Department of Mechanical and Aerospace Engineering

Design of an Optimized Nonlinear Pitch Angle Controller for Wind Turbines

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Abstract

Today, the use of wind turbines as one of the best ways of generating electricity from renewable sources has been considered. Wind turbines have different controllers for proper operation, one of which is pitch control. This thesis focuses on pitch control. To design the pitch controller, first the system model is extracted based on system dynamics. Then, the modified linear and nonlinear controllers are designed based on the model. Linear controller is modified by using gain scheduling method. To correctly compare the linear and nonlinear controllers, the control parameters are determined by an optimization algorithm. The wind turbine control system simulation and performance validation are performed based on the Wind PACT 1.5 MW wind turbine model in MATLAB/Simulink environment for different wind conditions. The results show better performance of the nonlinear controller.

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I must thank Behrouz his loving support. Furthermore, I wish to my Supervisor, Dr. M. Afsar for his dedication and creativity throughout this journey.

Table of Contents

1.0 Introduction..1

- 1.1 Wind energy market 1
- 1.2 The Role of Wind Energy on the Road to Net Zero 2
- 1.3 Wind Power Development 4
- 1.4 Wind power in UK... 5
- 1.5 Wind turbine technologies 6
- 1.5.1 The main components of horizontal-axis wind turbine 7
- 1.6 Pitch control in wind turbine 10
- 1.7 Research Question and Research Objectives 11
- 1.8 Thesis Structure 12

2.0 Literature Review...14

- 2.1 Introduction 14
- 2.2Aerodynamic subsystem [16]..15
- 2.2.1 Energy Conversion Rate………………………...……………………………..16
- 2.2.2 Pitch and Tip Speed Ratio……………………………………………………..17
- 2.2.3 Power……………………………………………………………………..19
- 2.2.4 Torque……………………………………………………………………19
- 2.3 Mechanical subsystem……………………………………………………………..20
- 2.3.1 Drive-train [15]………………………………………………………………...20
- 2.3.2 Tower [15]……………………………………………………………………..21
- 2.4 Electrical subsystem…………………………………………………………..21
- 2.4.1 Fixed-Speed Wind Turbines…………………………………………………...22

2.4.2 Variable-Speed Wind Turbines……………………………………………………..23

2.4.3Variable-Slip Wind Turbines…………………………………..………………..…23

2.4.4 Doubly-Fed Induction Generator (DFIG) Wind Turbines……………………..…..24

2.4.5 Full-Converter Wind Turbines……………………………………………………..25

2.5 Pitch Actuator Subsystem…………………………………………………………26

2.5.1 Closed-loop control……………………………………………………..….27

2.6 The importance of pitch control………………………………………………...28

2.6.1 Objectives of pitch control…………………………………………………..…28

2.7 Uncertainties in Wind Turbine Control Systems…………………………………...29

2.8 Control Algorithms…………………………………………………………………32

2.8.1 Linear Algorithms…………………………………………………………...32

2.8.2 Nonlinear Algorithms……………………………………………………….33

2.8.3 Intelligent Algorithms……………………………………………………….34

2.8.4 Combined Algorithms……………………………………………………….35

2.9 Literature Review of Control Methods for Wind Turbines…………………………35

2.10 How our Work differs from what appears in the literature…………………………36

2.11 Summary……………………………………………………………………………..41

3.0 Controller Design..…………41

3.1 Extracting state-space model of system…………..……………………...……...…41

3.1.1 Turbine mechanics 42

3.1.2 Aerodynamics 43

3.1.3 Generator dynamics 44

3.1.4 Pitch actuator dynamics 44

3.2 Nonlinear state space equations 44

3.3 Gain Scheduling PI Controller (GSPI)... 46

3.4 Feedback Linearization Controller (FLC) 47

3.5 Sliding Mode Controller (SMC) 48

3.6 Novel Application of a Harmonic Search Algorithm... 50

3.6.1 Determining the optimal parameters of the controllers 51

4.0 Simulation results...54

4.1 Wind Turbine Model…………………………………………………………….....54

4.2 Test at step wind speed……………………………………………………………..55

4.3 Test at random wind speed…………………………………………………………60

5.0 Conclusion and suggestions..63

5.1 Summary……………………………………………………………………………..63

5.2 The novel aspects of this work 63

5.3 Suggestions 64

6.0 References 65

List of Figures

Figure 1: A new record year for the wind industry [1] 2
Figure 2: Global warming well below 2 degrees Celsius [1] 3
Figure 3: Grams of CO2 per kilowatt electricity produced [3] 4
Figure 4: Global Wind Power Cumulative Capacity from 2001 to 2020 [5] 5
Figure 5: Taxonomy of wind turbines based on the axis of rotation of the blades [9] 7
Figure 6: Downwind and upwind design of the rotor [12] 8
Figure 7: The main components in a wind turbine [12] 10
Figure 8: Operating regions of wind turbines [13] 11
Figure 9: Roadmap of this work 13
Figure 10: Block diagram of this work 13
Figure 11: Relationship between subsystems of a wind turbine (reproduced from [17]) 15
Figure 12: Forces applied to the blades (reproduced from [20]) 18
Figure 13: Blade pitch angle control methods (wind direction from right to left) 18
Figure 14: Drive-train schematic (reproduced from [15]) 21
Figure 15: Overview of Fixed-speed wind turbines (reproduced from [11]) 22
Figure 16: Overview of Variable-slip wind turbines (reproduced from [11]) 24
Figure 17: Overview of Doubly-Fed Induction Generator (DFIG) Wind Turbines 25
Figure 18: Overview of Full-Converter Wind Turbines (reproduced from [11]) 26
Figure 19: Pitch controller in wind turbine (reproduced from [21]) 29
Figure 20: Two-mass model of wind turbine 42
Figure 21: Wind turbine system block diagram with GSPI controller 47
Figure 22: Flowchart of Harmony Search Algorithm 52
Figure 23: GSPI Controller implementation in MATLAB/Simulink 55
Figure 24: FLC implementation in MATLAB/Simulink 56
Figure 25: SMC implementation in MATLAB/Simulink 56
Figure 26: Step Wind Speed 57
Figure 27: Rotor speed under step wind test 57
Figure 28: Generator power under step wind test 58
Figure 29: Pitch angle under step wind test 58
Figure 30: Shaft torsion angle under step wind test 59

Figure 31: Random Wind Speed..60
Figure 32: Rotor speed under random wind test...60
Figure 33: Generator power under random wind test..61
Figure 34: Pitch angle under random wind test 61
Figure 35: Shaft torsion angle under random wind test...62

List of Tables

Table 1: Wind projects in Britain [8]. 6
Table 2: Articles in the field of wind turbine control. 38
Table 3: Harmonic search algorithm parameters. 53
Table 4: Optimal values of controller parameters. 53
Table 5: Parameters of a two-mass model 1.5 MW test wind turbine. 54
Table 6: Error criteria for a two-mass model under stepped wind 59
Table 7: Error criteria for a two-mass model under random wind 62

1.0 Introduction

The most important challenge in the world today is air pollution, which is caused by excessive energy consumption, especially the kind of energy supplied by fossil fuels that make human life today and future generations difficult.

Therefore, saving the planet ill be possible by replacing fossil fuels with renewable energy, the main advantages of which are sustainability and minimal polluition. These sources are unknown to many people because they have become very popular recently.

Renewable energy sources, including wind, solar, geothermal, tidal, hydro and wave, are naturally available in most geographic areas. In recent decades, Factors such as the abundance and lack of negative impact on the environment, technological innovations, cost reductions and government encouragement have led to the growth of renewable resources.

one of the main types of renewable energy sources is wind energy, and it is up to all countries to set new policies, investments, and partnerships that can address key issues such as infrastructure and construction networks, storage, speed of action. Build, develop, and design the market so that it can become a world with zero carbon emissions as soon as possible. One of the related challenges that could increase the time to reach zero in 2050 With the European Union, Canada, South Korea, South Africa, and Japan, each pledged to reach a net zero by 2050 and 2060 for China is the long-term ambitions of governments.

1.1 Wind energy market

Based on the Global wind report 2021, the role of renewable wind energy is recognized as one of the most resilient and cost-effective renewable sources in the world. Global wind energy with 93 GW installed new capacity 2021, a record year for the wind energy industry compared to previous years which are installed offshore 6.1 GW and onshore 86.9GW and this amount has almost quadrupled over the past decade, but enough to achieve a carbon-free world by 2050 is not. The United States and China are the two greatest energy markets in the world, providing about 75% of the world's wind energy facilities. The capacity of the wind farm worldwide is about 743 GW, which has prevented something like 1.1 billion tons of carbon emissions [1].

A new record year for the wind industry is shown in Figure 1.

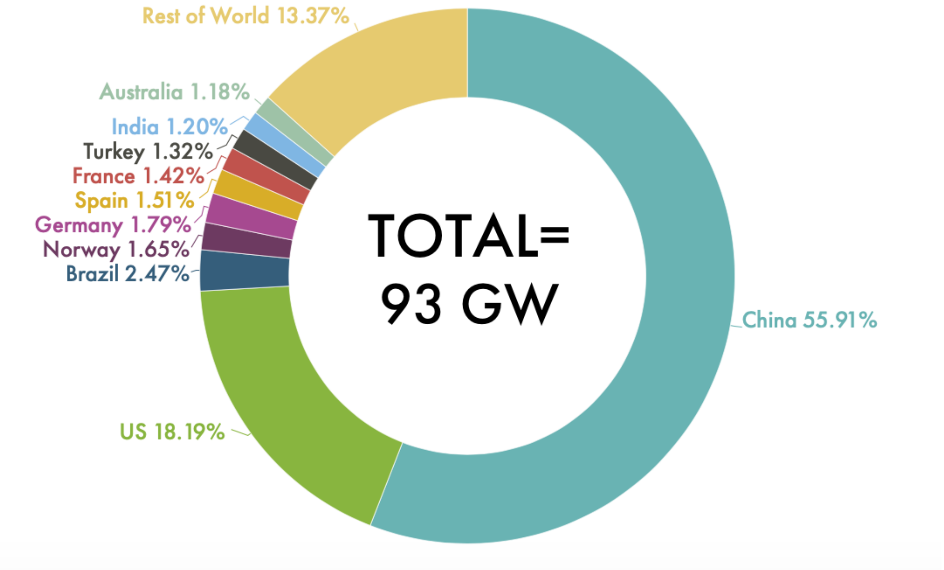


Figure 1: A new record year for the wind industry [1]

1.2 The Role of Wind Energy on the Road to Net Zero

A One of the global goals and agreements reached in 2009 by the Copenhagen Accord, was to tackle global climate change and limit global warming to below 2 degrees Celsius [1]. As is shown in Figure 2, to achieve this goal, the world must have an average of 180 GW of wind energy per year [1].

Subsequently, the British government and the European Union made commitments, following which the British government pledged to increase renewable energy production by 15% in 2020. The EU goal is to make less greenhouse gas emissions by 20%, Sets out the “20-20-20” directive for a closed climate policy [2].

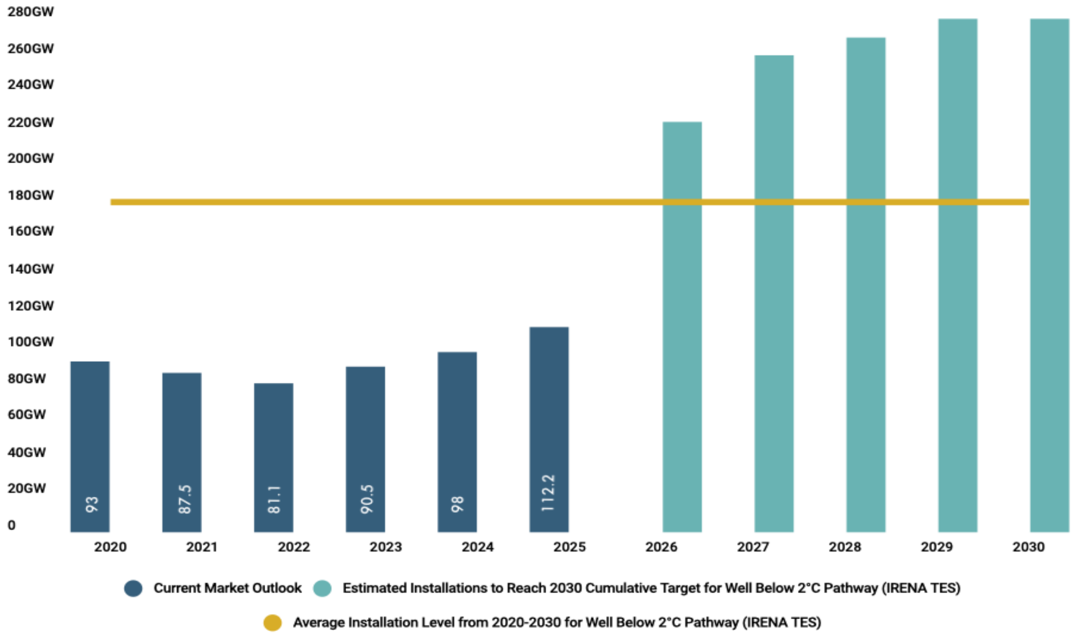


Figure 2: Global warming well below 2 degrees Celsius [1]

Based on the zero net IEA by 2050 scenario, the annual implementation rate should reach 160 GB by 2025 and 280 GB by 2030.

One of the reasons why most countries turn to wind energy is because the carbon footprint of wind power is the lowest compared to other types of energy.

Renewable energy sources, especially wind farms, have not yet released zero carbon due to the construction or production of wind turbines, but according to the NREL, the total greenhouse gas (GHG) emissions of coal is almost 90 times that of natural gas is almost 40 times larger than wind energy [3].

NREL says: “life cycle greenhouse gas emissions from solar, wind, and nuclear technologies are considerably lower and less variable than emissions from technologies powered by combustion-based natural gas and coal.” Also, based on the results of NREL scientists, they found that the amount of carbon dioxide produced by wind energy per kWh of electricity produced is 11 grams.

Figure 3 shows grams of CO2 per kilowatt electricity produced for various energy resources.

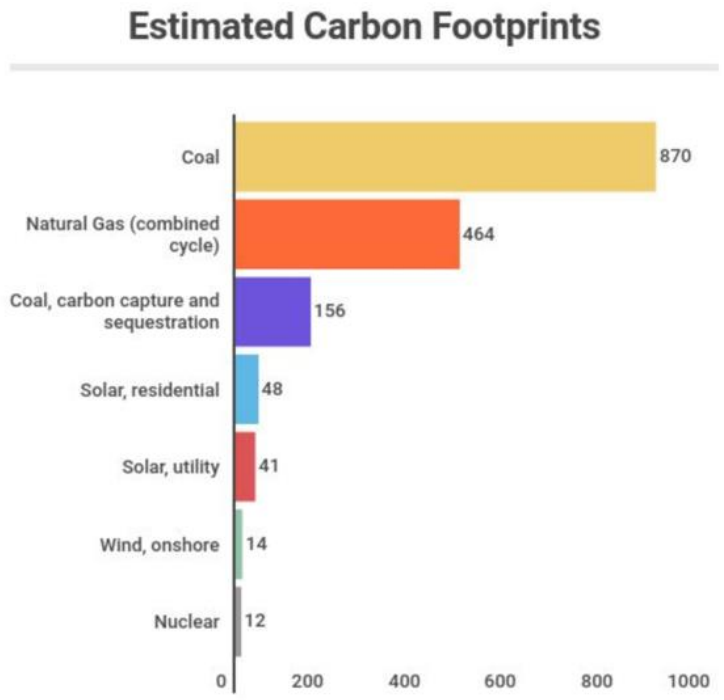


Figure 3: Grams of CO2 per kilowatt electricity produced [3]

1.3 Wind Power Development

Wind energy accounts for a large share of energy production among other renewable sources. Wind energy is the energy of moving air, when sun’s rays reach the rugged surface of the earth unevenly, it causes changes in temperature and pressure, and because of these changes, wind is created. Also, the Earth’s atmosphere transfers warmth from the topics to the polar regions due to the movement of the Earth’s position, which also causes wind.

Utilization of wind energy and applications of wind turbines covers a wide range of industries. In terms of performance in wind turbines, kinetic wind energy is converted into mechanical energy and then into electrical energy.

These turbines can also be combined with solar (photovoltaic) cells for optimal use and more power generation. Currently most of the installed capacity of wind turbines in the last few decades have been of the network connected types, and sometimes in remote areas, wind turbines disconnected from the network have been used [4].

According to IRENA's latest data, Over the past two decades, the global installed capacity of offshore wind and land production has increased by 75%. According to the latest data, from 7.5 GW in 1997 to about 564 GW in 2018. The total capacity of wind energy generated and installed worldwide from wind energy has increased rapidly since the beginning of the 21st century.

Offshore and onshore wind farms are on the rise and act as power plants, and power of large wind turbines reaches 6-8 MW [5]. Some developing models will be able to generate a capacity of about 15 MW [6].

Figure 4 shows the rate of change in wind power capacity during the years 2001 to 2020.

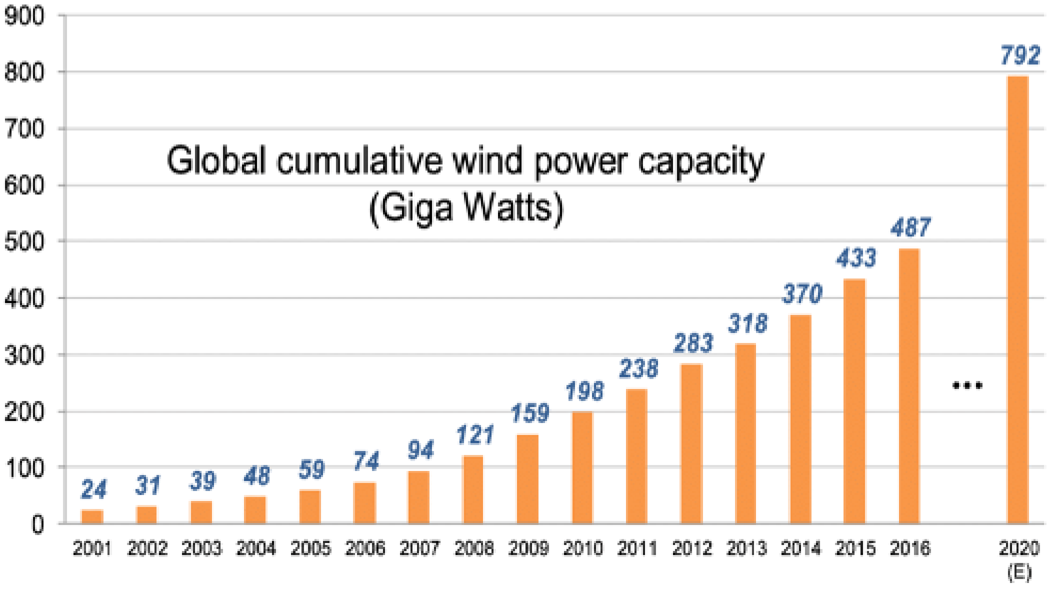


Figure 4: Global Wind Power Cumulative Capacity from 2001 to 2020 [5]

1.4 Wind power in UK

British electricity surpasses renewables from fossil fuels in EU renewable energy, wind turbines provide almost a quarter of electricity in 2020 [7].

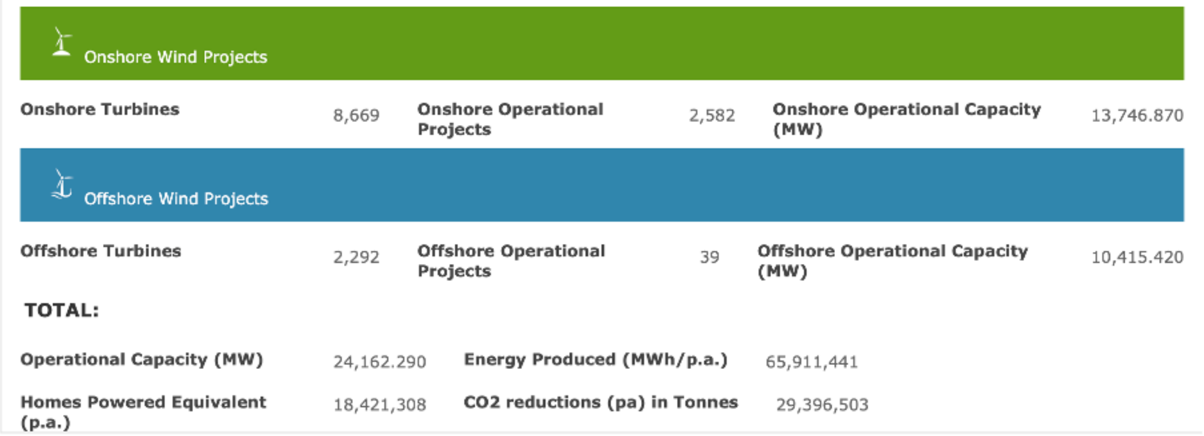
The growing sustainability of Britain's wind farms was one of the main reasons for the country's renewable record.

Wind energy, especially in the UK coast, has become one of the biggest successes in recent years. The country’s wind turbines are the main supplier of clean and renewable energy system.

Recent plans by the UK government to become “zero carbon” for the sector require that the area be converted to fully carbon zero by 2050 and that is wind turbine capacity be increased to 30 GW by 2030 and 75 GW by 2050.

About one-third of UK electricity power is produced by renewable energy sources, half of which are offshore and onshore wind power. Britain has lunched more than 12 GW onshore wind power, that generated 9% of Britain's energy needs in 2017. The UK is the world leader in offshore wind, the installed capacity produced over 10% of Britain's electricity by 2020 [8]. Table 1 shows data on onshore and offshore wind projects in the UK.

Table 1: Wind projects in Britain [8].



Onshore Wind Projects					
Onshore Turbines	8,669	**Onshore Operational Projects**	2,582	**Onshore Operational Capacity (MW)**	13,746.870
Offshore Wind Projects					
Offshore Turbines	2,292	**Offshore Operational Projects**	39	**Offshore Operational Capacity (MW)**	10,415.420
TOTAL:					
Operational Capacity (MW)	24,162.290	**Energy Produced (MWh/p.a.)**	65,911,441		
Homes Powered Equivalent (p.a.)	18,421,308	**CO2 reductions (pa) in Tonnes**	29,396,503		

1.5 Wind turbine technologies

Wind turbines can be studied from several perspectives based on the rotation of the turbine blades. For example, around the axis, the turbine blade can rotate around a horizontal or vertical axis [9]. According to this, wind turbines are categorized into the following two types:

- Horizontal Axis Wind Turbines (HAWTS)
- Vertical Axis Wind Turbines (VAWTS)

Horizontal axis wind turbines have a longer history and are still the most common today. In contrast, the advantage of a vertical axis wind turbine is insensitivity to the direction of the wind and no need for a high base. Currently, horizontal-axial wind turbines are used more than vertical axis models. Horizontal axis turbines, although more complex and expensive, have a very high efficiency. These types of turbines work in all conditions, even at low wind speeds. Figure 5 shows these two types of wind turbines [9].

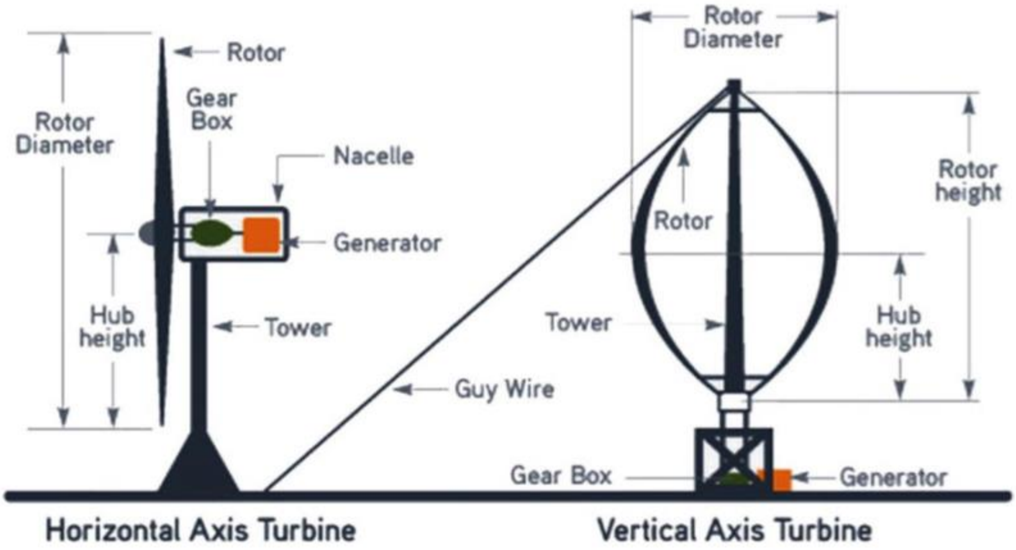


Figure 5: Taxonomy of wind turbines based on the axis of rotation of the blades [9]

Another category based on how turbine works, and its components is as follows [9, 10]:

- Fixed-Speed Wind Turbines
- Variable-Speed Wind Turbines

Today's modern turbines consist of three blades that have very good dynamic performance. The use of many blades causes the passage of one blade to disturb the air dynamics and increase the mechanical stress on the next blades. The use of two blades is used only in turbines with high power generation capability. One of the disadvantages of using two blades is the high tension that is created when these blades pass by the nozzle retaining tower [11].

1.5.1 The main components of horizontal-axis wind turbine

Horizontal-axis wind turbines are composed of various components, the following are the most important parts of this type of turbine [9].

- Anemometer: This device measures the wind speed and delivers the resulting information to the controllers.
- Goniometer: Wind turbines that use this technology also work in the opposite direction of the wind; Conventional turbines, on the other hand, must face the wind to blow.

- Wind Vane: It is a device that measures the direction of the wind and helps to keep the direction of the turbine relative to the wind.
- Blade: This is one of the main parts of a wind turbine and its role is to produce the necessary force to rotate the main axis of the wind turbine. The blade is built in such a way that it has a very high strength and endurance against dynamic and aerodynamic forces. The wind turbine blades absorb and rotate the wind energy by slowing it down. Today, two-blades and three-blades turbines are more common. The intensity of the vibration can be reduced by increasing the number of blades. Therefore, in three-blades turbines, compared to two-blades turbines, the amount of noise and depreciation is less.
- Rotor: The wind turbine rotor includes blades, hubs, nasal, and blade bearings. The rotor of a horizontal-axis wind turbine, in short, consists of several blades mounted radially around an axis parallel to the wind, thus forming a rotor that rotates perpendicular to the wind direction. The rotor is usually placed at a suitable height from the ground by a tower.

  According to Figure 6, the rotor can be installed downwind of the tower (back to the wind) or upwind of the tower (facing the wind).

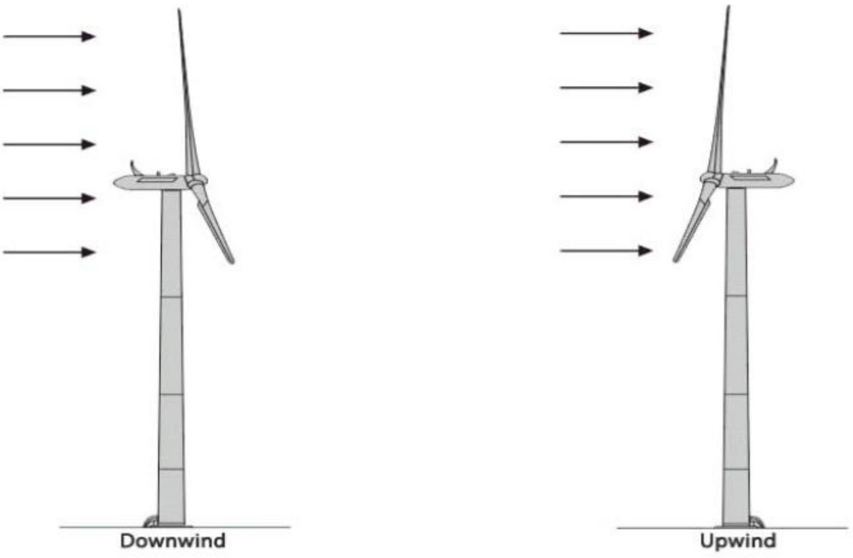


Figure 6: Downwind and upwind design of the rotor [12]

- Tower: Steel lattice structures, steel, or concrete cylindrical towers, as well as cable-supported columns are the most common retaining towers. For towers, the height is usually considered to be between 1 and 1.5 times the diameter of the rotor. The choice of tower type depends on the site conditions. Turbines mounted on taller towers receive more energy.

- Nacelle: It includes the outer cover of the turbine, chassis, and rotation system around the axis of the tower to which the rotor is connected. Nacelle is located above the tower.
- Transmission System: The transmission system consists of wind turbine rotating components. These components mainly include the low-speed shaft (on the rotor side), the gearbox and the high-speed shaft (on the generator side). The job of the high-speed shaft is to move the generator. The rotor rotates around a low-speed shaft with a rotational speed of 30 to 60 rpm. Other components of this system include bearings, one or more couplings, mechanical brakes, and rotating generator components. In this set, the function of the gearbox is to increase the nominal speed of the rotor from a small value (in the range of several tens of revolutions per minute) In high quantities (in the range of several hundred or several thousand revolutions per minute) That's perfect for triggering a standard generator.
- Generator: The function of the generator is to generate Alternating Current (AC) power. The kinetic energy of the wind is converted by the wind turbine blades into rotational in the transmission system, and then the generator is activated and delivers the energy received from the turbine to the power system.
- Brake: This device is used in emergencies when we intend to stop the rotor. Braking can be done mechanically, hydraulically, or electrically.
- Controller: When the wind speed reaches 8 to 12 mph, the controller starts the machine and when the speed exceeds 65 mph, it commands the system to shut down. This is because turbines are unable to move when the wind speed reaches 65; Because in this situation, the generator will heat up quickly.
- Yaw Drive: It is a device that assesses the condition of the turbine and, if necessary, issues an order to position the nacelle so that the rotor is facing the wind.
- Yaw Motor: Used to move the yaw drive.

Figure 7 shows a picture of the components of a wind turbine.

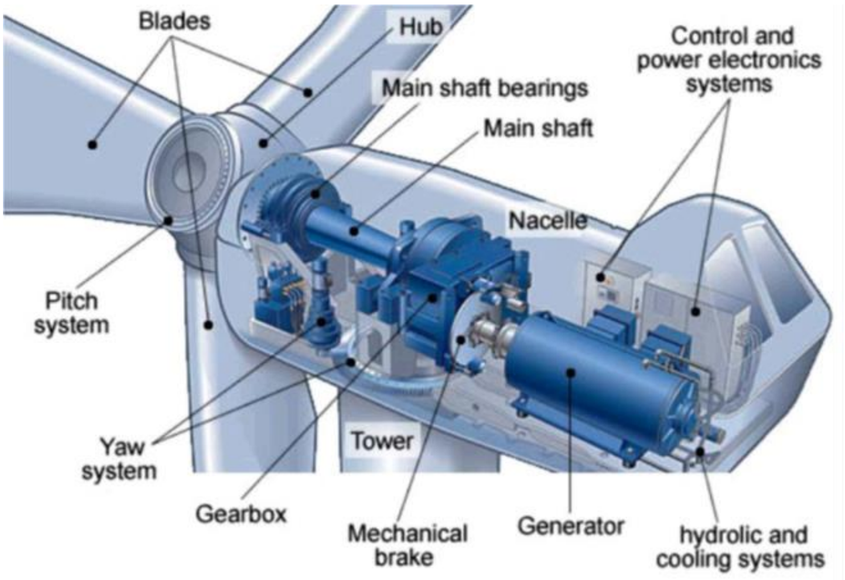


Figure 7: The main parts in a wind turbine [12]

1.6 Pitch control in wind turbine

A wind turbine control system includes sensors, actuators, and a system for integrating these components. A software or hardware system processes the input signal from the sensors and generates the output signal for the actuators. The main purpose of the controller is to change the operating mode so that the safety of the wind turbine is maintained, the output power is maximized, and the fault conditions are identified.

In conventional wind turbines, different operating areas are defined. The operating range of a wind turbine, as shown in Figure 8, can be divided into the following four regions:

1. In region I, the wind speed is less than the wind Cut-in speed. In this case, only the torque control is active, and the pitch control is inactive. In this region, only the system start-up command is executed.
2. In region II, when wind speed is lower than the nominal speed, the goal is to maximize the output power.
3. In region III, the wind speed exceeds the nominal value. At this stage, the pitch angle control enabled, and it tries to get the maximum power from the generator. The main purpose of control at this stage is to keep the output power constant at the nominal value of the power so that no pressure is applied to the internal components of the turbine and additional turbine overheads are reduced.

4. In region IV, the wind speed is higher than the wind cut-out speed. At this stage, the wind turbine must be switched off to avoid potential hazards.

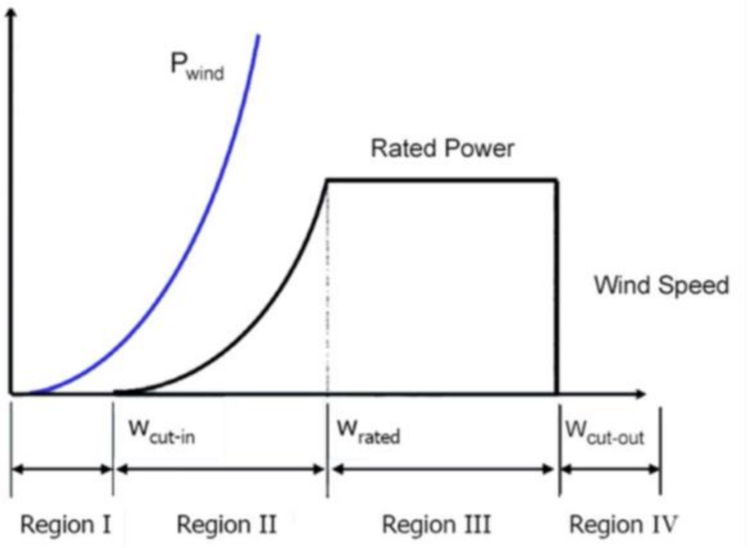


Figure 8: Operating regions of wind turbines [13]

As the use of wind turbines increases around the world, researchers are increasingly paying attention to controlling the system to achieve maximum output power [14]. In all speed-variable turbines, the output power must be controlled as a general feature; otherwise, the balance in the mechanical rotation of the system cannot be maintained; In addition, it will be impossible to keep the rotor speed constant at certain values [15].

Today, various mechanisms are used to achieve control goals in wind turbines. Some turbines perform the control operation passively (for example, by keeping the pitch angle constant and using the stall control system). In this method, the blades are designed to limit the output power in region III. So, they do not need to control the pitch. In general, in these turbines, control is applied only to start and turn off the turbine. In contrast, rotors that can adjust the pitch perform better than the stall method in controlling the output power. The pitch adjustment operation is performed in such a way that the output power is kept constant in region III. Pitch control in this type of turbine must provide an immediate response so that the system is able to properly adjust the power in the presence of sudden wind and vibrations.

1.7 Research Question and Research Objectives

The aim of this thesis is to control the wind turbine pitch angle so that the rotor rotational speed is closest to the nominal value and finally we have proper control over the power and torque produced.

But what is the problem and what is the solution? If wind fluctuations are high at high wind speeds, the blades will be pressurized and mechanical damage to the system may occur. Different strategies have been proposed to limit the output power of the system, which prevent additional overhead in the wind turbine. One of the most common of these strategies is pitch angle control in variable-speed turbines. This method gives the ability to keep the output power constant within the allowable range. Pitch angle control in variable-speed turbines is important because we have a safe, efficient, and stable system with this.

The main purpose of a closed loop controller can be simply stated. For example, the main purpose of pitch control can be to limit the output power or rotor speed at high wind speeds. Goals can be more than one main goal, in this case, the use of pitch control to optimize energy intake at low wind speeds.

In general, the following objectives can be considered when designing a pitch angle controller:

- Optimize power generation at low wind speeds
- Adjust or limit torque aerodynamics at high wind speeds
- Reduce maximum fluctuations in gearbox torque
- Avoid excessive activity in the pitch
- Control vibration of the tower and reduce additional overhead in the turbine

Variable angle wind energy conversion system is a new development in the industry and its advantages are increased efficiency and more energy. This has made pitch angle control an essential role in modern wind energy conversion systems.

1.8 Thesis Structure

This thesis consists of 5 chapters that is shown in Figure 9. An introduction was given in the current chapter.

In chapter 2, we describe the wind turbine types and an overview of the research works done to pitch angle control of the turbine.

Chapter 3 includes introduction of control algorithms and the proposed method for controlling the wind turbine pitch angle.

In chapter 4, numerical simulation of the proposed method and its results are presented.

Finally, chapter 5 contains conclusions and suggestions.

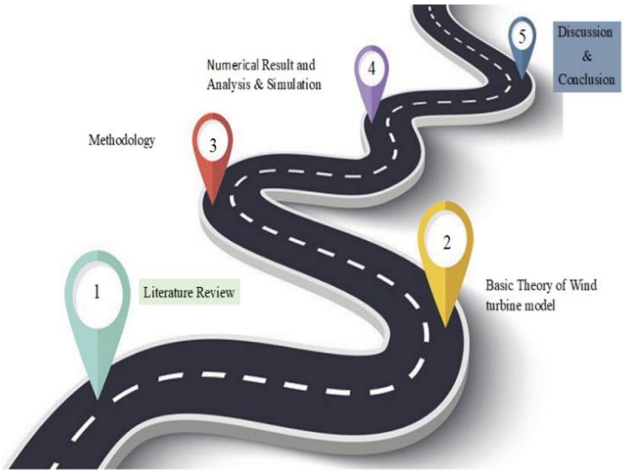
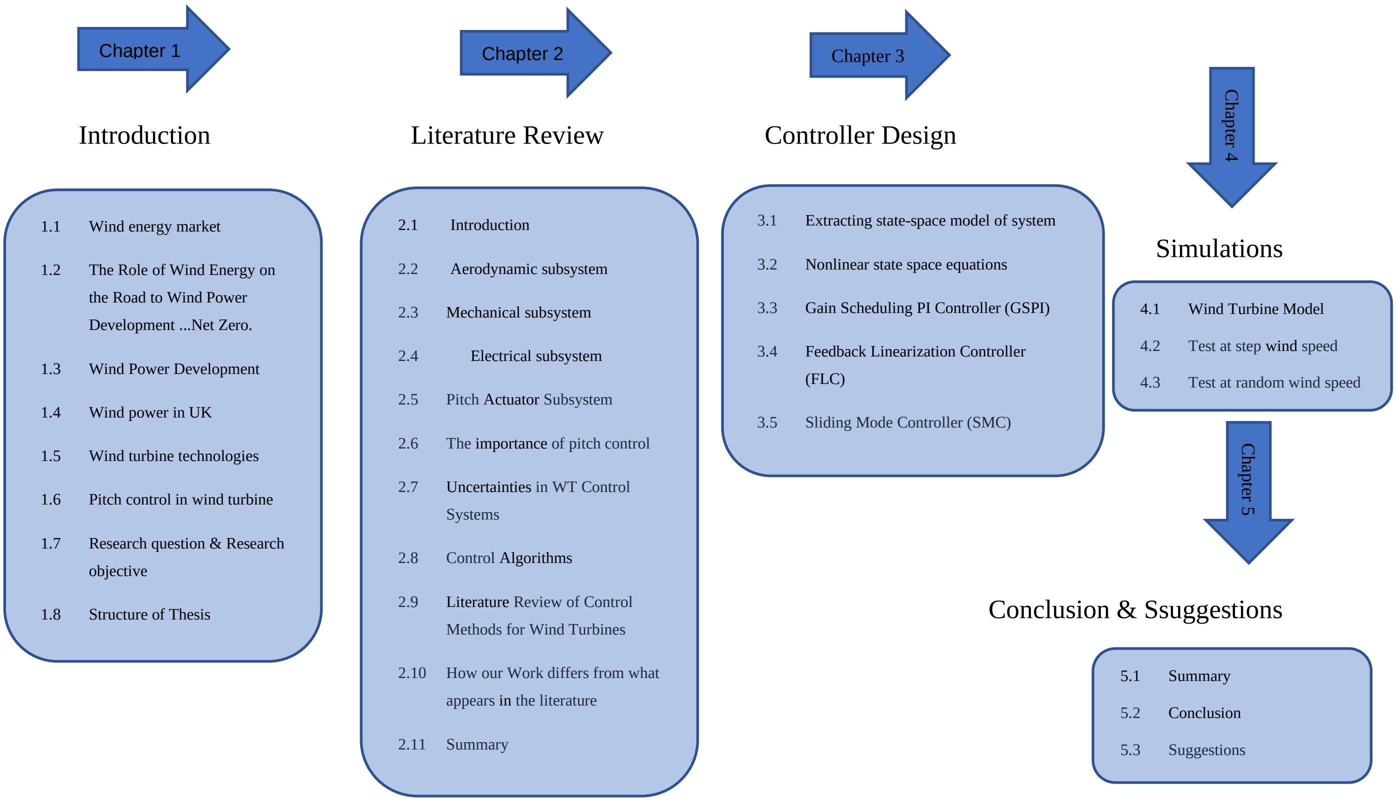


Figure 9: Roadmap of this work



1.1 Wind energy market
1.2 The Role of Wind Energy on the Road to Wind Power Development ...Net Zero.
1.3 Wind Power Development
1.4 Wind power in UK
1.5 Wind turbine technologies
1.6 Pitch control in wind turbine
1.7 Research question & Research objective
1.8 Structure of Thesis

2.1 Introduction
2.2 Aerodynamic subsystem
2.3 Mechanical subsystem
2.4 Electrical subsystem
2.5 Pitch Actuator Subsystem
2.6 The importance of pitch control
2.7 Uncertainties in WT Control Systems
2.8 Control Algorithms
2.9 Literature Review of Control Methods for Wind Turbines
2.10 How our Work differs from what appears in the literature
2.11 Summary

3.1 Extracting state-space model of system
3.2 Nonlinear state space equations
3.3 Gain Scheduling PI Controller (GSPI)
3.4 Feedback Linearization Controller (FLC)
3.5 Sliding Mode Controller (SMC)

4.1 Wind Turbine Model
4.2 Test at step wind speed
4.3 Test at random wind speed

5.1 Summary
5.2 Conclusion
5.3 Suggestions

Figure 10: Block diagram of this work

2.0 Literature Review

2.1 Introduction

The main purpose of this chapter is to review different types of wind energy conversion systems and review research works done to control of wind turbine pitch angle.

For this, we divide the system into the following four main subsystems [16]:

1. Aerodynamical subsystem: This subsystem is dedicated to harnessing wind energy and converting it into useful mechanical energy.

2. Mechanical subsystem: This subsystem is divided into two main parts: The drivetrain and the structural support. The actuator transmits aerodynamic torque of the blades to the generator shaft, which includes the rotor, conversion unit and mechanical parts of the generator. The second part, the support structure, includes the tower and the foundation and supports the rotor and other mechanical components against the applied axial forces.

3. Electrical subsystem: This subsystem includes a converter that converts the mechanical power generated by the generator shaft into electrical power.

4. Pitch Actuator Subsystem: Includes a hydraulic or electromechanical system that rotates the blades around their longitudinal axis to change their angle. By combining these four subsystems, a general model for the wind energy conversion system is obtained. Figure 8 shows these subsystems separately [17]. Since the dominant dynamics is in the mechanical subsystem, the wind energy conversion system can be considered as a mechanical structure that is subject to external forces independent of the air flow and the electric machine [16].

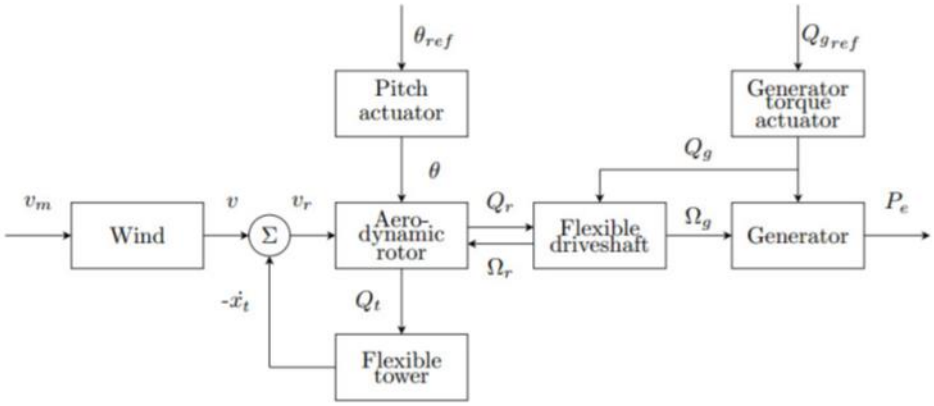


Figure 11: Relationship between subsystems of a wind turbine (reproduced from [17])

As shown in Figure 10, wind speed v_m is specified as system input and generator power P_e is specified as system output. The reference angle θ_{ref} and the generator torque Q_{ref} are control inputs. Wind force is one of the most important forces affecting the system. Wind speed is uncontrollable and related to the aerodynamic system. Therefore, there is a direct relationship between wind speed and rotor speed. The aerodynamic subsystem is affected by the rotor blade angle, rotor speed and wind speed. The final output of the system, power, comes from the generator [17, 18]. For better wind turbine performance, the generator torque and turbine pitch angle (parameters both in the aerodynamic subsystem) must be adjusted.

In order to maximize the efficiency of the wind turbine in the first region (low speed wind region), as the wind speed increases, the rotor speed also increases so that the pitch angle remains constant at θ_0. In the third region (high speed wind region), the rotor speed is kept constant at its nominal speed. In this region, the pitch angle is adjusted so that the output power remains constant at the nominal power value [19].

2.2 Aerodynamic subsystem [16]

The aerodynamic subsystem includes a three-dimensional wind field, which results in forces applied to the blades. The main purpose of a wind turbine is to extract as much energy as possible from the wind. Like other energy conversion systems, wind turbines will not be able to extract all the energy in the wind. The amount of energy in the wind can be calculated according to Equation (2.1):

$$E_k = \frac{1}{2} m V^2 \tag{2.1}$$

$$m = \rho AVt \tag{2.2}$$

The power in the wind, according to Equation (2.3), is obtained from the equation of energy in the wind, in a certain period:

$$P_W = \frac{1}{2}\rho AV^3 \tag{2.3}$$

where $E_k[J]$ is kinetic energy in the body, $P_W[W]$ is power in the wind, $m\ [kg]$ is mass of body, $\rho\ [kg/m^3]$ is body density, and $A\ [m^2]$ is body area.

2.2.1 Energy Conversion Rate

The rate of energy conversion is commonly known as power coefficient C_P, which is the ratio of power drawn from the wind to actual power of wind:

$$C_P = \frac{P_r}{P_W} \tag{2.4}$$

So that C_P is called the power coefficient and $P_r[W]$ is power drawn from the wind by the rotor. The power that can be drawn from the wind depends on the forces acting on the rotor and the wind speed applied the rotor. The wind speed in the rotor can be calculated from the wind speed in front of the rotor and an axial flow interference factor α.

This factor describes how the wind speed is slowed down by a running wind turbine.

$$P_r = F_D V_D \tag{2.5}$$

$$V_D = V(1-\alpha) \tag{2.6}$$

$$F_D = 2\rho AV\alpha V_D \tag{2.7}$$

$$P_r = 2\rho AV^3\alpha(1-\alpha)^2 \tag{2.8}$$

where $F_D[N]$ is force applied to the blades by the wind, $V_D[m/s]$ is the wind speed applied to the rotor plate and α is the axial flow interference factor. Axial flow interference factor is different for each turbine. This factor is a critical factor in maximizing the extracted power from the turbine.

According to Equations (2.8) and (2.3), the formula for the power coefficient calculated in Equation (2.4) can also be expressed as (2.9):

$$C_P = \frac{P_r}{P_W} = \frac{2\rho AV^3\alpha(1-\alpha)^2}{\frac{1}{2}\rho AV^3} \tag{2.9}$$

$$C_P = 4\alpha(1-\alpha)^2 \tag{2.10}$$

To maximize the value of C_P, the value of α must be found. The Betz limit rule theoretically defines this value as $\alpha = \frac{1}{3}$. Thus, the value of C_P is also calculated as $C_P = \frac{16}{27} = 0.593$. For today's wind turbines, this value is about 0.45. Of course, more values have also been reported.

2.2.2 Pitch and Tip Speed Ratio

The power coefficient C_P is not a fixed value but varies depending on the angle of attack (AOA). The angle of attack depends on the pitch and tip speed ratio. The tip speed ratio of blade is the ratio of the speed of rotation of the blades to the wind speed, which is calculated according to Equation (2.11).

$$\lambda = \frac{\Omega_r R}{V} \tag{2.11}$$

Where λ is tip speed ratio of blades, $\Omega_r[rad/s]$ is speed of rotation of the blades, $R[m]$ is blade radius, and $V[m/s]$ is wind aped.

The angle of attack is defined according to Equation (2.12). Changing the angle of the blades is one of the control components during which the rotation speed of the turbine blades can be increased or decreased. The angle between the relative wind speed and the direction of rotation of the blades, ϕ, varies according to the wind speed and the rotation speed of the blades. The higher the value of λ, the smaller the angle ϕ will be, and vice versa.

$$\alpha = \phi - \beta \tag{2.12}$$

In this equation, $\alpha[°]$ is the angle of attack, $\phi[°]$ is the angle between the relative wind speed and the direction of rotation of the blades, and $\beta[°]$ is the angle of the blade.

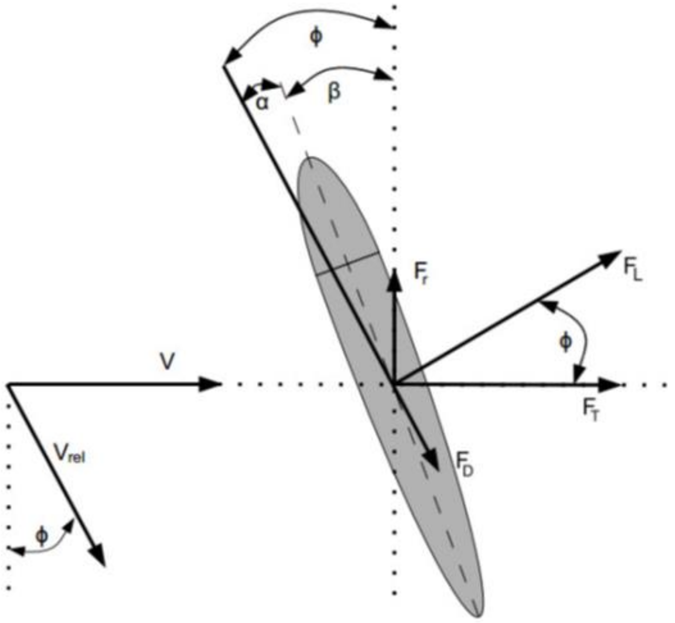


Figure 12: Forces applied to the blades (reproduced from [20])

In Figure 10, the forces acting on the blades, $F_r[N]$ the rotational force of blade, $F_T[N]$ the thrust force of the blade, $F_L[N]$ the lift force of the blade, $F_D[N]$ the drag force of the blade are strongly dependent on the wind direction. Wind speed and direction are denoted by $V[m/s]$ and relative wind speed and direction that affect the blades are denoted by $V_{rel}[m/s]$. As the relative direction of the wind changes according to the wind speed and rotation speed, it is necessary for the blade to change the angle to the relative wind to receive the maximum torque from the wind. The rotational force F_r can be controlled by changing the pitch angle. There are two main ways to reduce rotational force on a turbine using pitch control: Pitch towards Stall and Pitch towards Feather. These two methods are shown in Figure 11 [20].

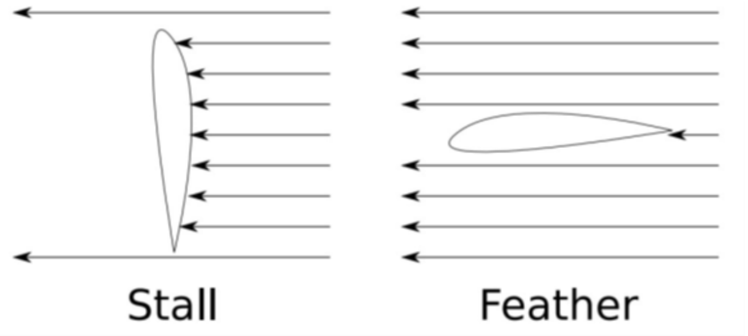


Figure 13: Blade pitch angle control methods (wind direction from right to left) (reproduced from [20])

2.2.3 Power

Equation (2.4) can be written as Equation (2.13):

$$P_r = P_W C_P \tag{2.13}$$

By merging the two equations (2.3) and (2.13), equations (2.14) and (2.16) are obtained.

$$P_r = \frac{1}{2}\rho A V^3 C_P \tag{2.14}$$

$$A = \pi R^2 \tag{2.15}$$

$$P_r = \frac{1}{2}\rho \pi R^2 V^3 C_P \tag{2.16}$$

The area swept by the blades can be calculated using Equation (2.15). When the wind speed exceeds the nominal value, C_P decreases to keep the output power constant.

$P_r[W]$ is the wind power extracted by the rotor, $P_W[W]$ is the wind power, C_P is the power coefficient, $\rho[kg/m^3]$ is the air density, $A[m^2]$ is the area swept by the blades, $V[m/s]$ is the wind speed and $R[m]$ is blade radius.

2.2.4 Torque

The torque from the wind energy applied to the turbine can be calculated from the equation of power and rotational speed of the blades. The torque applied to the rotor is defined as the product of the torque in the wind and the torque coefficient C_Q. The torque coefficient can be calculated using the power coefficient. Using the definition of rotor torque as a function of C_Q, and Equation (2.11), Equation (2.19) is obtained.

$$T_r = \frac{P_r}{\omega_r} \tag{2.17}$$

$$T_r = \frac{1}{2}\rho \pi R^3 V^2 C_p \frac{1}{\omega_r} \tag{2.18}$$

$$T_r = \frac{1}{2}\rho \pi R^3 V^2 C_Q \tag{2.19}$$

$$C_Q = \frac{C_p}{\omega_r} \tag{2.20}$$

2.3 Mechanical subsystem

Horizontal axis wind turbine is a complex mechanical system consisting of devices interacting with varying degrees of flexibility. To model a wind energy converter system, the most important and most extensive part is its mechanical infrastructure. The complexity resulting from the interactions between the flexible structures of the foundation, the tower and the drive-train is significant. Each of these structures is fixed to a reference framework whose rotation is also interdependent. This leads to complex nonlinear models. In addition, the forces exerted by the three-dimensional field of the wind are also important. A wide range of computational tools have been developed specifically for design whose models are very useful and efficient in validating results and evaluating them. However, usually due to the very high complexity of these models, control models must be simple and executable [16,21].

Control models of wind energy conversion systems are typically derived from the multi-body system approach. This technique creates order reduction models. Thus, the mechanical structure is modelled with several rigid bodies joined together by flexible joints. The number of these joints or degrees of freedom of the system determines the degree of the model. Even low degrees of freedom have complex nonlinear degrees. It is therefore important that in the model, only those degrees of freedom that are not directly in relation to the controller determine the dynamic behaviour of the whole system, but are effective in control, for proximity to the objectives [22, 23].

2.3.1 Drive-train [15]

In this section, a simplified schematic of the mechanical model of a wind turbine is presented. The drive-train is divided into four main parts: the low-speed shaft, the high-speed shaft, and the spring-loaded gearbox, which is simply shown in Figure 8. The drive-train input for the wind turbine system is the torque from the aerodynamic subsystem, T_r, and the reaction torque of the generator, T_g, and the output of the system is the changes in the rotor speed ω_r, and the generator speed ω_g. The terms rotor inertia J_r, generator inertia J_g, shaft stiffness K_s and shaft damping B_s are the model parameters.

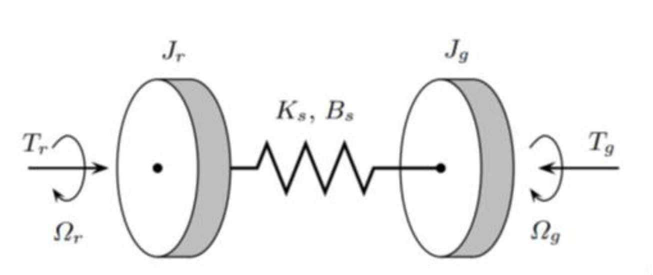


Figure 14: Drive-train schematic (reproduced from [15])

2.3.2 Tower [15]

The force exerted on the tower is the force exerted primarily on the rotor. The tower can be modelled with a spring and a damper. The tower equation can be described using equation governing the spring and damper according to Equation (2.22).

$$M_t \ddot{x}_t(t) = F_t(t) - B_t \dot{x}_t(t) - k_t x_t(t) \quad [N] \tag{2.21}$$

In this equation, B_t is the damping coefficient of the tower, $F_t(t)$ is the wind force on the turbine, k_t is the rotation coefficient of the tower, M_t is the mass of the tower and $x_t(t)$ is its displacement of tower.

2.4 Electrical subsystem

Due to the differences in power generation technology, wind turbines are divided into the following four main categories [14]:

1. Fixed-Speed Wind Turbines
2. Variable-Speed Wind Turbines
    - (a) Variable-Slip Wind Turbines
    - (b) Doubly-Fed Induction Generator (DFIG) Wind Turbines
    - (c) Full-Converter Wind Turbines

2.4.1 Fixed-Speed Wind Turbines

Fixed-speed wind turbines are commonly known as Dawnish designs. These turbines usually use Squirrel-Cage Induction Generator (SCIG). Figure 13 shows an overview of this type of turbine.

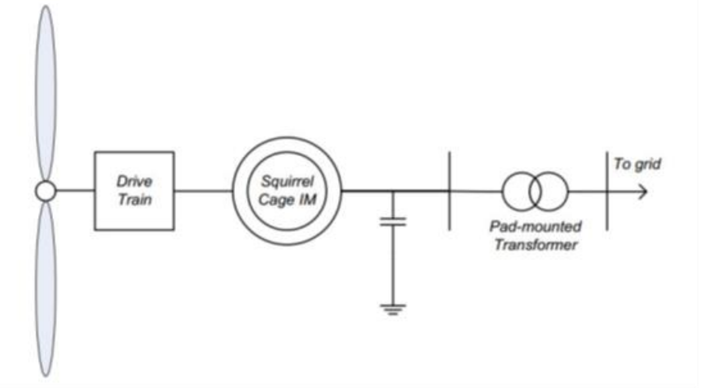


Figure 15: Overview of Fixed-speed wind turbines (reproduced from [11])

Synchronous generators are not usually used in this method due to their high manufacturing cost. The generator stator, in this case, is connected directly to the grid. The turbine blade rotor is connected to the generator rotor via a gearbox. Therefore, the turbine can use the kinetic energy stored in the turbine blades. In general, fixed-speed turbines have a simple structure, but because they cannot track wind speed fluctuations, their energy production is not as efficient as that of variable-speed turbines [14].

Because these turbines operate within a certain speed range, these turbines tend to have a sudden increase in torque, which can cause mechanical damage and instability in the electrical circuit. To adjust the output power at high wind speeds, we can use the methods of adjusting the stall, active adjusting the stall or adjusting the pitch angle [11].

The advantages of this type of turbine, in addition to simplicity in structure, are low cost and simplicity of the control system. In contrast, low efficiency, control and structural limitations, severe voltage fluctuations and thus reduced system stability are the disadvantages of this type of turbine [14].

The following led wind turbine engineers to design new generators that could produce high quality output power and improving power system performance simultaneously [11]:

- Affordable power converters
- Advances in Modern Control
- Study of the science of elastic or aeroelasticity (interaction between static, elastic, and aerodynamic forces when a resilient body is exposed to a fluid flow)
- Fast processing capability in microprocessors

2.4.2 Variable-Speed Wind Turbines

The following three groups fall into the category of speed-variable wind turbines. Speed-variable wind turbines are designed in such a way that the rotor speed can vary over a wide range. To adjust the output power of this type of turbine, the pitch angle controller is usually used [11]. The advantages of these turbines are achieving more energy, even getting the maximum wind power, reducing power fluctuations and consequently more constant output power, less mechanical pressure and reducing the noise effect compared to speed-constant turbines. These systems are relatively stable, but we must pay a lot of money to build and control them. The complex structure and use of more components in this type of turbine will require more complex and difficult control than fixed-speed turbines [14].

2.4.3 Variable-Slip Wind Turbines

In this type of variable-speed wind turbines, wound-rotor induction machine is used, which allows access to the stator and rotor of the machine. The rotor circuit is connected to an ac/dc converter and a fixed resistor. The converter is switched to control the effective resistance in the rotor circuit in such a way as to provide a wide range of speed changes in the range of operation (up to 3% increase). Electric power is dissipated in the form of heat in the external circuit resistance of the rotor. To solve this problem, a controller can be designed to change the effective external resistance of the rotor to achieve optimum power. An overview of this type of wind turbine can be seen in Figure 14.

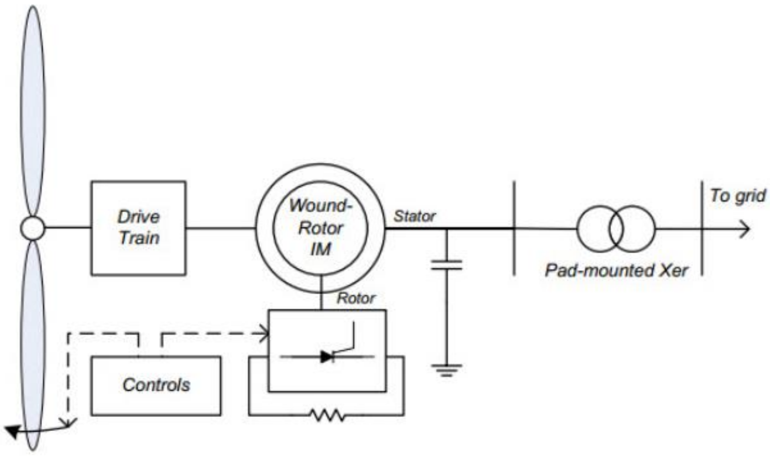


Figure 16: Overview of Variable-slip wind turbines (reproduced from [11])

2.4.4 Doubly-Fed Induction Generator (DFIG) Wind Turbines

Wind turbines with doubly-fed induction generators solve the problem of power loss in the rotor circuit by using an ac/dc/ac converter. Rotor flux vector control controls the separation of active and reactive output powers as well as the production of maximum output power and reduction of mechanical stresses.

In the case of a doubly fed induction generator, the stator winding is connected directly to the grid. But the rotor winding is connected to the power system with an ac/dc/ac converter. Therefore, the electrical frequency will be different from the mechanical frequency. This converter uses active or reactive power control, either using a constant power factor or a constant voltage [14].

These turbines usually use blade pitch angle control to adjust power. The disadvantages of this technology, compared to previous methods, are high cost and greater complexity. These turbines are usually the most popular type of turbine on the market and are widely used. An overview of this type of wind turbine can be seen in Figure 15. Doubly-fed induction generators are one of the most widely used electric machines.

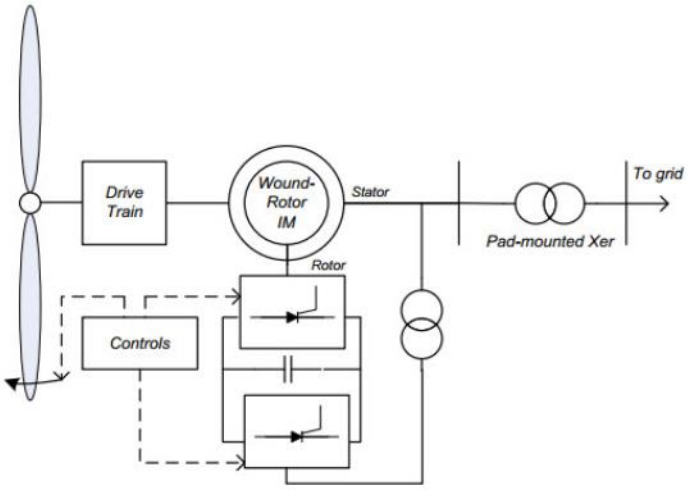


Figure 17: Overview of Doubly-Fed Induction Generator (DFIG) Wind Turbines (reproduced from [11])

2.4.5 Full-Converter Wind Turbines

In full- converter wind turbines, an ac/dc/ac converter is the only interface between the wind turbine and the grid. Therefore, there is no direct connection to the grid and the converter must be configured to control output power. These turbines usually use synchronous generators to operate at low speeds and increase gearbox reliability [11]. In the case of a synchronous generator, the wind turbine can rotate at any speed to achieve maximum output power. Therefore, the frequency of electricity generated can change due to rapid wind changes. In this case, the generator cannot be connected directly to the grid because it will produce low output power. In variable-speed applications, these generators are connected to the grid by an ac/dc/ac converter connected to a synchronous generator stator. The output frequency of the generator is first converted to an ac variable frequency, then to dc, and finally to ac again. This design makes the stator independent of the output power of the system and its frequency changing. Therefore, the output power of the wind turbine generator will not change during several repeated events. Figure 16 shows an overview of this type of wind turbine.

In these turbines, active and reactive power control can be performed independently, and a pitch angle controller is used to adjust the output power. Although these turbines are relatively expensive, but the increased reliability and simplicity of control, compared to doubly fed induction generator turbines, attracts the attention of researchers to this type of turbine-Especially in offshore facilities that have high maintenance costs.

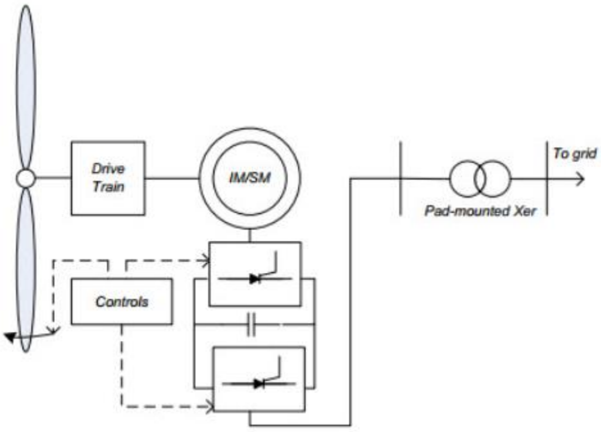


Figure 18: Overview of Full-Converter Wind Turbines (reproduced from [11])

2.5 Pitch Actuator Subsystem

The controller is the mastermind of an industrial process. When industrial processes are placed in the control loop alone and without the use of a controller, they usually do not have the desired responses in terms of transient or steady state properties; Therefore, selecting and setting a suitable controller is one of the most important steps in an industrial process. A controller summarizes the following steps:

1. First, the output signal from the sensor enters the controller and is compared with the reference value.
2. The result of the comparison in step 2, which is the error signal, is usually amplified inside the controller and depending on the type of controller and the desired parameters, special operations are performed on it.
3. The result obtained from step 2 enters the next block as the controller output signal.

The control system, in addition to guiding wind turbines for optimal use, is also a tool to protect it against various weather events. Some of the factors that are monitored by control systems are [21]:

- Control of sudden voltage rise due to various phenomena such as lightning and so on
- Control, for quiet shutdown of wind turbine system
- Protection of sensors for detecting meteorological parameters (wind speed and direction, ambient temperature, and ambient pressure)

- Control of grid characteristics (such as phase voltage equipment, current intensity, transformer voltage and generated power frequency)
- Control the turbine shaft in the best conditions in the direction of the wind direction
- Control the speed of the blades by applying the brakes at the required times
- Control of pitch angle, rotor speed and of course generator power

Control plays a key role in modern wind energy conversion systems. Output power generation must be limited to avoid overhead. In addition, a well-designed control system greatly reduces the mechanical and aerodynamic load of the system, thus increasing the life of the facility [24].

2.5.1 Closed-loop control [21]

The closed-loop controller is usually a software-based system that automatically adjusts the operating mode of the turbine to keep the turbine constant in a predefined position. The following are some examples of closed loop control systems:

- **Pitch control** is applied to adjust the output power, or the speed of the rotation (to a fixed-point value or values that change slowly). Pitch control is one of the most common aerodynamic power control methods produced by turbine rotors. When the wind speed is less than the nominal speed, the turbine can easily generate the necessary electricity, so there is no need to change the pitch angle, because the optimal pitch angle will not change much as the wind speed increases. When the wind speed is higher than the nominal limit, pitch control is one of the most effective tools for regulating the output power generated by the rotor. Of course, to achieve the desired set-point, by changing the environment, pitch control, requires fast response and action. In this case, the controller strongly interacts with the turbine dynamics, so it needs to be carefully designed.
- **Generator torque control** is performed in variable-speed turbines to adjust the rotational speed. When the aerodynamic torque in a constant-speed turbine changes, the rotor speed will also change slightly. Therefore, the generator torque changes in line with the aerodynamic torque. In this case, the generator torque cannot be controlled directly. If a frequency converter is placed between the generator and the network, the generator speed will be able to change. This frequency converter can be actively

controlled to have a constant value at high wind speeds, generator torque or output power.

- **Yaw control** is used to minimize the tracking error. If the turbine nozzle can start, the turbine will normally be blown. But it might not be exactly facing the wind, in which case we need an active control to change the nozzle angle to maximize output power.

Some of these closed-loop control methods require an immediate answer to avoid the turbine from moving away from optimal performance. In designing such controllers, care must be taken that the desired performance does not affect other aspects of the system. In controls such as angle, because design is slow, accuracy in design is less important.

2.6 The importance of pitch control

If wind fluctuations are high at high wind speeds, the blades will be pressurized and mechanical damage to the system may occur. Different strategies have been suggested to limit the output power of the system, which prevent additional overhead in the wind turbine. One of the most common of these strategies is pitch angle control in variable-speed turbines. This method gives the ability to keep the output power constant within the allowable range. Pitch angle control in variable-speed turbines is important because we have a safe, efficient, and stable system [11].

Variable angle wind energy conversion system is a new development in the industry and its advantages are increased efficiency and more energy. This has made pitch angle control an essential role in modern wind energy conversion systems.

2.6.1 Objectives of pitch control [21]

The main purpose of a closed loop controller can be simply stated. For example, the main purpose of pitch control can be to limit the output power or rotor speed at high wind speeds. Goals can be more than one main goal, in this case, the use of pitch control to optimize energy intake at low wind speeds.

In general, the following objectives can be considered when designing a pitch angle controller:

- Optimize power generation at low wind speeds
- Adjust or limit torque aerodynamics at high wind speeds
- Reduce maximum fluctuations in gearbox torque

- Avoid excessive activity in the pitch
- Control vibration of the tower and reduce additional overhead in the turbine

Some of these goals conflict with each other, so the design process must be done in such a way as to have the necessary balance in weighting these goals.

The wind turbine has a pitch angle control system for each blade. Each control system consists of a closed-loop system that allows the pitch angle to reach the desired value of β_{ref} at any time. The pitch controller is a nonlinear controller whose position in the wind turbine model is shown schematically in Figure 18.

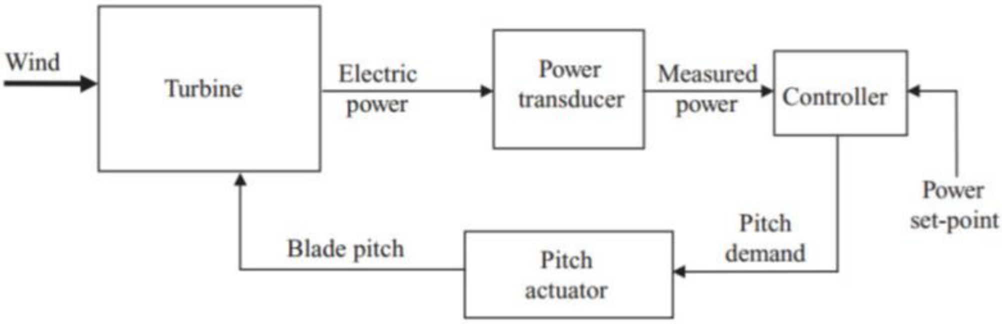


Figure 19: Pitch controller in wind turbine (reproduced from [21])

Pitch control is the most common method for aerodynamic control of power generated by a turbine rotor. Wind turbines equipped with a pitch adjustment mechanism have an active control system that reduces the torque by changing the angle of the blades in fixed-speed turbines, and in variable-speed turbines, reduces the rotational speed of the rotor. This type of control is usually used at high wind speeds (which is more likely to cause mechanical damage). In this type of wind turbines, if the wind reaches the nominal speed, they will increase the output power by increasing the wind speed. At higher than nominal speeds, as the wind speed increases, the output power will remain constant until the pitch controller is no longer able to limit the torque and rotational speed of the rotor.

2.7 Uncertainties in Wind Turbine Control Systems

Many systems in the industry have nonlinear behaviour. This has led researchers to develop methods for controlling nonlinear systems. To overcome the many problems that arise in the field of control of nonlinear systems, and to meet the various demands of control, it is necessary to use new control methods. Because classical control methods do not fully meet these needs.

Classic control systems are mainly regulatory systems whose design goals are to stabilize and reduce the steady state error of relatively simple systems. But nonlinear systems have uncertain and variable parameters and face a set of different perturbations. Under these conditions, constant gain control will not work well. Because, the linear controller is acceptable in a limited and certain area of the system operation, but when the system performance range is in a larger region, the linear controller does not behave well. A common method for dealing with nonlinear systems is to linearize the system around an operating point and design a controller using this linear system, which approximates a nonlinear system near the operating point. As mentioned, this method is not always appropriate, because by distancing the system from the operating point, the design will not be responsive. Therefore, a more robust control system is needed for these types of systems.

One of the important properties of control systems is their robustness. To clarify the concept of robust control systems, we briefly review how the control system is designed. Normally, to control a dynamic system, we must have enough information about that system. While different control methods determine different controller structures and control inputs, regardless of the controller that is applied, having sufficient information about the system is necessary and obvious in all control methods. Usually, the mathematical model of a dynamic system, which contains all the necessary information about the system, is the basis for starting the design of the control system. Obviously, the closer the mathematical model of a dynamic system is to the reality of that system, the better the controller, which is based on the mathematical model. On the other hand, in practice, accurate and complete modelling of the system is almost impossible. In other words, every model we build from a real system is somewhat accurate, and there is no model that accurately represents a real system. So, every mathematical model is somewhat inaccurate. The inaccuracy of the mathematical model of dynamic systems can be due to two factors:

1. **Structured or Parametric Uncertainty:** This uncertainty is due to the uncertainty in the value of the parameters used in the model. For example, in wind turbines, the amount of moment of inertia of the rotor and generator that enter the two-mass model can be one of these uncertainties. Another point is that system parameters are usually measured in one state, such a state is called normal system performance. In practice, different environmental conditions take the system away from its normal operating conditions to some extent. For example, environmental conditions and wind conditions can affect the aerodynamics of the blades. So, the measured parameters each have a

normal value, which can be called the nominal value of that parameter. However, the measured value of this parameter differs from this nominal value in different conditions. Therefore, in each system, each parameter does not have only a constant value but the value of the parameters changes, while in the model, each parameter has only one value.

2. **Unstructured Uncertainty:** This type of uncertainty is caused by eliminating the complexity of the mathematical model and simplifying the model. The assumption that a nonlinear system is linear means that although the real system is nonlinear, to simplify the mathematical model, its linear model is used around one of the equilibrium points of the nonlinear system. Reducing the order of transfer functions by removing high-frequency terms (terms with a small time constant) is another example of unmodeled uncertainty. As mentioned, in all control methods, it is essential to have sufficient information about the system. The important point is that in most modern control methods, the mathematical model of the system must be available, and this mathematical model must be accurate. In other words, if the mathematical model of the system is accurate, the methods used in modern control can optimally control the system. On the other hand, if the mathematical model is inaccurate, not only will the desired control not be created, but even the closed loop system will show inappropriate and unstable behaviour with the modern control system.

Unlike modern control systems, systems designed with classical control methods do not have this drawback. That is, even if the mathematical model of the system is not accurate, the control system still shows the desired behaviour. This advantage of classical control systems and the disadvantages of modern control systems have led to the definition of a new type of control structure design called robust control and the appearance of a new branch of control of the same name. If a control system is resistant to external disturbances, (i.e., despite external disturbances, the feedback control system behaves well and eliminates or reduces the effect of external disturbances on the system behaviour), such a system is called Noise Robust. Also, if a system is resistant to structural or parametric uncertainties or unmodeled uncertainties, such a system is called Parameter Robust. Since the usual methods of modern control cannot be used for systems with inaccurate models, so the issue of robust control emerged as a branch of control theories to apply modern control methods in such systems.

2.8 Control Algorithms

Due to the simplicity of the process of designing and implementing linear controllers, the use of these controllers has always

For nearly half a century, researchers have developed various algorithms and techniques for controlling wind turbines. These algorithms can be divided from different perspectives. In this chapter, the division is based on the type of model used (e.g., linear, nonlinear, etc.). Based on this, the control methods presented in relation to the control of wind turbines can be divided into the following four general classified:

- Linear algorithms
- Nonlinear algorithms
- Intelligent algorithms
- Combined algorithms

The details of each of these approaches and the efforts made in the last decade are summarized below. Also, the advantages and disadvantages of each are briefly stated.

2.8.1 Linear Algorithms

Due to the simplicity of the process of designing and implementing linear controllers, the use of these controllers has always been of special interest to researchers. Classic feedback controllers, on the other hand, are somewhat resistant to parameter changes and perturbations. Therefore, they are used in many cases. In the following, some of the efforts made in this regard will be mentioned.

In [22] basic structure of wind turbines is reviewed, and their control systems and control loops are examined. Park et al. [23] used single and collective control algorithms to control the wind turbine angle. Both algorithms use the LQR control technique along with Kalman filters to estimate system states and wind speeds. In [24] a PI controller is used to improve system performance under different operating conditions. In this paper, particle swarm optimization method is used to find the optimal controller parameters. The generator model used was also a permanent magnet synchronous generator.

Experiments and simulations performed on previous research have shown that satisfying the factors resulting from dynamic changes in the system, especially in cases where the system is complex and requires high control accuracy is beyond the power of linear controllers. In fact, there are many factors that need to be considered, such as changes in environmental conditions, changes in system characteristics, and nonlinear changes in the aerodynamics of the turbine blades. As a result, robust and adaptive control methods have received much attention.

Moradi et al. [25] compared the PID and H∞ controllers in the presence of model/environmental uncertainties to control the wind turbine pitch angle. In this paper, PID controller is designed by root locus analysis method and the H∞ controller is designed by μ-synthesis method.

2.8.2 Nonlinear Algorithms

A linear control algorithm can be effective when assuming the behavior and performance of the main system as almost linear. In fact, wind turbine systems have highly nonlinear behavior, and the idea of linearization around an equilibrium point cannot be efficient. In such cases, nonlinear control techniques must be used.

Other nonlinear methods include feedback linearization. By applying a control input, this idea eliminates nonlinear factors in the system dynamics, and therefore the nonlinear system becomes a simplified linear system that is easy to control. Kumar et al. [26] used a non-linear feedback linearization controller with a generalized Kalman filter to control the wind turbine model at higher wind speeds. The results of the controller showed a reduction in the equivalent loads of damage due to fatigue, power and speed adjustment compared to the controller of integral proportional interest tabulation.

Although this idea is very suitable for using linear control techniques, the resulting control signal is often a high voltage or current amplitude due to the elimination of nonlinear factors. In addition, some nonlinear terms are useful and therefore their removal is not recommended. Therefore, in some cases, other ideas of nonlinear control should be used.

Sliding mode control is one of the most powerful variable structure control techniques and one of the robust control methods that protects the system against mathematical model uncertainties and external perturbations and guarantees very high control accuracy. In 2008, Beltran et al. [27] used the sliding mode control method to control the wind turbine power in the area below the rated speed. The designed controller was resistant to turbine and generator parametric uncertainties as well as power grid disturbances. A year later, in [19] the authors used a higher order sliding mode controller to control power.

2.8.3 Intelligent Algorithms

If the dynamic equations governing a system are known, it will not be difficult to provide an algorithm to control it. But in the case of a wind turbine system, providing a reasonable dynamic equation is a major problem, so if a control algorithm can be found that does not require dynamic system equations, many problems will be solved. In fact, intelligent control algorithms have this capability. For example, we can name control algorithms based on fuzzy logic and neural networks. The details of each of these approaches and related efforts are summarized below.

Because of its self-learning, self-organizing, and self-adapting capabilities, the neural network has become a powerful tool for many complex applications, including robotics, inverted pendulum, wind turbines, and optimization. In fact, we do not need to analyze the complex components of the model by replacing a suitable neural network. In controlling wind turbines, due to the non-linear nature of the governing equations and the existing uncertainties, the use of neural networks is very common.

Yilmaz et al. [28] proposed a pitch angle controller based on an artificial neural network for wind turbines. Lin et al. [29] used an improved Elman neural network-based algorithm to optimally control the wind turbine by tracking the maximum power point. In this paper, the neural network controller is designed using back-propagation algorithm with optimized particle swarm optimization to control the pitch angle to adjust the power. In [30] this optimization method has been used for optimal training of RBF neural network based on PI controller to control the pitch angle of 5 MW wind turbine.

As mentioned, parametric uncertainties and nonlinear factors are the main challenges related to control algorithms. On the other hand, research has shown that the fuzzy control method is effective for complex and uncertain systems. A key feature in the development of a conventional fuzzy controller is that this method can create a quantitative mapping from an arbitrary set of fuzzy variables to achieve an arbitrary set of control objectives without the need for detailed descriptions of a typical mathematical model of the system. In the last few years, many efforts have been made to reduce non-linear effects and parametric uncertainty in wind turbines using fuzzy control.

In [31] fuzzy logic is used to control the pitch angle at wind speeds less than the nominal value to smooth the power extracted from the wind, while in [32] Chiang this method is used to control the pitch angle at wind speeds above the nominal value.

Perhaps the question arises as to why, despite intelligent control techniques, a large portion of research still focuses on linear and nonlinear methods. In response, it should be said that although the simulation results of these techniques have been very successful in most cases, however, the use of these techniques does not regulate the stability of the system. The reason can be sought in the fact that these studies are performed in a discrete space. Therefore, the behavior of the system at the borders cannot be predicted.

2.8.4 Combined Algorithms

Due to the positive features of nonlinear control techniques and the efficiency of intelligent control methods, some studies have focused on the combined use of the two. Of course, the efficiency of these algorithms has now been proven to be a matter of theory and simulation.

2.9 Literature Review of Control Methods for Wind Turbines

In this section, wind turbine control works are reviewed. Shehata [33] provides a robust sliding mode controller to improve the performance of direct power control, without complicating the overall design. This controller is designed to adjust the active and reactive powers of the doubly-fed induction generator stator. The network side converter is controlled based on the principle of direct power control to regulate both DC- link voltage and overall reactive power.

Hong et al. [29] proposed a sliding mode controller and an artificial neural network controller to control the speed of the induction generator. The controller is designed to adjust the speed of the turbine to extract the maximum power from the wind and adjust the power.

Hussein et al. [34] have proposed a control mechanism for extracting maximum power without a simple sensor less maximum power extraction control strategy for a variable speed wind turbine system with a permanent magnet synchronous generator. Generator side converter control is used to achieve maximum power. This is done by estimating the speed of the generator and using the estimated speed to calculate the mechanical power generated by the wind.

Tang et al. [35] proposed a non-linear feedback/feedforward controller for variable speed wind turbines with doubly fed induction generators. This controller has been able to do the following:

1) Active power control in two modes of maximum power tracking and power adjustment. 2) Continuous switching between the two modes and 3) Reactive power control so that the desired power factor is maintained.

Moljadi et al. [36] investigated the pitch control performance of variable speed wind turbines. The designed controller has been able to get the most energy by minimizing the load. Two methods have been considered to regulate aerodynamic power: pitch control and generator load control, both of which are used to control the operation of wind turbines.

Chinchilla et al. [37] investigated the performance and control of a direct-excited synchronous generator with direct excitation at a variable speed in a wind turbine. The generator is controlled to achieve maximum power from random wind with maximum efficiency under different loads. This paper demonstrates the dynamic performance of the overall system. Various experimental tests have been performed to validate the designed controller.

Smida et al. [38] investigated the performance and control of a direct-excited synchronous generator for a wind turbine. In this paper, different pitch angle control strategies are examined.

Battista et al. [39] examined the power regulation of a variable speed wind turbine system. A sliding mode controller is designed for the system that ensures stability in the turbine operating areas and provides an ideal feedback control despite the uncertainty in the will model.

Beltran et al. [19] investigated the control of power generation in variable speed wind turbines. A high-order slip mode controller is designed to ensure stability in the turbine operating areas, providing ideal feedback control despite model uncertainty. The designed controller has interesting features such as being resistant to uncertainty in turbine parameters.

Vidal et al. [40] investigated the control of power generation in horizontal speed-variable wind turbine-variable wind turbines under high wind operating conditions. A dynamic chattering torque control and a proportional integral pitch control strategy are presented and validated using the National Renewable Energy Laboratory wind turbine simulator FAST (Fatigue, Aerodynamics, Structures, and Turbulence) code. Validation results show that the controller designed for power regulation is effective and has shown good performance for other mode variables for turbulent wind conditions.

Rubio et al. [41] have proposed a control strategy that solves the problem of adjusting the output power of a variable speed wind turbine by combining a linear control for the blade angle with a $H\infty$ torque control that reduces the effects of external disturbances at system inputs and outputs. The designed controller shows better power and speed adjustment compared to classic linear controllers.

Bennouk et al. [42] have provided a feedback linearity controller for a wind turbine with a permanent magnet synchronous generator. A generator side converter is designed using feedback linearization to control the electromagnetic torque and speed of the generator. Standard vector techniques are used to control the grid side converter.

Barambones et al. [43] proposed a sliding mode controller for variable speed wind turbines. The proposed scheme uses vector-oriented control theory to simplify the dynamic equations of a doubly-feed induction generator. The stability analysis of the proposed controller under variable winds and uncertainties has been performed using Lyapunov stability theory.

Matas et al. [44] designed a non-linear controller for converter-based wind turbines that ensures that currents remain within the design range. This controller is based on feedback linearization theory and is applied to the system through a sliding mode approach. This controller is resistant to turbulence and uncertainties.

Ren et al. [45] proposed a nonlinear proportional integral pitch angle controller with a perturbation observer to predict and compensate for nonlinear and variable perturbations with indefinite time. The designed controller does not require a precise model and uses only a set of proportional integral parameters to provide an overall optimal performance at variable wind speeds. The designed controller has the dynamic performance of better power regulation, reduction of load stresses and actuator consumption, compared to the normal proportional integral, and the controller of the tabulation of interest and better resistance against model uncertainties than the control of feedback linearization.

Tiwari et al. [46] proposed a fuzzy logic-based pitch angle controller. Their controller is model-free and overcome the nonlinearity and ripple in the torque. But for designing fuzzy rules an expert is required.

In [47], Pathak and Gaur proposed a fractional order fuzzy-PID controller. Their controller provides good behavior for a nonlinear wind turbine system. This controller is somewhat complex and costly to implement.

Chen et al. [48] proposed a reinforcement-based robust variable structure to pitch control. They have combined adaptive control with optimal control using computer intelligence technology.

The variation of the pitch angle command of this controller is relatively gradual, which reduce the energy consumption of the variable pitch actuator.

Table 2 provides review articles in the field of wind turbine control in the order of the year.

Table 2: Timeline of Articles in the field of wind turbine control.

Year	Authors	Features
2000	Battista et al.	• Sliding mode controller design for the system • Ensuring stability in the turbine operating regions • Resistant to uncertainty in the model
2001	Moljadi et al.	• Achieving maximum energy by minimizing loads • Two methods for adjusting aerodynamic power have been explored: pitch control and generator load control, both of which are used to control wind turbine performance.
2006	Chinchilla et al.	• Achieve maximum power from random wind with maximum efficiency under different loads • Perform various experimental tests designed to validate the controller
2008	Matas et al.	• Design based on feedback linearization theory • Applying controller through sliding mode approach to system and resistant to perturbation and uncertainty
2009	Beltran et al.	• Design of high order sliding mode controller to ensure stability in turbine operating regions and resistant to uncertainty in the model
2011	Tang et al.	• Design of nonlinear feedback/feedforward controller • Active power control in two modes of maximum power tracking and power adjustment • Continuous switching between the two modes and reactive power control while maintaining the desired power factor
2011	Rubio et al.	• Combining a linear control for the blade angle with a torque control H_∞

		• Reduce the effects of external disturbances that occur at the input and output of the system
2012	Vidal et al.	• Provide a dynamic chattering torque control and a proportional integral pitch control strategy
2012	Barambones et al.	• Design of sliding mode controller • Use of vector-oriented control theory to simplify the dynamic equations of doubly fed induction generator • Stability analysis of the controller presented under variable winds and performing uncertainties using Lyapunov stability theory
2012	Hussein et al.	• Provide control strategy of extracting maximum power without sensor • Control of generator side converter to achieve maximum power from available wind power • Estimate generator speed and use estimated speed to calculate mechanical power generated from wind
2014	Hong et al.	• Sliding mode controller design and an artificial neural network controller to control the speed of the induction generator • Adjust the turbine speed to extract the maximum power from the wind • Adjust the power and design a sliding mode speed controller based on the sliding surface
2015	Smida et al.	• Investigate different pitch angle control strategies
2015	Bennouk et al.	• Design of feedback linearization controller • Design of a generator side converter using feedback linearization to control electromagnetic torque and generator speed • Use of standard vector methods to control grid side converter
2015	Shehata	• Robust and simple sliding mode controller design to improve the performance of direct power control without complexity in the general design • Adjusting the active and reactive powers of the double-fed induction generator stator

		• Controlling the network side converter based on the principle of direct power control to regulate both DC link voltage and total reactive power
2016	Ren et al.	• Design of nonlinear proportional integral pitch angle controller with design of an augmented state and perturbation observer to predict and compensate for nonlinear and variable perturbations with indefinite time • No need for exact model • Better dynamic power adjustment performance • Stress reduction Operator load and consumption compared to conventional proportional integral and gain scheduling controller and better robustness to model uncertainties than feedback linearization control
2018	Tiwari et al.	• Fuzzy logic-based pitch angle controller • Model-free controller and ability to overcome the nonlinearity and ripple in the torque • An expert is required for designing fuzzy rules
2019	Pathak and Gaur	• Fractional order fuzzy-PID controller • Good behavior for a nonlinear wind turbine system • Somewhat complex and costly to implement
2020	Chen et al.	• Relatively gradual variation of the pitch angle command of controller • Reduce the energy consumption of the variable pitch actuator

2.10 How our Work differs from what appears in the literature

Nonlinear controllers are a good solution for nonlinear systems and ensure stability of system, but they have complex calculations. Linear controllers, on the other hand, are less computational and simpler, but only perform well at operating points.

One of the common problems of nonlinear controllers we studied, is response time. These methods usually do not optimize control parameters. In this thesis we will use an optimization algorithm to do this.

For linear controllers, we also use a gain scheduling method so that the system does not have problems by changing the wind conditions.

We design three controllers: One optimized PI controller. The difference between this controller and previous works is that we use gain scheduling method to overcome wind changes effects on system. Two others are the feedback linearization controller and sliding mode controller. We use an optimization algorithm to determine the control coefficients to respond faster and reduce errors. The details of the design are given in the next chapter.

2.11 Summary

In this chapter, we provided a literature review of wind turbine dynamics, wind turbine conversion systems, and wind turbine controllers. Wind turbines are simply divided into four subsystems: aerodynamic, mechanical, electrical, and blade angle actuator, and each of these subsystems were described in detail. The importance and goals of pitch angle control was presented. Finally, research works for controlling wind turbine were reviewed.

3.0 Controller Design

In this chapter, we design the wind turbine pitch angle controllers. First, based on what we explained in the previous chapter, we extract the system model.

3.1 Extracting state-space model of system

In this section, a two-mass mathematical model of a wind turbine will be extracted. A simplified mathematical model is a real system that should describe the main features of the system. The main features of a wind turbine that are also considered in this thesis are:

- Turbine mechanics
- Aerodynamics
- Generator dynamics
- Pitch Actuator dynamics

3.1.1 Turbine mechanics

Deformation in wind turbine blades due to their height and material can cause simulation errors. Therefore, different methods for modeling the mechanical part have been proposed. Discrete masses are usually used in modeling this part. One-mass, two-mass, three-mass, and even six-mass models are common in wind turbine modeling.

It has been shown that the two-mass model, while simple, has acceptable accuracy in turbine modeling, especially in transient conditions. In this thesis, a two-mass model is used. Figure 19 shows a schematic of this two-mass model.

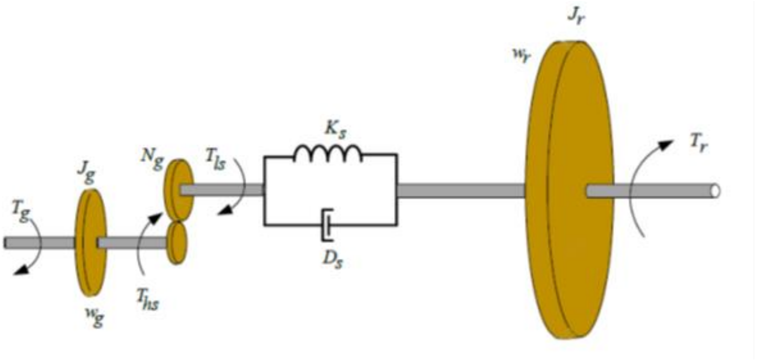


Figure 20: Two-mass model of wind turbine

The turbine is divided into two parts by the transmission system: the rotor part and the generator part. The inertia J_r of the rotor and the inertia J_g of generator are indicated by two disks on the right and left, respectively. The shaft that connects the rotor to the transmission system is subjected to a very large torque that causes it to twist. As a result, the shaft is properly modeled with a spring and damper. The dynamic nature of the shaft (transmission system dynamics) is indicated by a damper D_s and a spring with a constant factor K_s. The gear ratio N_g is indicated by two disks in the middle of the figure. In direct-drive wind turbines equipped with synchronous generators with permanent magnets, the gearbox is removed from the assembly. The model on the right and left is under the rotor torque T_r and the generator torque T_g, respectively. The torques T_{ls} and T_{hs} are the torques on both sides of the gearbox that are related by equation (3.1):

$$T_{hs} = \frac{T_{ls}}{N_g} \tag{3.1}$$

Equations that describe the dynamics of this model are derived from Newton's second law for rotating objects. This leads to two equations: one for the rotor part (3.2) and the other for the generator part (3.3).

$$\dot{\omega}_r J_r = T_r - T_{ls} \tag{3.2}$$

$$\dot{\omega}_g J_g = T_{hs} - T_g T_{hs} = \frac{T_{ls}}{N_g} \tag{3.3}$$

Introducing variable δ[rad], which represents shaft torsion, we come to Equation (3.4), which describes flexible shaft torsion:

$$T_{ls} = D_s\dot{\delta} + K_s\delta \tag{3.4}$$

where

$$\delta = \theta_r - \frac{\theta_g}{N_g},\ \dot{\delta} = \omega_r - \frac{\omega_g}{N_g}, \tag{3.5}$$

θ_r and θ_g are the shaft angles in the rotor and generator, respectively.

3.1.2 Aerodynamics

The aerodynamic blades in the rotor convert the kinetic energy of the wind into mechanical energy, which produces the torque T_r, which can be expressed by Equation (3.6):

$$T_r = \frac{P_r}{\omega_r} \tag{3.6}$$

where the power P_r is in the form of Equation (3.7):

$$P_r = \frac{1}{2}\pi\rho R^2 v^3 C_p(\omega_r, \beta, v) \tag{3.7}$$

Where R is the rotor radius, ρ is the air density, v is the wind speed, and C_p is the power coefficient, which is a nonlinear function of the pitch angle β and the blade tip velocity ratio λ.

The power coefficient C_p for wind turbines is obtained by performing numerical calculations and is presented in tables. In this thesis, the aerodynamic power coefficient is used as equation (3.8):

$$C_p = 0.22(116\lambda_t - 0.4\beta - 5)e^{-12.5\lambda_t} \tag{3.8}$$

where,

$$\lambda_t = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \tag{3.9}$$

$$\lambda = \frac{\omega_r R}{v} \tag{3.10}$$

3.1.3 Generator dynamics

The generator is responsible for converting kinetic energy into electrical energy. Wind turbines use different generators depending on their type of operation. Squirrel cage generators used in constant speed turbines, doubly-fed induction, and permanent magnet synchronous generators are the three most common types of generators among wind turbines. In this thesis, a first-order system for generator modeling is used.

$$P_e = \eta T_g \omega \tag{3.11}$$

Tt generator torque T_g can be controlled but these changes can not be instantaneous. Therefore, the dynamic response of the generator is modeled by a first-order model with a time constant τ_g.

$$\dot{T}_g = \frac{1}{\tau_g}(T_{g,r} - T_g) \tag{3.12}$$

However, since the aim of this thesis is to control the pitch angle in the full load region, the value of generator torque is assumed to be constant in its nominal value. At high speeds, the nominal speed $T_{g,r}$ can be calculated from Equation (3.13). At speeds lower than the rated speed, a controller is used to adjust $T_{g,r}$.

$$T_{g,r} = \frac{P_{nom}}{\omega_g} \tag{3.13}$$

3.1.4 Pitch actuator dynamics

The blades of variable-pitch wind turbines can rotate around their longitudinal axis. This period is usually applied by a hydraulic or mechanical actuator. A simplified model of the dynamics of these actuators used in this thesis can be expressed by the first-order equation (3.14).

$$\dot{\beta} = \frac{1}{\tau_\beta}(\beta_r - \beta) \tag{3.14}$$

Where, τ_β is the time constant of the pitch angle actuator.

3.2 Nonlinear state space equations

Equation (3.2) can be written as follows:

$$\dot{\omega}_r = \frac{T_r - T_{ls}}{J_r} \tag{3.15}$$

By placing equations (3.4) and (3.6) in equation (3.15), we get the following equation:

$$\dot{\omega_r} = \frac{1}{J_r}\left(\frac{P_r(\omega_r,\beta,v)}{\omega_r} - (D_s\dot{\delta} + K_s\delta)\right) \tag{3.16}$$

and using equation (3.5) we have:

$$\dot{\omega_r} = \frac{1}{J_r}\left(\frac{P_r(\omega_r,\beta,v)}{\omega_r} - (D_s(\omega_r - \frac{\omega_g}{N_g}) + K_s\delta)\right) \tag{3.17}$$

Similarly, by placing equations (3.4) and (3.5) in equation (3.3), we can write

$$\dot{\omega_g} = \frac{1}{J_g}\left(\frac{\omega_r D_s}{N_g} - \frac{\omega_g D_s}{N_g^2} + \frac{\delta K_s}{N_g}\frac{T_g}{J_g}\right) \tag{3.18}$$

Putting equations (3.17), (3.18), (3.5) and (3.14) together, we reach the set of first-order differential equations in state-space form.

$$\dot{\omega_r} = \frac{1}{J_r}\left(\frac{P_r(\omega_r,\beta,v)}{\omega_r} - \omega_r D_s + \frac{\omega_g D_s}{N_g} - \delta K_s\right) \tag{3.19}$$

$$\dot{\omega_g} = \frac{1}{J_g}\left(\frac{\omega_r D_s}{N_g} - \frac{\omega_g D_s}{N_g^2} + \frac{\delta K_s}{N_g}\frac{T_g}{J_g}\right) \tag{3.20}$$

$$\dot{\delta} = \omega_r - \frac{\omega_g}{N_g} \tag{3.21}$$

$$\dot{\beta} = -\frac{1}{\tau_\beta}(\beta_r - \beta) \tag{3.22}$$

By defining state and input vectors as (3.23),

$$x = [x_1 \quad x_2 \quad x_3 \quad x_4]^T = [\omega_r \quad \omega_g \quad \delta \quad \beta]^T$$

$$u = \beta_r \tag{3.23}$$

the equations can be written in compressed form (3.24):

$$\dot{x} = h(x,u) \tag{3.24}$$

Finally, the system can be rewritten as Equation (3.25):

$$\dot{x} = f(x) + gu = \begin{bmatrix} \frac{1}{J_r}\left(\frac{P_r(x_1,x_4,v)}{\omega_r} - x_1 D_s + \frac{x_2 D_s}{N_g} - x_3 K_s\right) \\ \frac{1}{J_g}\left(\frac{x_1 D_s}{N_g} - \frac{x_2 D_s}{N_g^2} + \frac{x_3 K_s}{N_g}\frac{T_g}{J_g}\right) \\ x_1 - \frac{x_2}{N_g} \\ -\frac{1}{\tau_\beta} x_4 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ \frac{1}{\tau_\beta} \end{bmatrix} u \quad (3.25)$$

3.3 Gain Scheduling PI Controller (GSPI)

In this thesis, a pitch angle controller based on PI control is used to adjust the rotor speed or wind turbine output power in its nominal value. To achieve the optimal parameters for this controller, an optimization algorithm has been used.

Due to the extreme aerodynamic nonlinearities of wind turbines and the time-varying wind speed in these systems, the PI controller, which uses a series of fixed optimized coefficients, cannot have acceptable optimal performance when the turbine operating point changes. In order to deal with this problem, an adaptive controller by gain scheduling method has been proposed.

An adaptive controller using the gain scheduling method needs to measure the wind speed to adjust the controller parameters. One of the things that comes to mind is the use of data from an anemometer installed on the nozzle. But this anemometer can only measure wind speed at a specific point, which is not very accurate in large wind turbines to achieve effective wind speed. To achieve a more accurate forecast of effective wind speed, wind speed itself can be used as a sensor and more accurate wind speed prediction can be obtained by solving the Newton-Raphson method.

Since the use of the prediction method mentioned above requires a complex online wind speed prediction and may lead to rapid switching between parameters due to rapid changes in wind speed, an improved gain scheduling controller based on pitch angle switching are suggested. At different wind speeds, the optimal parameters controlling the gain scheduling are obtained using the Harmony Search algorithm.

To achieve a continuous switching based on the pitch angle, the gain scheduled parameter is obtained by multiplying the fixed parameters of the PI controller by a gain scheduling parameter named $K(\beta)$ which is a function of the pitch angle. The tabulated parameter $K(\beta)$ has been proposed to compensate for changes in aerodynamic sensitivity, $\frac{\partial P_r}{\partial \beta}$ [49].

$$u = K(\beta)\left(k_p + \frac{k_i}{s}\right)(\omega_r - \omega_{r-rated}) \tag{3.26}$$

where

$$K(\beta) = \begin{cases} 1.6 & -1° < \beta < 0° \\ 0.001\beta^2 + 0.01\beta + 1.6 & 0° < \beta < 30° \\ 1 & \beta > 30° \end{cases} \tag{3.27}$$

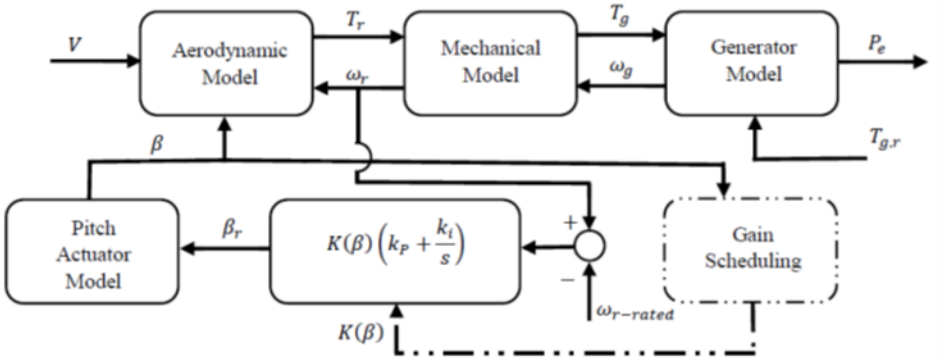


Figure 21: Wind turbine system block diagram with GSPI controller

3.4 Feedback Linearization Controller (FLC)

Feedback linearization is a nonlinear control method that has been considered by researchers in recent years. The main idea of this method is to make the dynamics of the nonlinear system linear so that linear control methods can be used for it. The idea of feedback linearization can be applied to a group of nonlinear systems that are so-called conventionally controllable. In the feedback linearization method, the relationship between the output of the system, i.e., the rotor speed $y = x_1$, and the input of the system, i.e., the control pitch angle $u = \beta_r$, is derived from the output until the control input appears. Considering (3.25), we can write the dynamic equation of the rotor:

$$\dot{x_1} = \frac{P_r(x_1,x_4,V)}{x_1 J_r} - \frac{x_1 D_S}{J_r} + \frac{x_2 D_S}{J_r N_g} - \frac{x_3 K_S}{J_r} \tag{3.28}$$

Differentiation of the equation ensures that the system is stable and non-singular in all its operating points [26].

Therefore, by using Lie derivatives [26] for equations (3.25) and (3.28), we can write:

$$\frac{d^2 x_1}{dt^2} = \Delta_f(x) + \Delta_g(x)u \tag{3.29}$$

where, Δ_f and Δ_g are calculated as follows (V is a time-variant independent variable and we add differentiation of f_1 respect to it as well state variables.)

$$\Delta_f = \frac{\partial f_1}{\partial x_1} f_1 + \frac{\partial f_1}{\partial x_2} f_2 + \frac{\partial f_1}{\partial x_3} f_3 + \frac{\partial f_1}{\partial x_4} f_4 + \frac{\partial f_1}{\partial V} \dot{V} \tag{3.30}$$

$$\frac{\partial f_1}{\partial x_1} = -\frac{1}{x_1 J_r} \left\{ \frac{P_r}{x_1} + 0.11\pi\rho R^3 V^2 \frac{178.5 - 1450\lambda_t + 5x_4}{(\lambda + 0.08x_4)^2} e^{-12.5\lambda_t} \right\} - \frac{D_s}{J_r} \tag{3.31}$$

$$\frac{\partial f_1}{\partial x_2} = \frac{D_s}{J_r N_g} \tag{3.32}$$

$$\frac{\partial f_1}{\partial x_3} = -\frac{K_s}{J_r} \tag{3.33}$$

$$\frac{\partial f_1}{\partial x_4} = \frac{0.11\pi\rho R^2 V^3}{x_1 J_r} \left\{ (178.5 - 1450\lambda_t + 5x_4) \left[\frac{-0.08}{(\lambda + 0.08x_4)^2} + \frac{0.105x_4^2}{\left(x_4^3 + 1\right)^2} \right] - 0.4 \right\} e^{-12.5\lambda_t} \tag{3.34}$$

$$\frac{\partial f_1}{\partial V} = \frac{0.11\pi\rho R^3 V}{J_r (\lambda + 0.08x_4)^2} \{178.5 - 1450\lambda_t + 5x_4\} e^{-12.5\lambda_t} \tag{3.35}$$

$$\Delta_g = \frac{\partial f_1}{\partial x_4} g_4 = \frac{0.11\pi\rho R^2 V^3}{x_1 J_r \tau_\beta} \left\{ (178.5 - 1450\lambda_t + 5x_4) \left[\frac{-0.08}{(\lambda + 0.08x_4)^2} + \frac{0.105x_4^2}{\left(x_4^3 + 1\right)^2} \right] - 0.4 \right\} e^{-12.5\lambda_t} \tag{3.36}$$

In the above equations $\dot{V}$ is a derivative of wind speed. To achieve the linearization control rule, the virtual control input is selected so that the closed-loop dynamic dynamics are stable. that's mean

$$\frac{d^2 x_1}{dt^2} = v \tag{3.37}$$

$$v = \gamma_1 \dot{e} + \gamma_2 e \tag{3.38}$$

In equation (38), $e = \omega_r - \omega_{r-rated}$ is rotor speed stabilization error. γ_1 and γ_2 are positive control parameters. Finally, the control law will be in Equation (3.39):

$$u = \frac{1}{\Delta_g} (\gamma_1 \dot{x_1} + \gamma_2 e \Delta_f) \tag{3.39}$$

For the system to be able to find the desired trajectory, the error must be reduced to zero, and for the stability of the system, coefficients γ_1 and γ_2 must be considered positive.

3.5 Sliding Mode Controller (SMC)

Sliding mode control is one of the nonlinear methods resistant to system uncertainties and parametric changes. in this part sliding mode controller is designed to control the wind turbine pitch angle. Time variant sliding surface $S(X,t)$ in $R^{(n)}$ space with equation $S(X,t)=0$ is expressed by equation (3.40):

$$S(X,t)=\left(\frac{\mathrm{d}}{\mathrm{dt}}+\alpha\right)^{\mathrm{n}-1} e(t) \tag{3.40}$$

Where $e(t)$ is error between the rotor speed and its reference value, n is order of the system and α is a positive design parameter. To control the pitch angle, the second order sliding surface is considered as (3.41):

$$S=\dot{e}(\mathrm{t})+\alpha e(t) \tag{3.41}$$

To achieve the control law, the sliding mode is obtained by derivative from Equation (3.41) with respect to time:

$$\dot{S}=\ddot{e}(\mathrm{t})+\alpha\dot{\mathrm{e}}(t)=x_1(\mathrm{t})+\alpha\dot{x_1}(t) \tag{3.42}$$

By placing equation (3.29) in equation (3.42) and equating the relation to zero, we have:

$$\dot{S}=\Delta_f(x)+\Delta_g(x)u_\zeta(\mathrm{t})+\alpha\dot{x_1}(t)=0 \tag{3.43}$$

The control law is defined as equation (3.44):

$$u=u_\zeta+u_\eta \tag{3.44}$$

Where u_η is switching control signal and u_ζ is derive from equation (3.39). The switching signal tries to direct all paths to the sliding surface S and keep them on the surface. Adding a switching term ensures that the system reaches a sliding surface despite disturbance and uncertainty. A common mode for switching control is to use the sign function. However, since the behavior of sign function shows a lot of ambiguity and to achieve the desired accuracy in control, a smaller boundary layer is needed. Therefore, a proper balance must be struck between position error and chattering. This is done by adjusting the thickness of the boundary layer δ, which has a positive value. As a result, the final control law becomes (3.45):

$$u=-\frac{1}{\Delta_g}\left(\alpha\dot{x_1}(t)+\Delta_f+K_1S+K_2sat(\frac{S}{\delta})\right) \tag{3.45}$$

Where K_1 and K_2 are positive design parameters that determine how fast S converges to zero. sat is a saturation function and is expressed as relation (3.46):

$$sat\left(\frac{S}{\delta}\right) = \begin{cases} sgn\left(\frac{S}{\delta}\right) & if\ \ |S| > \delta \\ \frac{S}{\delta} & if\ S \le \delta \end{cases} \tag{3.46}$$

3.6 Novel Application of a Harmonic Search Algorithm

The harmonic search algorithm is inspired by musical phenomena. This algorithm is based on the process of improvising music, in which musicians' step by step play their instruments to achieve more harmony and better sound. The above process is like the optimization process in which the optimal solution can be searched by evaluating the objective function. In this algorithm, the solution vector is called "harmony". In other words, each harmony is a vector whose components are the values assigned to the decision variables of an issue. If the optimization problem has N variables, then the harmonic vector will also have N components. Advantages of this algorithm are the following:

- Easy to understand, easy to implement and free of difficult math problems and formulas.
- Since this algorithm uses random numbers, we do not need any additional information.
- Unlike other algorithms that use maximum of two vectors to generate a new generation, this algorithm uses all vectors to generate a new generation.

The main steps of this algorithm include 5 steps as follows:

6.0 Initial definition of the problem and parameters of the algorithm.

7.0 Initialization of harmonic memory with random solution vectors.

8.0 Improvise or generate a new harmonic vector.

9.0 Update harmonic memory.

10.0 Check the stopping criterion and repeat steps 3 and 4.

Figure 21 shows the flowchart of the algorithm. More details about this algorithm are given in [50].

3.6.1 Determining the optimal parameters of the controllers

The optimal parameters of the controllers are obtained using the harmonic search algorithm. Criterion ITAE is also proposed as a cost function in the optimization process as Equation (3.47):

$$Cost\ Function = \int_0^\infty t|e(t)|dt \qquad (3.47)$$

where, $e(t)$ indicates the rotor speed error. Also, the parameters used by the algorithm are given in Table 3 and the optimal parameters of the controllers are given in Table 4.

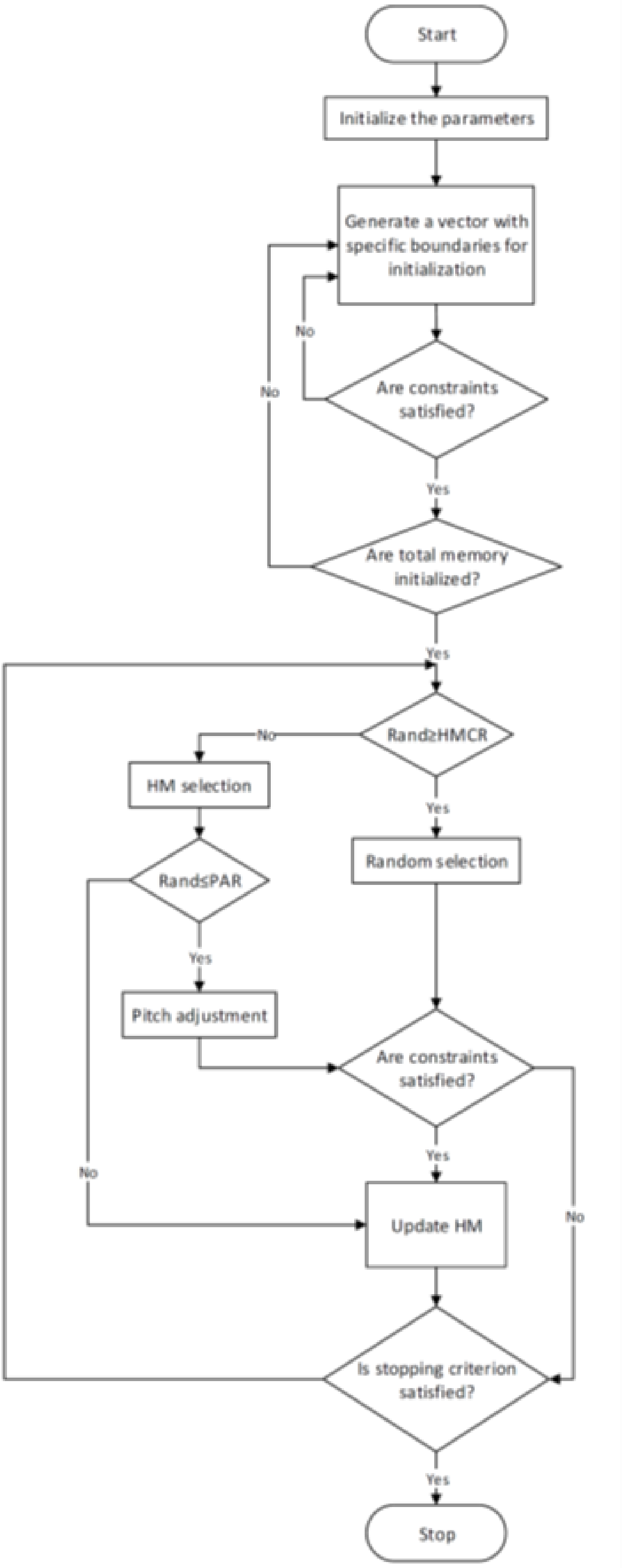


Figure 22: Flowchart of Harmony Search Algorithm

Table 3: Harmonic search algorithm parameters.

Parameters	Value
HMS	20
HMCR	0.6
PAR	0.2
BW	0.1
NI	100

Table 4: Optimal values of controller parameters.

Parameters	Value
k_p	20
k_i	0.6
γ_1	0.2
γ_2	0.1
K_1	0.2619
K_2	0.3094
α	0.8752
δ	0.8536

4.0 Simulation results

In this chapter, simulation results of the controllers designed in the previous chapter will be presented. These results are presented for the two-mass model. The simulation tests are based on a real test wind turbine called WindPACT developed at the US National Renewable Energy Laboratory. The GSPI and feedback linearization (FL) controllers proposed in this thesis are tested and simulated on a simplified WindPACT two-mass model.

4.1 Wind Turbine Model

The wind turbine model used in this thesis is the WindPACT 1.5 MW wind turbine, which is a reference wind turbine and was developed by the US National Renewable Energy Laboratory from 2000 to 2002 in the Wind Partnership for Advanced Component Technologies (WindPACT) project. designed. This wind turbine is a three-bladed horizontal wind turbine that uses variable-speed variable-pitch control. More details about this wind turbine can be seen in [51]. The parameters of the two-mass model of this wind turbine are given in Table 5.

Table 5: Parameters of a two-mass model 1.5 MW test wind turbine.

Wind turbine parameters	Value	Unit
Rotor radius (R)	35	m
Air density (ρ)	1.225	kg/m^3
Rotor inertia (J_r)	2.96×10^6	$kg\ m^2$
Generator inertia (J_g)	53.0	$kg\ m^2$
Drive system stiffness coefficient (K_s)	5.6×10^9	Nm/rad
Drive system damping coefficient (D_s)	1.0×10^7	N.m.s/rad
Gearbox ratio (N_g)	87.965	-
Pitch angle actuator time constant (τ_β)	1	s
Rated output power (P_e)	1.5	MW
Nominal speed of the rotor ($\omega_{r-rated}$)	2.1428	rad/s

Nominal torque of the generator ($T_{g-rated}$)	8376.6	Nm
Pitch angle range ($\beta_{min} - \beta_{max}$)	-1 to 90	$\circ$
Pitch rate range ($\dot{\beta}_{lim}$)	± 10	$\circ/s$
Wind turbine efficiency (η)	0.95	-

4.2 Test at step wind speed

Figure 22 to 24 show controller's implementation in MATLAB/Simulink. The pitch angle controller is designed to regulate the rotor speed under turbulent winds. The performance of the designed controllers that are under the step wind speed and simulated on a simplified two-mass model is shown in Figures 26 to 29. In the simulation in which the controllers control the pitch angle in the full load area, the generator torque is kept constant at its nominal value.

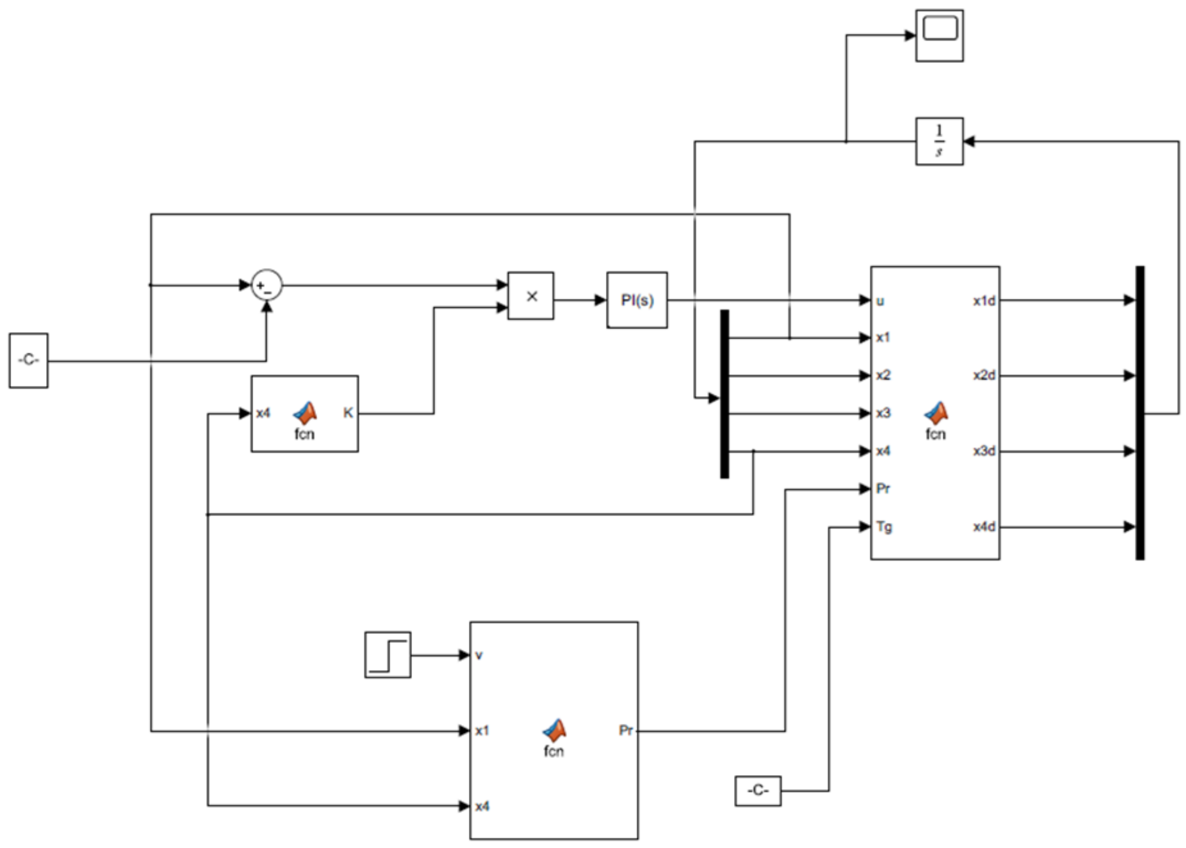


Figure 23: GSPI Controller implementation in MATLAB/Simulink

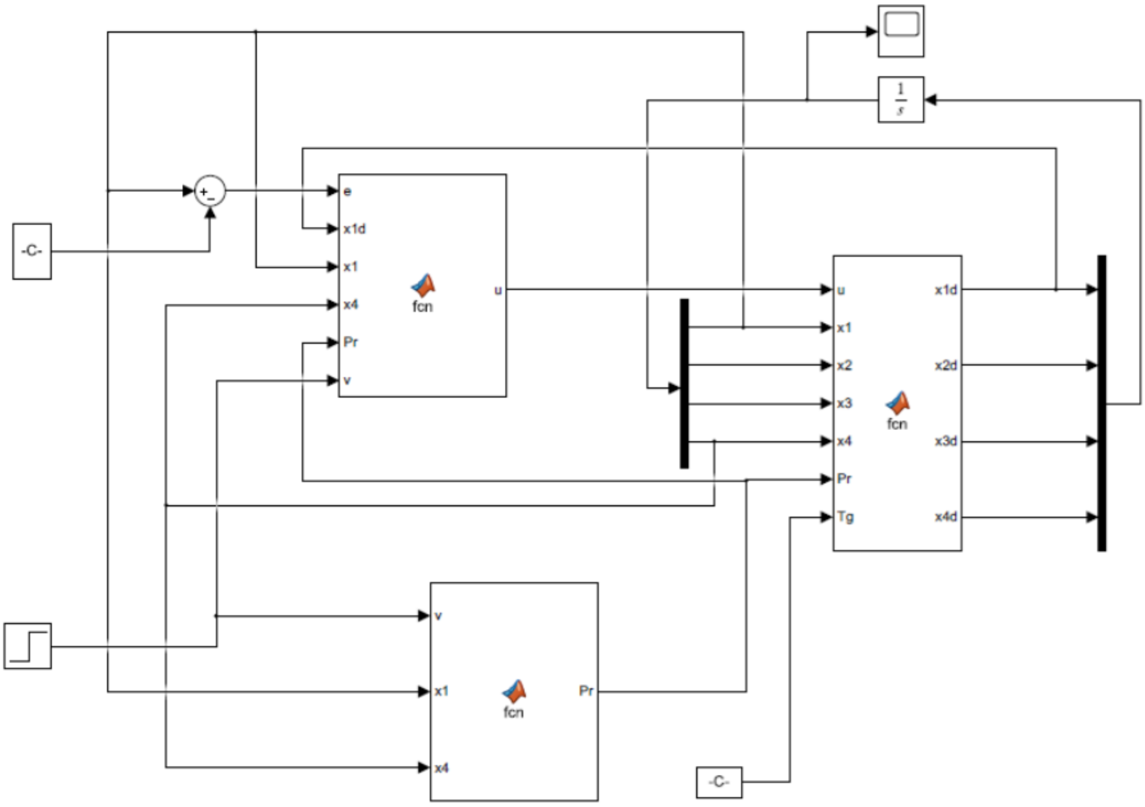


Figure 24: FLC implementation in MATLAB/Simulink

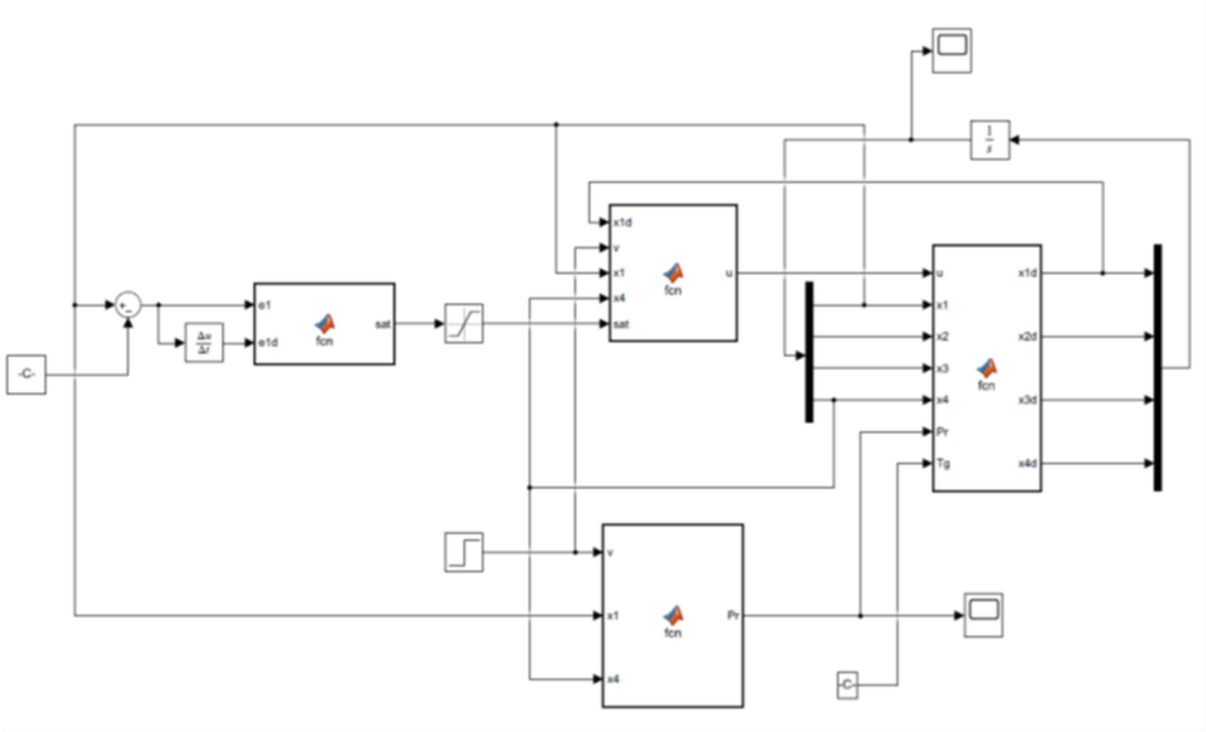


Figure 25: SMC implementation in MATLAB/Simulink

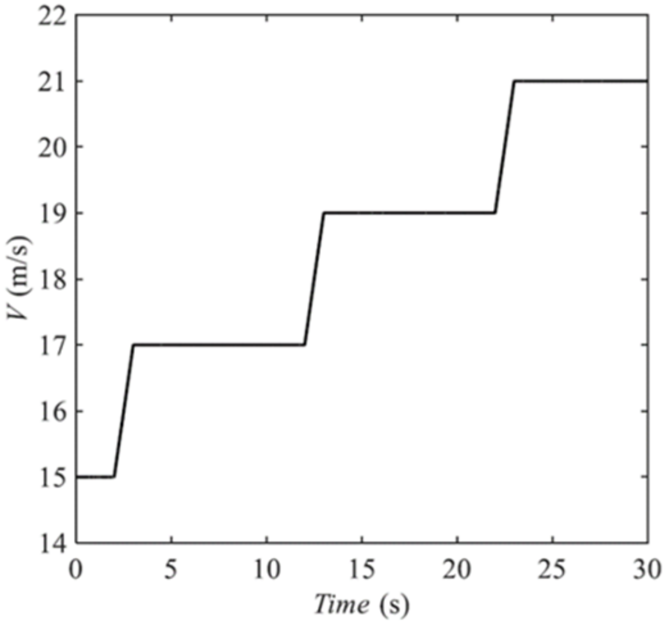


Figure 26: Step Wind Speed

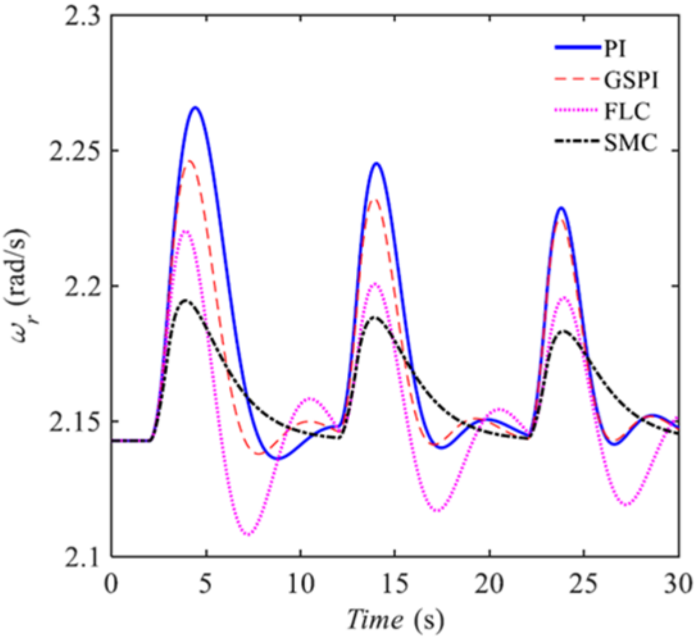


Figure 27: Rotor speed under step wind test

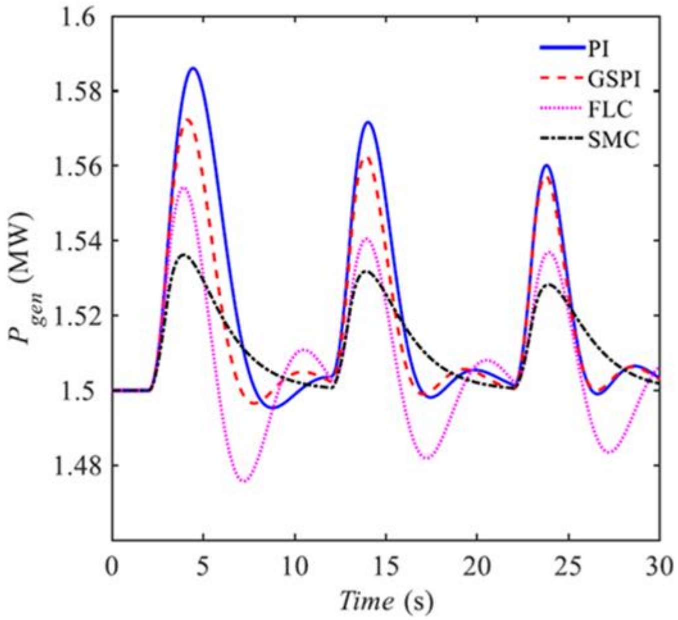


Figure 28: Generator power under step wind test

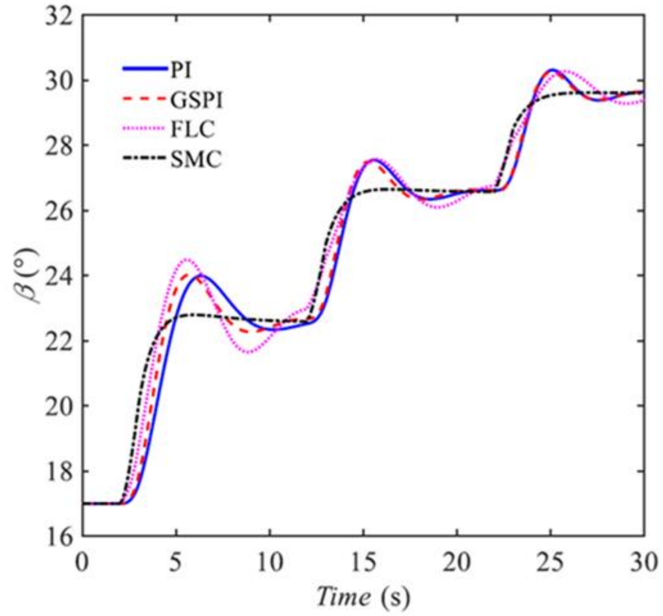


Figure 29: Pitch angle under step wind test

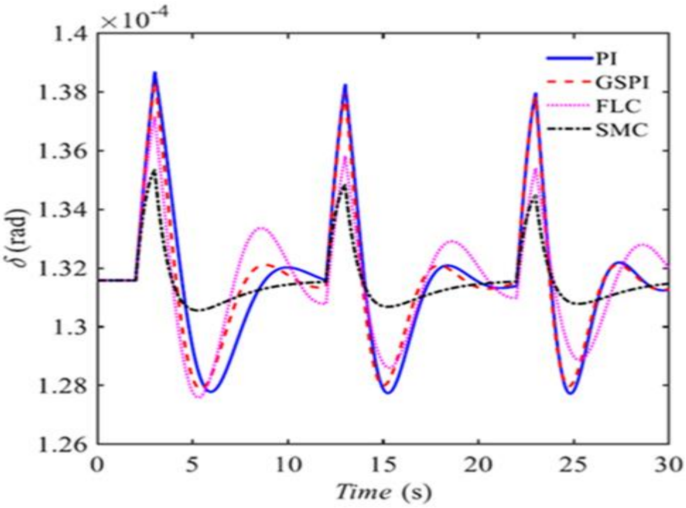


Figure 30: Shaft torsion angle under step wind test

When the wind speed increases in the form of step values, the aerodynamic power increases by three degrees, and the result is an increase in the rotational speed of the rotor, followed by an increase in the output power of the turbine. That is, if the pitch angle control is not applied, the output power of the generator exceeds the nominal value of 1.5 MW and causes damage to the wind turbine system, especially the generator. Therefore, as the wind speed increases as shown in Figure 22, the wind turbine pitch angle also increases by the command issued by the controller. This increase in pitch angle eventually regulates the rotational speed of the rotor and the output power of the wind turbine. As can be seen in the simulation results, all controllers were able to eliminate the effect of changing turbine operating points due to changes in wind speed. However, a comparison of the error criteria presented in Table 6 for step winds shows that the power tracking error and rotor speed for the gain scheduling PI controller is less than the PI controller. On the other hand, the overshoot of the sliding mode controller is less than the feedback linearization controller and the other two controllers.

Table 6: Error under step change of wind speed

Controller	Integral Time Absolute Error
PI	10.9046
GSPI	9.3688
FLC	8.8042
SMC	7.3471

4.3 Test at random wind speed

The results of a random wind simulation with an average value of 18 m/s (Figure 27) are performed on a simplified two-mass model and can be seen in Figures 31 to 34.

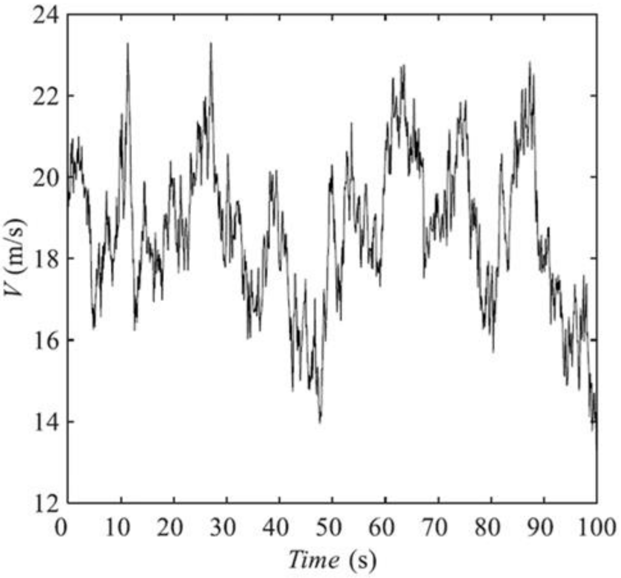


Figure 31: Random Wind Speed

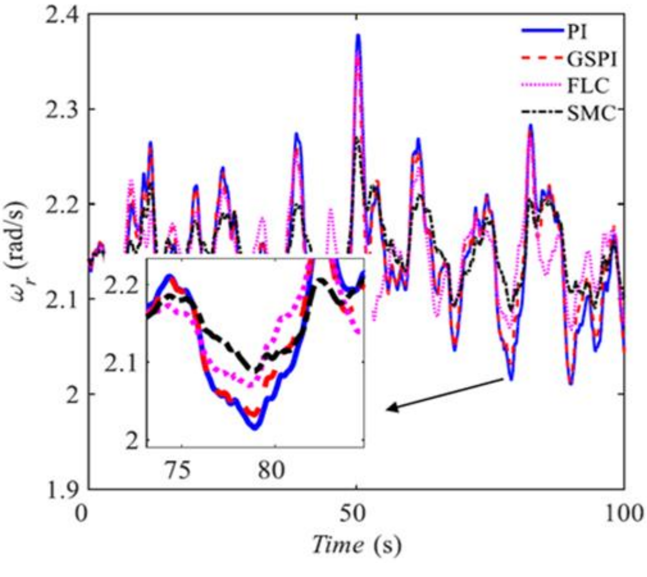


Figure 32: Rotor speed under random wind test

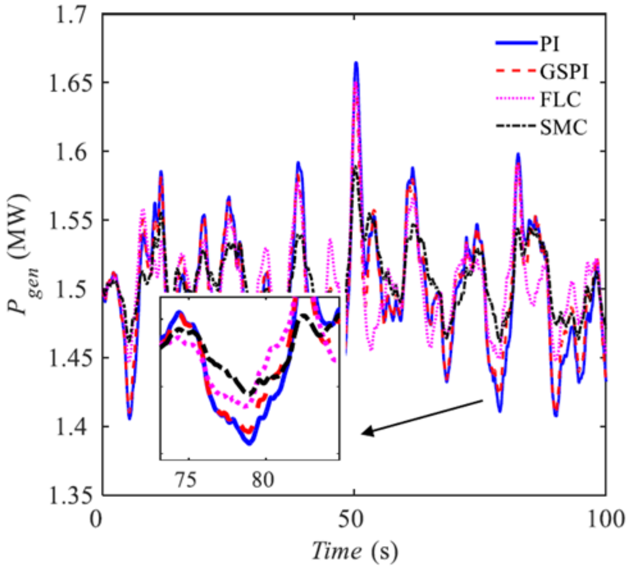


Figure 33: Generator power under random wind test

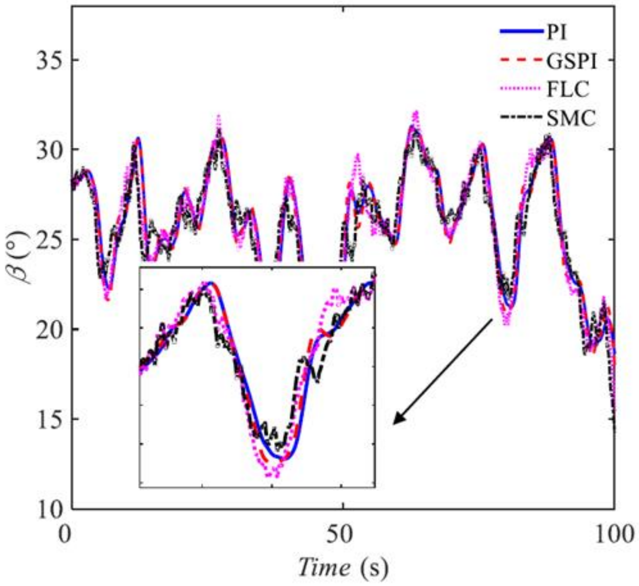


Figure 34: Pitch angle under random wind test

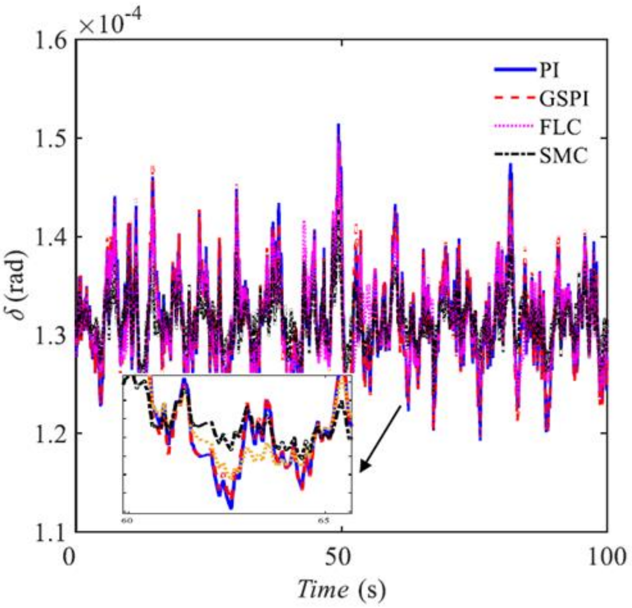


Figure 35: Shaft torsion angle under random wind test

As the simulation results and the error criteria in Table 7 show, the PI controller performed worse. This malfunction is due to the fact that the PI controller is a linear controller whose control parameters are optimized at only one operating point, while the other two controllers are nonlinear controllers whose control parameters are based on nonlinearities elimination or gain scheduling techniques are suitable for all wind speed regions. The performance of the gain scheduling PI controller is not as good as that of the feedback linearization controller. The SMC in the random wind speed mode, like the step wind speed, has a smaller overshoot and has been able to bring the rotor speed and generator output power closer to their rated values better than other controllers. A comparison of the error criteria presented in Table 7.

Table 7: Error under random change of wind speed

Controller	Integral Time Absolute Error
PI	570.8474
GSPI	500.5383
FLC	373.7077
SMC	294.8271

5.0 Conclusion and suggestions

5.1 Summary

In this thesis, two controllers are designed to control the wind turbine pitch angle. The controller’s simulation is implemented on a two-mass model based on WindPACT 1.5 MW wind turbine. This thesis is entitled “Optimized nonlinear pitch angle controllers design for wind turbines" in five chapters according to the following topics: In Chapter 1 (Introduction), first introduction and then wind energy position in world, Then the types of wind turbines are introduced. In Chapter 2 (literature review), wind turbine components, types of wind energy conversion systems and a review of previous works are presented. In the Chapter 3 (controller design), the mathematical model of a wind turbine is presented as a two-mass model under different subsystems of mechanics, aerodynamics, generator, and pitch angle actuator. Then three controllers (gain scheduling PI, feedback linearization and sliding mode) are designed. Then, to verify the designed controllers, the WindPACT 1.5 MW wind turbine in Chapter 4 (simulation) was used. Summary, conclusion, and suggestions are expressed in this chapter.

5.2 The novel aspects of this work

In this thesis, nonlinear and linear controllers were used to control the pitch angle. The wind turbine was modelled as a state-space model and the governing equations were based on its aerodynamic, mechanical, generator and screw angle actuator parts. The optimal coefficients of the controllers in this dissertation were obtained using the harmonic search algorithm. Because the PI controller uses fixed coefficients, it cannot have acceptable optimal performance. Therefore, to deal with this problem, an adaptive controller using gain scheduling method was used. Feedback linearization controller is designed to control the pitch angle after modelling. The simulation results on the two-mass model showed that the amount of power tracking error and rotor speed are acceptable for the gain scheduling and feedback linearization controllers.

The novel aspects of this work are:

1. Optimized PI controller design based on gain scheduling
2. Nonlinear controller design based on optimization algorithm

5.3 Suggestions

For the future works, the following items are suggested:

- Model-based control systems are designed based on the governing equations. For this reason, their practical performance depends on the accuracy of the model. If we use more accurate models with more complex dynamics, the controller will work better.

- According to the fact that wind turbines are affected by agents such as wind speed, the use of predictive and adaptive controllers that are updated online and according to environmental conditions, can have a good performance.

- Sometimes the pitch angle actuators may fail, hence the performance of the system is affected. For this reason, examining this effect on dynamic response of the system will be useful for better system performance.

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