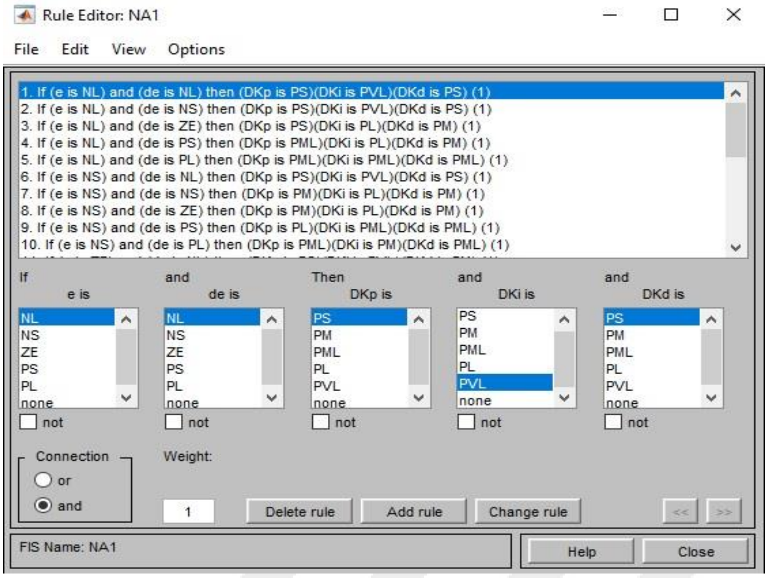


Figure 4.34 Rules of Type-2 FLC-PID

Table 4.8 below show a Type-2 FLC-PID rules matrix

Table 4.8 Type-2 FLC-PID rules matrix

DKp					
E / DE	NL	NS	ZE	PS	PL
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
DKi					
E / DE	NL	NS	ZE	PS	PL
NL	PVL	PVL	PVL	PM	PS
NS	PVL	PL	PL	PML	PM
ZE	PVL	PML	PML	PL	PS
PS	PM	PML	PS	PL	PS
PS	PS	PML	PS	PVL	PS
DKd					
E / DE	NL	NS	ZE	PS	PL
NL	PS	PS	PM	PM	PML
NS	PS	PM	PM	PML	PML
ZE	PS	PM	PML	PL	PVL
PS	PM	PML	PL	PL	PVL
PL	PML	PVL	PL	PVL	PVL

The system's performance was improved using Fuzzy Type 2 Turing PID parameters for pitch angle control. After the wind turbine's blades' pitch angle is changed, they operate efficiently. Figure 4.36 shows the output power while Figure 4.35 shows the pitch angle.

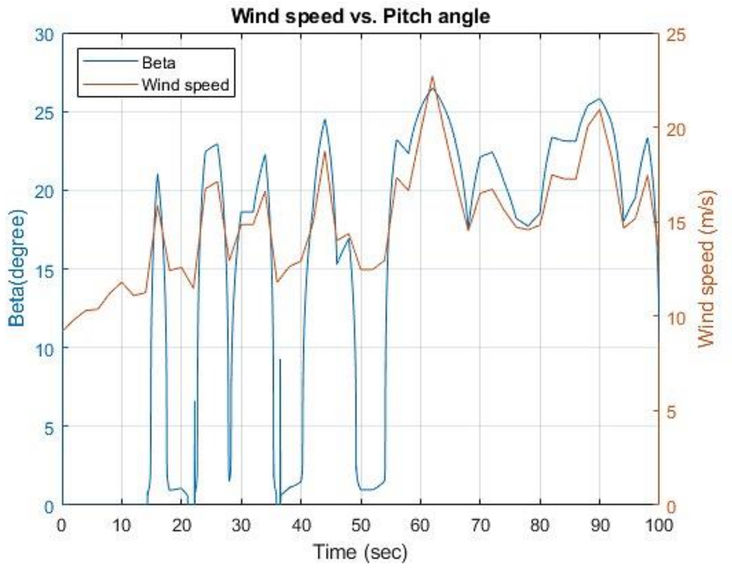


Figure 4.35 Type-2 FLC-PID Pitch angle control output (degree)

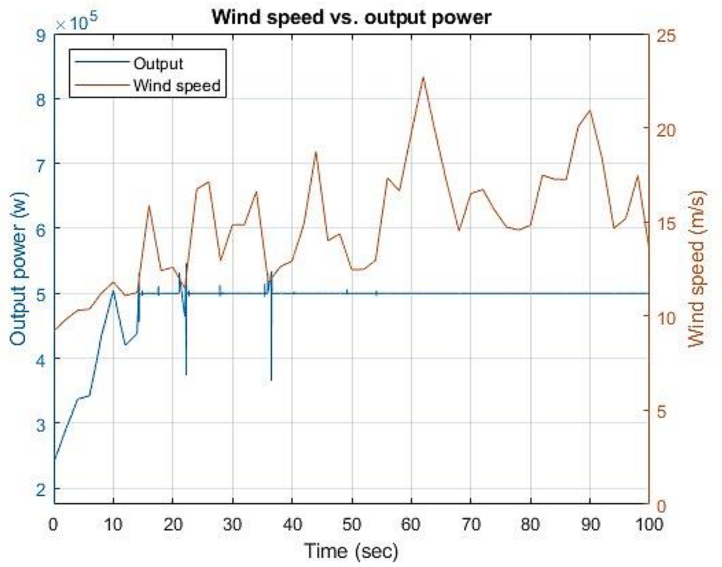


Figure 4.36 Type-2 FLC PID control output power (w)

When PID control is added to the traditional Type-2 FLC structure, the entire system works in the same way as Type-1 FLC plus gaining time.

The suggested version maintains the simplicity and simplicity of design that are hallmarks of PID controllers. Most crucially, the inner form of the suggested Type-2 FLC offers the opportunity to acquire the output in a closed shape in terms of the shown tuning parameters. There are more degrees of freedom in type-2 FLC sets than in previous interval FLC types. Hence, using only the derived closed structure, the Type-2 FLC controller output in terms of errors may be precisely represented.

5 CONCLUSIONS AND RECOMMENDATION

The complexity of the wind turbine as an energy source is influenced by a number of factors, including air density, wind speed, the power coefficient as a function of blade pitch angle, and the blade tip speed. In order to stabilize the power generated by such systems, this research set out to build a range of controllers for use in controlling the pitch angle of wind turbine blades. The wind turbine generator has been simulated using MATLAB Simulink. The model uses a controller reference value as its nominal output power and uses wind speed as its controller input variable. The research looked at how different wind speeds affected the requirement for varied blade angles in wind turbines.

The research applied different types of controls to maximize output efficiency. The research concludes the wind turbine blade pitch angle has a big impact depending on the wind speed. This impacts the wind turbine parameters:

- High output power;
- High efficiency;
- Noise reduction is caused by the rotation of the blades.
- Reduced the number of accidents that occur at high wind speed.
- Obtaining an almost constant rotational speed in a wind turbine.

The effectiveness of controller the blade pitch angle in a wind turbine has been evaluated based on observations of simulated results and the following points are concluded:

1- The modeling of the wind turbine was implemented by using MATLAB Simulink to calculate the output power and the mechanical load via the individual pitch angle control of the wind turbine.

2- Five different controls were implemented in MATLAB Simulink and compared based on the calculated output power related to the nominal power.

3- The output results show that Fuzzy logic and the Fuzzy Type-2 controllers are too sensitive to the input wind speed. Therefore, these controllers are enforced by adding a PID controller with tunned parameters to get better results.

4- As a result, the Fuzzy Type 2-PID showed the best control performance in terms of blade pitch angle control.

For future work, the research recommends to enhance the Fuzzy Type 2-PID controller using optimization algorithms.

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