Mechanical Engineering Department

Final Year Project 2

MCB 4044

Dissertation

Investigation on the Dynamic Response of a Horizontal Axis Wind Turbine with Active Blade Pitch Control

Prepared by

Abdul Qayyum B Shahrul Amar

16493

With a supervision from

Dr. Joga Dharma Setiawan

Dr. Jundika Candra Kurnia

Dissertation submitted in partial fulfillment of
the requirements for the
Bachelor of Engineering (Hons)
Mechanical Engineering

January 2016

CERTIFICATION OF APPROVAL

INVESTIGATION ON THE DYNAMIC RESPONSE OF A HORIZONTAL AXIS WIND TURBINE WITH ACTIVE BLADE PITCH CONTROL

by

Abdul Qayyum B Shahrul Amar

16493

A project dissertation submitted to the
Mechanical Engineering Programme
Universiti Teknologi PETRONAS
In partial fulfillment of the requirement for the
BACHELOR OF ENGINEERING (Hons)
(MECHANICAL)

Approved by,

____

(Dr. Joga Dharma Setiawan)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

JANUARY 2016

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contain herein have not been undertaken or done by unspecified sources or persons.

ABDUL QAYYUM B SHAHRUL AMAR

ACKNOWLEDGEMENT

Special thanks to my supervisor, Dr. Joga Dharma Setiawan for his dedication in helping me and spending his precious time to teach and guide me despite he had many other works and obligations. My gratitude towards friends for sharing their expertise and knowledge to teach me about the software and always keeping their doors open. Many thanks to my family especially my parents back home for their sacrifices coupled with their continuous encouragement and support to me in order to complete this project. Special thanks to my course mates that have helped me to complete this project and patiently taught me the technical basic of the project and for brainstorming ideas in order to encounter the problems. Each and every helps of them means the world to me.

ABSTRACT

The fluctuation and variation of wind speed could potentially damage the wind turbine blades. When large aerodynamic torque is exerted on the blade, the forces on the blade is enormous and will literally tear the turbine apart. An active blade pitch control system in a horizontal axis wind turbine could produce right amount of electricity by automatically adjusting its blade pitch to capture an optimum amount of wind energy.

In this project, the dynamic response and transient response (torque and angular velocity) analysis of the horizontal axis wind turbine by using active blade pitch control have been studied. The performance of this system is tested by running simulations. SolidWorks Motion Analysis Simulation is used for dynamic modelling in order to evaluate and determine the force and torque of the mechanical structure in a small wind turbine model. In particular, this project focuses more on how the angle of servo and angle of blade pitch would affect the power output variation. The results that will be compared and analyzed by using different angle of blade pitch and the velocity of wind as well.

Keywords: SolidWorks, torque, active blade pitch control, dynamic response, simulation, force

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Over the last 35 years, global demand for energy has become a greater concern about greenhouse effect due to fossil incineration and fuel consumption. To overcome these problems, wind energy has become an important part of the solution. There is no CO_2 emission produced by the wind turbine to generate electricity and therefore wind turbine could reduce the greenhouse effect. Significant effort has been devoted to develop a high performance wind turbine. a wind turbine converts the kinematic energy in the wind to mechanical energy in a shaft using the propellers. The mechanical energy is converted into electrical energy in generator eventually. However, one of the inherent drawbacks of wind turbine is that wind energy can only be produced when nature provides sufficient wind to spin the blades.

Blade pitch control is one of the techniques that is capable of increasing energy capture and minimize loads during high winds. The function of pitching is to rotate each blade around its span wise axis in order to adjust the effective angle of attack to the particular wind. Active control blade pitch is needed as a part of mechanism in wind turbine to obtain a balanced rotational speed of the rotor despite the changing of wind speed. When the wind speed is extremely low, the blade pitch is such that it automatically exposes more surface area to the wind. Conversely, the blade pitch is such that it exposes less surface area to the wind when the wind speed is high.

1.2 Problem Statement

The amount of wind that is likely to blow in certain places at a particular time is unpredictable. The prominent challenge of generating electricity using wind turbine is that the wind speed can never be predicted. Every wind turbine is highly dependent on the availability of wind. There will be no electricity produced when there is no wind blowing. Due to the fact that this form of energy is not reliable to generate electricity, numerous wind turbine designs have been proposed and evaluated.

The rotation of blades plays a vital role in generating electricity from the turbine. In order to produce the right amount of electric power, the wind turbines need to at the right pace. It is uneconomical to run a turbine when the wind speed is significantly slow.

It is very crucial to analyze the efficiency of the turbine. Thus, this project needs a systematic procedure and simulation to run and calculate the output of the electricity generated by the wind turbine and come out with a subsequent performance improvement opportunity for the betterment of wind energy industry.

1.3 Objectives

The main objectives of this project are:

- To design and run the simulation of active blade pitch control that study the trade-off between minimum of torque variations and maximum energy gain
- To evaluate the effect of active blade angle on the performance of horizontal axis wind turbine

1.4 Scope of Study

This project is mainly focused on a new approach for control of the pitch angle of wind turbine in an unstable wind conditions. The aim of this project is to investigate on torque variation and modeling of the pitch angle of wind turbine blade in adverse circumstances via SolidWorks Motion Analysis. SolidWorks modeling software will be used to design the blade, bearings and connectors.

CHAPTER 2

LITERATURE REVIEW

2.1 Horizontal Axis Wind Turbine (HAWT)

The path of the wind flow will be parallel to the axis of the rotor's rotation for in horizontal axis wind turbine. The working principle for horizontal axis wind turbine is when the strong wind passes the upper side of the airfoil shaped blade, thus creating a different level of pressure which is a lower-pressure area above the airfoil. The result of the different pressure at the top and bottom of the surfaces will create an aerodynamic lift, thus make the blades move. The pitch-change mechanism controls the angle of each blade to adjust the angle of attack[1]. This mechanism also adjusts wind turbine's starting torque, peak power and stopping torque. Figure 1.1 shows the internal equipment in a horizontal wind turbine.

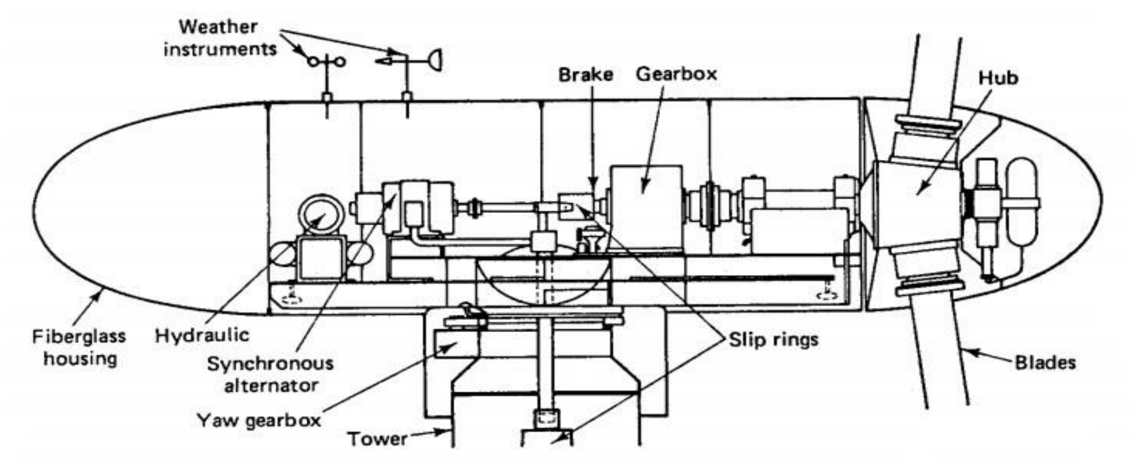


Figure 1.1 Major components in a horizontal wind turbine

2.2 The Lanchester-Betz Limit

The power coefficient descends rapidly at higher angles of attack, regardless of values of the other parameters[2]. According to Betz limit, 16/27 (59.3%) is the maximum amount of power that is able to extracted from the wind flow. The viscous force of the outer flow on the stream tube will produce heat from the kinetic energy from the wind[3]. The power coefficient, C_p is the ratio of power output from wind turbine to power available in the wind [9].

Power output from wind turbine, $P = \frac{1}{2} \rho A u^3 C_p$

Power available in wind, $P_{wind} = \frac{1}{2} \rho A u^3$

2.3 Active and Passive Stall Control

The blade will be positioned onto the rotor hub at an optimal angle of attack in passive stall controlled wind turbines. The stalling of the blades will take place when the wind speeds exceed the maximum level. As a result, the lift force on the rotor decreases and restrain the turbine in the permissible speed limit[4]. This phenomenon could prevent the damage of the turbine by providing an effective means to limit the power capture[5]

In active-stall control, the blades are controlled by the system to turn more into the wind when the speed exceeds the rated value. Thus, by adjusting the blade angle of attack, the captured power can be maintained[5]. Maximum efficiency is obtainable even at low wind speeds by pitching the blades as in a pitch-controlled wind turbine[4].

2.4 Pitch Control in Wind Turbine

The pitch control system is a vital part of the modern wind turbine. The blade pitch angle is adjusted by collective pitch control for wind turbines with respects to the changes of the wind speed over the rated wind speed[6]. The pitch structure operates to ensure the maximum energy can be gained by controlling the mechanical energy absorption and adjusting generator output power to sustain the stability of the wind turbine[6]. The generator speed, drive train and tower motions are controlled mainly by the collective pitch controller. Collective pitch controller gives a little impact on the blade motions because the angle of attack of each individual blade is periodic due to wind shear and other cyclic loads. Different wind speed condition changes the flow angle of the wind turbine. In order to meet the flow angle requirements, the pitch angle needs to be adjusted at certain points along blade length[2]. In pitch-controlled wind turbines, the angle of attack and the lift force is reduced when the wind speed is higher than rated wind[5].

Technically, each blade has its own actuator and controller due to the differences of load at different rotation positions of the blade [8]. In wind energy industry, hydraulic controlled system dominates wind turbine around the world. Apart from supplying power control, the blade pitch system is used to accelerate the blades from standing idle to operational speed and positioning the rotor back to a secure idling situation in case of any functional errors occur [10]. Besides that, a pitched blade has its own significant function which it can act as an aerodynamic brake and it does not require to include tip brakes as on a stall regulated machine[7].

2.5 Wind Turbine Blade Design

Carbon fiber has been used in the load-bearing spar structure of the wind turbine blade because it shows a significant effect in the stiffness of the blade and cost-effective weight reductions as well [11]. Changes the angle of attack as a function wind load on the wind turbine blade is very crucial in designing the blade [12]. Apart from that, the abrupt change of thickness of blade could cause damage by producing eccentricity in the transmission load. Due to generating bending moments, the laminate of the blade does not work uniformly over the thickness [13].

The weakest point on the blade is at its joint. The weakness will be consequently accentuated if any of the joints are associated to the presence of defects. The forces and performance of a wind turbine depends heavily on the construction and orientation of its blades. Pitch angle β; located between chord line and plane of rotational is one of the parameters on each wind turbine blade. Plane of rotation is a field in which the tip of the blade is located when it rotates and chord line is a straight line that connects leading edge and trailing edge.

CHAPTER 3

METHODOLOGY/PROJECT WORK

3.1 Project Simulation

3.1.1 SolidWorks Software

The actual model of the horizontal axis wind turbine will be designed in 3D model by using SolidWorks. SolidWorks is used to make the process of simulation more clear and reduce errors in executing the project. The assembly of the model can be exported to the other software by changing the filename. The mass properties of each component of the wind turbine can be defined in SolidWorks and can be read automatically in ADAMS and other software. The design can be viewed in three different angles; top view, side view and front view.

3.1.2 Motion Analysis of Wind Turbine

In SolidWorks, the dynamics of rigid body can be analyzed by using motion analysis. This simulation offers an easy approach for solving any issues regarding the inertial forces or joint reactions of wind turbine. In this project, it is significant to measure and calculate the forces acting on wind turbine in order to get how much torque is exerting on the blades of the model. The torque and the inertial forces exerting on the blades will be different if the blade pitch angle is changing. Motion analysis simulation will be performed at various blade pitch angle in order to analyze which angle is the best for wind turbine to be operated.

3.2 Project Flow Chart

For this project, the methodology is divided into four parts. The first part is the identification and simulation of the wind turbine using software such as Simulink, ADAMS and SolidWorks. The functionalities of the software will be further discussed in the latter section. Analysis of operational wind turbine using given parameters will be conducted after the simulation. Designing a prototype will be done after all data have been analyzed using ADAMS. Improving the output efficiency and performance is the final step of this project.

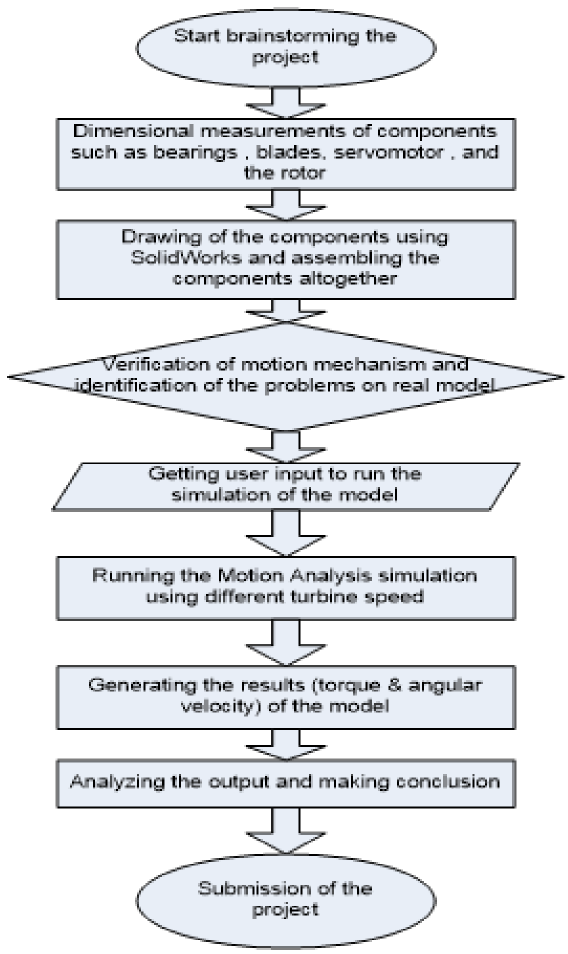


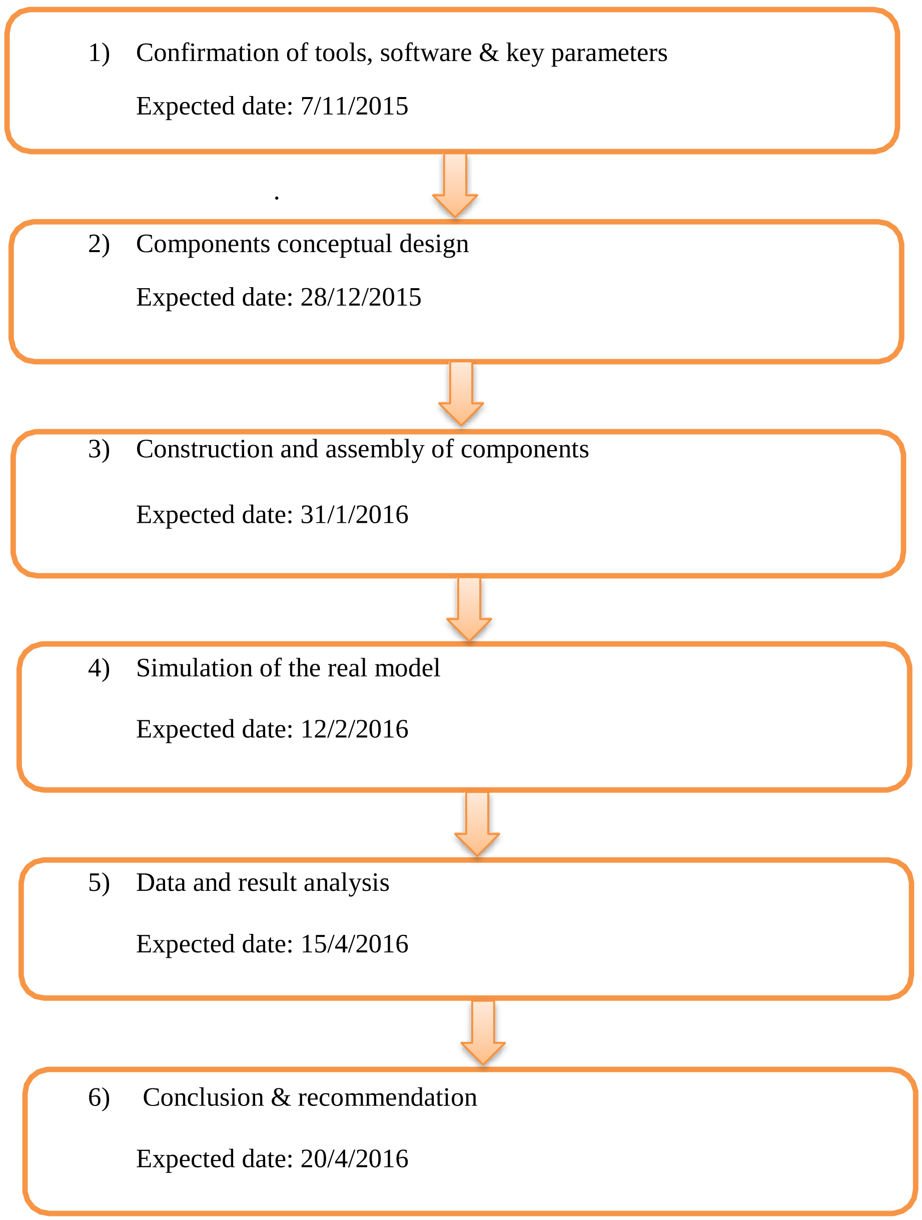
Figure 3.1 Project
Flow Chart

3.3 Gantt Chart

			FYP 1				FYP 2				
ACTIVITY	Start	End	Sep-15	Oct-15	Nov-15	Dec-15	Jan-16	Feb-16	Mar-16	Apr-16	May-16
Project Initiation & Literature Study			1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4
Topic Selection & Background Study	16-Sep-15	13-Oct-15									
Literature Review on Pitch Control	27-Sep-15	30-Mar-16									
Literature Review on The Lanchester-Betz Limit	27-Sep-15	30-Mar-16									
Literature Review on Active & Passive Stall Control	27-Sep-15	30-Mar-16									
Project Preliminary											
Dimensional Measurement of Components	18-Oct-15	30-Nov-15									
Construct and Draw Each of The Components	3-Nov-15	21-Dec-15									
Assembly of Components to Form a Complete Model	2-Nov-15	30-Jan-16									
Study on SolidWorks Motion Analysis	2-Jan-16	15-Feb-16									
Project Simulation											
Verification of Motion Mechanism	1-Jan-16	29-Jan-16									
Run the Simulation on the Model	2-Jan-16	30-Apr-16									

Perform User Testing	3-Apr-16	30-Apr-16																																				
Project Analysis																																						
Data Collection from Simulation	15-Mar-16	30-Apr-16																																				
Data Analysis & Comparison	27-Mar-16	30-Apr-16																																				
Conclusion & Recommendation	17-Apr-16	30-Apr-16																																				

KEY MILESTONE OF FYP



CHAPTER 4

RESULTS AND DISCUSSION

4.1 Planning Process

The objective of this project is to design and characterize a horizontal wind turbine model by using SolidWorks and motion analysis of the model. The design issues and considerations are discussed in more details in this chapter. In designing the components of wind turbine, dimensional measurements must be done. Assembling and drawing all the components are done by using SolidWorks software. By using SolidWorks motion, the inertial force and torque of the model can be measured to analyze the performance of the wind turbine.

Motion analysis in SolidWorks is used to study the dynamics response in wind turbine and understand the system performance by looking at how the forces and loads are distributed throughout the whole systems. Table 1 below shows the list of components to design a complete wind turbine. In this project, the motion analysis is performed in order to design safer and better prototype. This simulation will calculate and measure the velocities and reaction forces on the model when it moves.

No.	Components
1.	Shaft
2.	Blade
3.	Hub
4.	Link 1
5.	Link 2
6.	Link Connector Rotor
7.	Link Connector Stator
8.	Link 3
9.	Link 4
10.	Servomotor

Table 4.1. Components of wind turbine

4.2 Wind turbine model

All the main components and specifications of the wind turbine model will be discussed in this chapter. The main components have been measured and modeled using SolidWorks.

Specifications and main components

The following table 4.2 illustrates main specifications of the model

BLADES		
Blade length	0.380	Meter (m)
Material	Acrylic	-
Width	0.046	Meter (m)
ROTOR		
Rotation direction	Clockwise (facing the hub)	-
Hub height	0.358	Meter (m)
Type	Pitch-controlled	-
Swept area	0.485	Meter square (m^2)
Rotor diameter	0.786	Meter (m)
TOWER		

Table 4.2 Specifications of main components

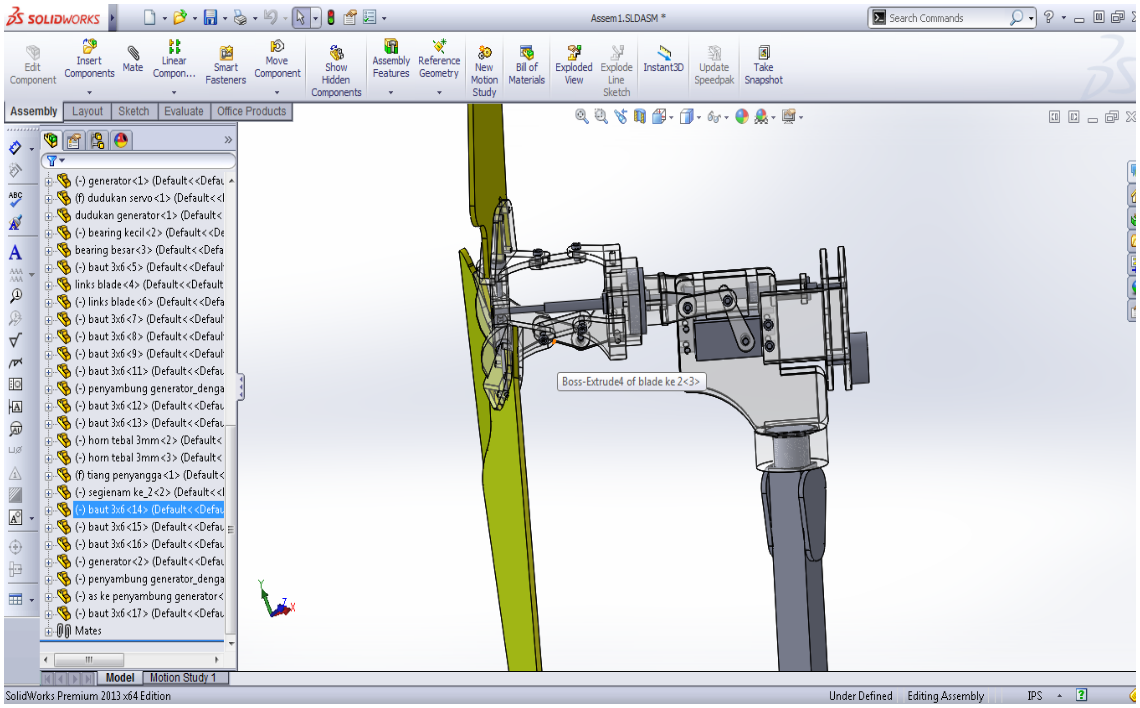


Figure 4.1 Wind turbine main components

As shown in figure 5.1, the model of wind turbine consists of components that has been drawn and assembled by using SolidWorks. All the parts are drawn separately and assembled together to produce a complete wind turbine according to the given parameters and dimensions. The model consists of three blades, rotor, generator, links, tower, pitching system, main shaft and servomotor.

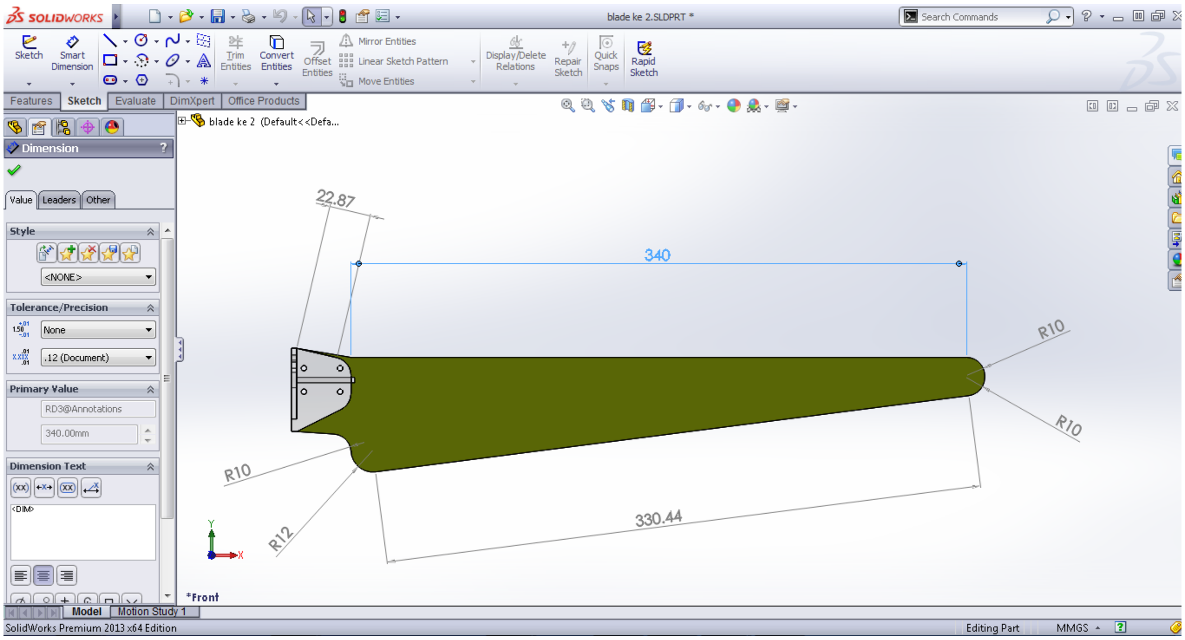


Figure 4.2 Blade of the model

The diameter of a wind turbine can be defined by using the diameter of the imaginary circle made around the turbine. The distance from one of the tips to the hub is the radius of the wind turbine. Blades of wind turbine is the most important part to capture the wind energy. Thus, they must be designed efficiently in order to get the optimum output value.

The blade is made up of acrylic with the dimension of 340mm length. In this project, three blades will be used and each blade will be placed 120^{o} apart from each other at the hub. The plastic is being used for blades because of its ability to be easily formed, pressed and shaped. Apart from that, the reason of using plastic is because of its suitability of being used for the prototyping process.

The rotor of 0.786m in diameter is one of crucial parts of the wind turbine where it is used to convert the extracted power from wind energy into mechanical power in terms of torque and rotational frequency. The generator is used to generate power and it was selected according to certain conditions and requirements. The specifications of the generator must be defined in order to calculate the output power of the wind turbine. The type of generator that will be used in this project is RF-300FA-12350. Table 4.3 shows the description of the generator.

GENERATOR	
Type of generator	RF-300FA-12350
Manufacturer	Mabuchi Motor
Voltage (nominal)	3V Constant
Speed (max efficiency)	2320 r/min
Torque (max efficiency)	4.3 g-cm
Output (max efficiency)	0.10 W
Current (max efficiency)	0.093 A

Table 4.3 Details of generator

4.3 Complete Model

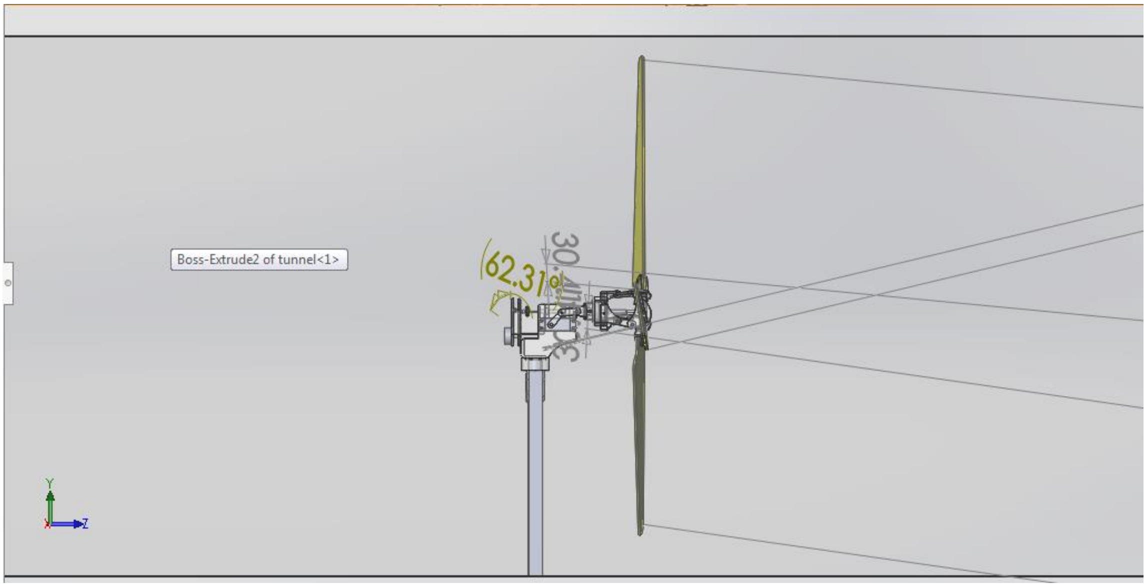


Figure 4.3 Complete model

This model represents a horizontal axis wind turbine with an active blade pitch control mechanism. The base part is fixed on the ground (wind tunnel) and cannot be moved. The blades and the three links were connected to each other with the screws. The mates were created on each of the components in order to put the parts in place and built one complete model. Once the simulation was running in SolidWorks Motion, all the mates would automatically be translated into the internal joints.

4.4 Data Analysis

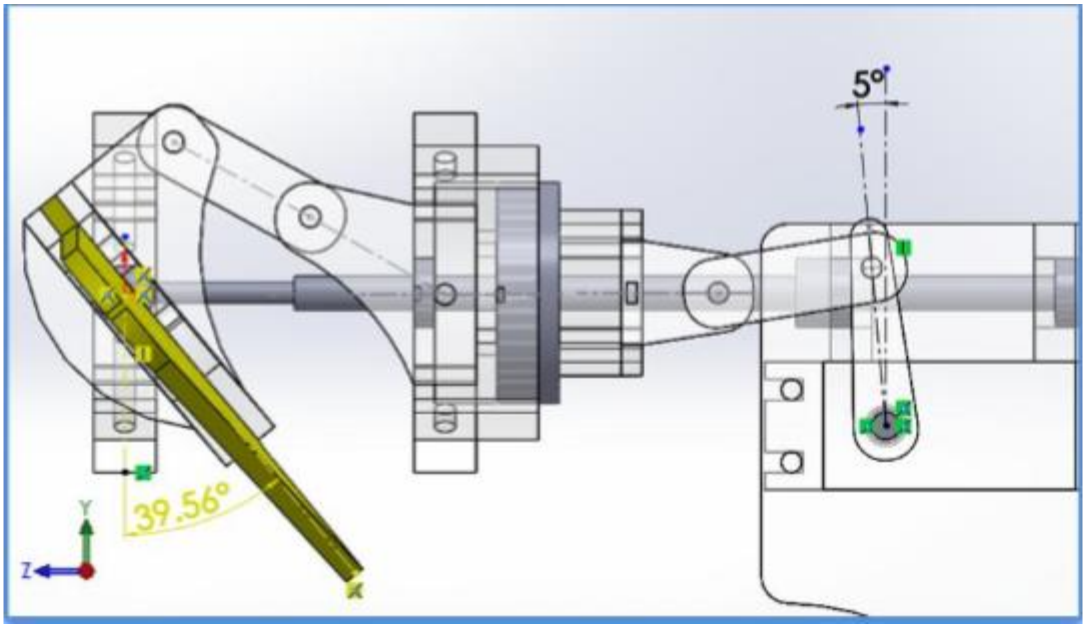


Figure 4.4 Measurement of wind turbine model

Different angles of servo were performed to analyze the performance of each angle as shown in the table 4.3 below. These measurements were taken to determine the movement of the blade resulting from the various angle of servo. The changing of servo angle would result the movement of blade pitch angle on the model.

Servo angle	**Blade pitch angle**
30º	64.7º
40º	70.1º
50º	75.3º

Table 4.4 Servo angle measurements

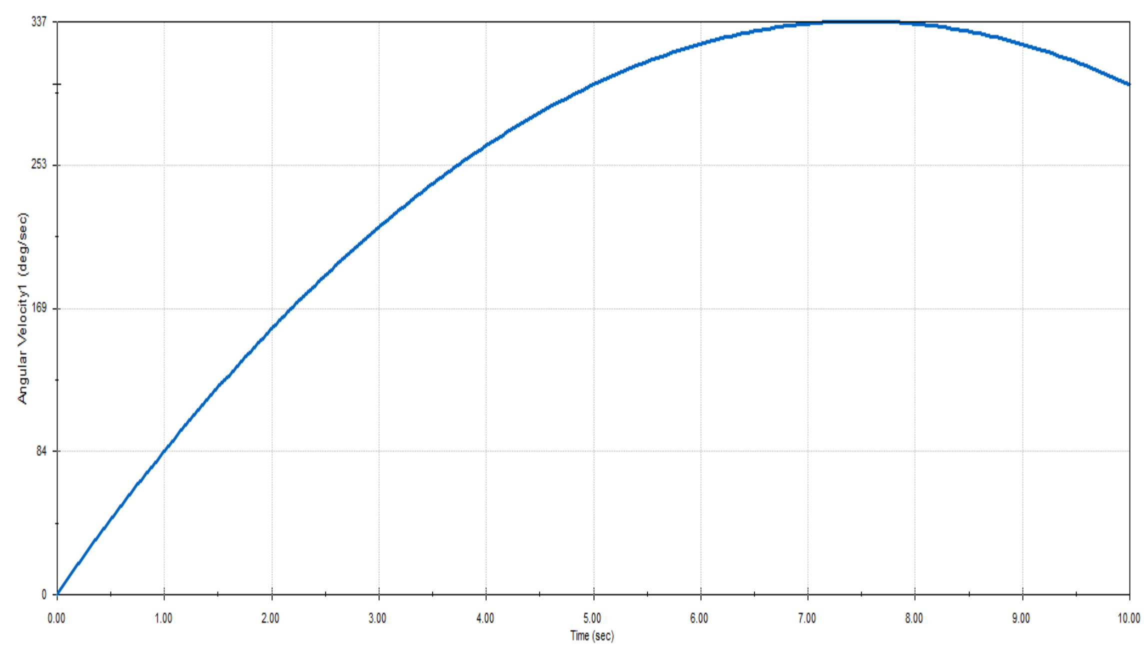


Figure 4.5 Angular velocity of 50 rpm

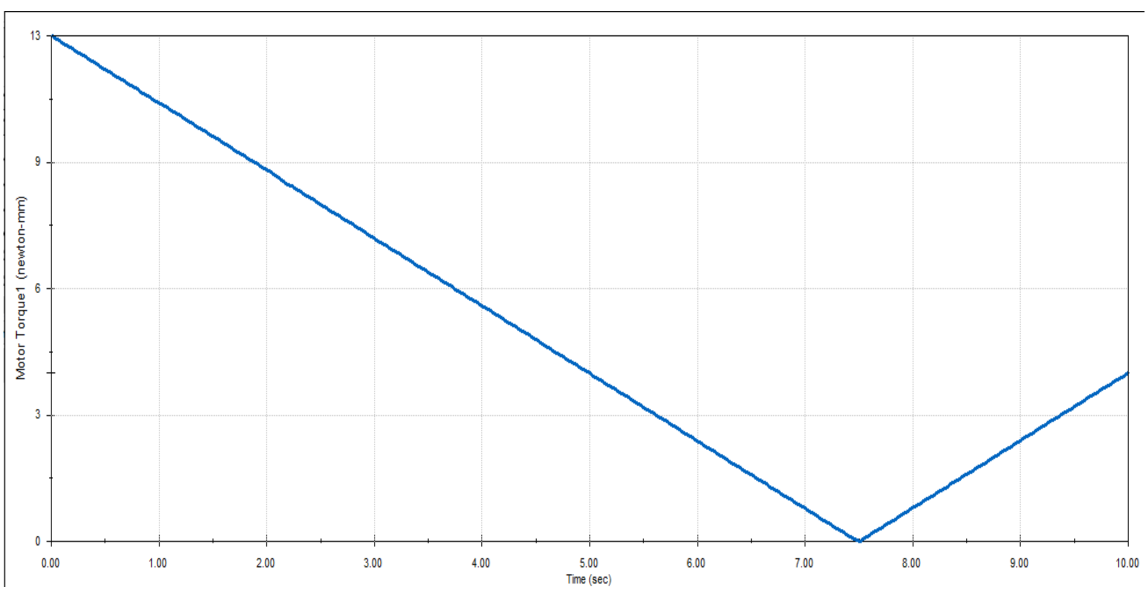


Figure 4.6 Motor torque of 50 rpm

Angular velocity is a quantitative expression of the amount of rotation that a spinning object undergoes per unit time. The magnitude of the angular velocity vector is directly proportional to the angular speed. In Figure 4.5, the curve shows that at the beginning of the simulation the angular velocity is 0 degree/second. As the time goes by, the value of angular velocity is increasing gradually until 7.5 seconds. The angular velocity reaches peak value at 7.5 seconds which is 337 degree/seconds. The value drops after reaching its maximum value. The simulation is run with the turbine speed of 50 rpm for 10 seconds.

In this project, finding the torque of the wind turbine blades is one of its objectives. Torque is a measure of how much a force acting on an object causes that object to rotate. Figure 4.6 shows the torque of the motor with the turbine speed of 50 rpm. The graph depicts the value of torque at the beginning of the simulation is the highest which is 13 Newton-mm. The value deceases directly proportional with the time. A highest torque at the beginning is required to rotate the blade of the model. The value of reaches its minimum value at 7.5 seconds as the angular velocity has its highest value at the particular time. After 7.5 seconds, the value of torque starts to increase as the model needs higher torque to sustain the rotation of the blade.

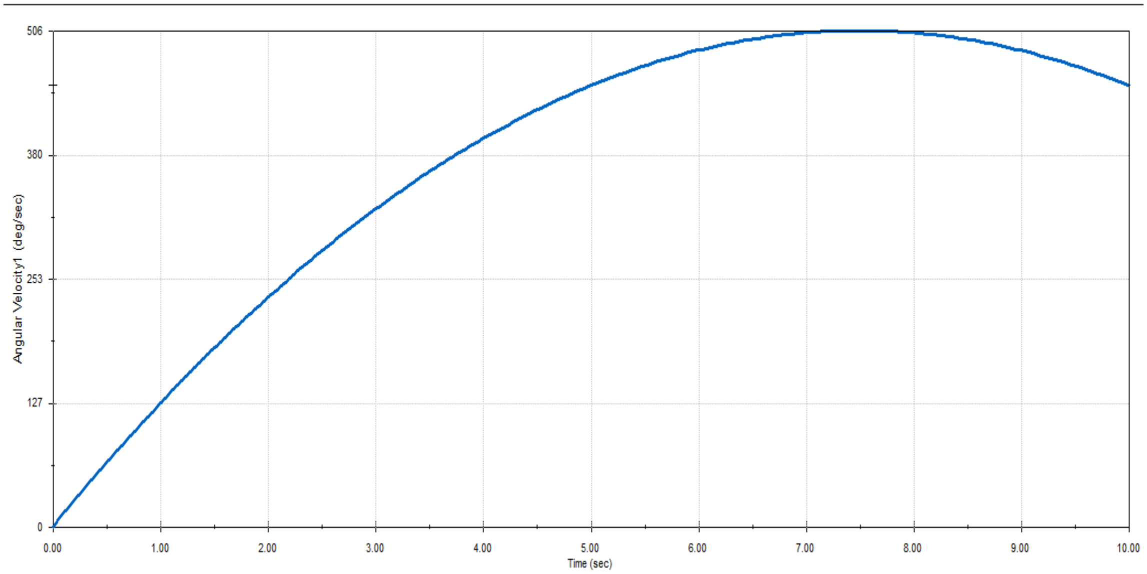


Figure 4.7 Angular velocity of 75 rpm

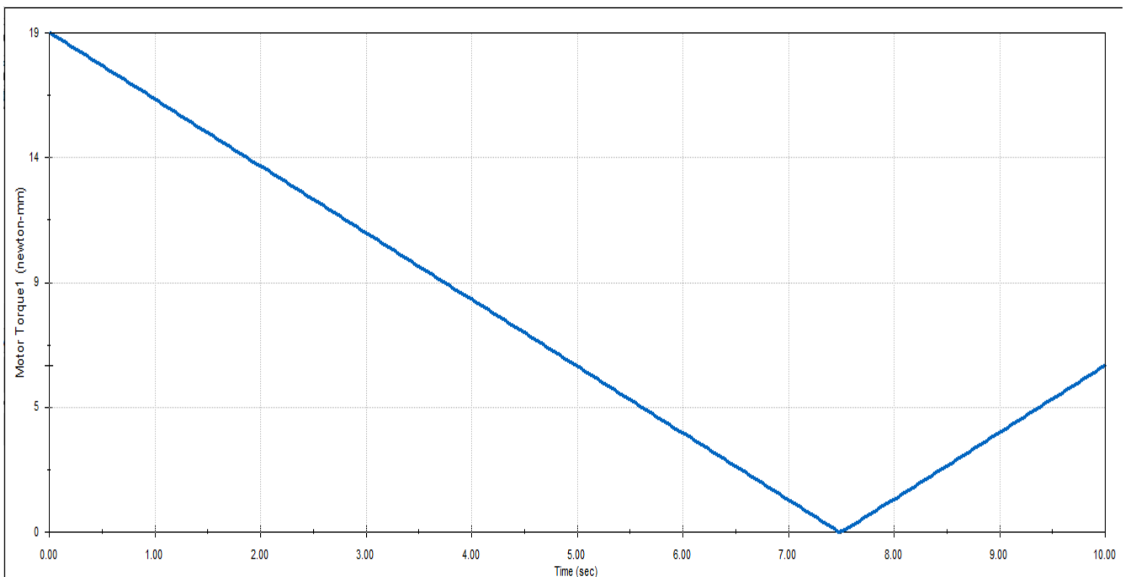


Figure 4.8 Motor torque of 75 rpm

In Figure 4.7, the graph shows that the angular velocity reaches its maximum value at 7.5 seconds with the value of 507 degree/seconds. It shows that as the turbine speed of the model increases, the value of the angular velocity increases as well. The graph shows that the angular velocity is zero at the beginning as the blades need high torque to start rotating. The result depicts that the value of angular velocity drops after 7.5 seconds due to the torque is getting lower.

The simulation is run with the different turbine speed which is 75 rpm. Figure 4.8 depicts the amount of torque needed to rotate the blade throughout 10 seconds of simulation. The reading gives different values at different period. The highest amount of torque is needed at 0 second. For 75 rpm, the value of torque needed to rotate the blades is 19 Newton-mm. It is slightly higher than the torque at the beginning for 50 rpm. The value is decreasing as the time goes by until it reaches 7.5 seconds. At this particular time, the angular velocity is the highest and the torque is at its lowest value. After 7.5 seconds of running the simulation on the model, the value of torque decreases as the blades start to stop rotating. The model needs higher torque to continue rotating.

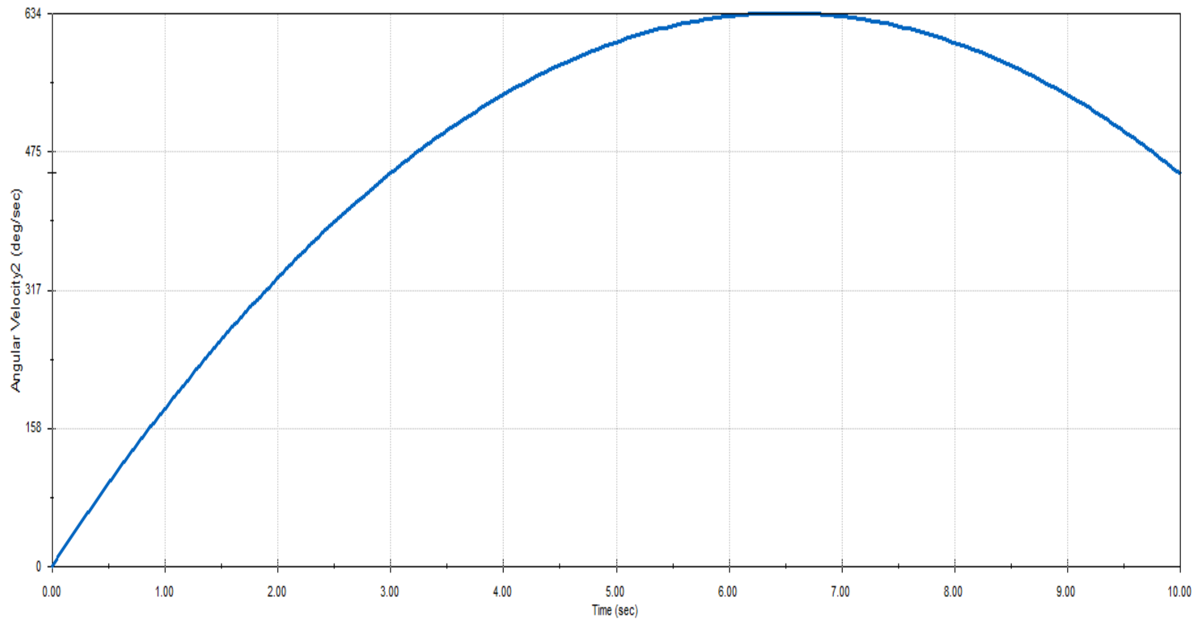


Figure 4.9 Angular velocity of 100 rpm

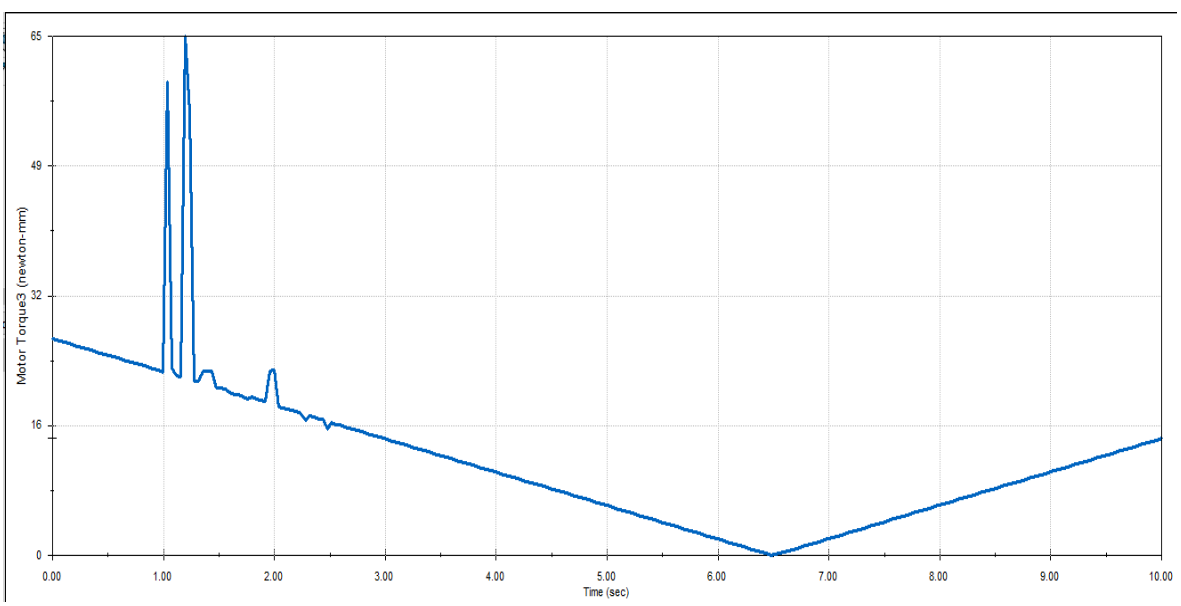


Figure 4.10 Motor torque of 100 rpm

With the 100 rpm of turbine shaft, the angular velocity of the model keeps elevated from 0 second to 6.5 seconds. The angular velocity has the greatest value at 6.5 seconds and it slightly drops after 6.5 seconds of simulation. The highest value of the angular velocity is 634 degree/second. This happens because the value of torque at 6.5 seconds is the lowest. It shows that when the model has the highest angular velocity, the value of torque is at the lowest because at a high angular velocity, the model does not require high torque to rotate the blades to generate more power. High torque is only required when the angular velocity is decreasing and low. This can be seen in Figure 4.9 and Figure 4.10 above.

Figure 4.10 shows that the value of torque starts with 27 Newton-mm and the model has overshot at 1s and 1.2s. The value reduces until 0 Newton-mm at 6.5s due to a high value of angular velocity. After 6.5s, the model requires more and high torque to sustain the rotation of the blade.

CHAPTER 5

CONCLUSION

As a conclusion, this project research will be conducted to simulate and analyze the efficiency of horizontal axis wind turbine by using active blade pitch control. It is a very significant measure as this project will determine the amount of torque needed to rotate the blades at certain wind speeds. The angular velocity of the model would affect the amount of torque required to rotate the blades in order to generate the electricity. The torque would have the highest value at the beginning of rotation and the angular velocity would have the lowest at the beginning. At the servo angle of 30º with the turbine speed of 100 rpm, the amount of torque needed is the highest which is 27 Newton-mm. This means the higher the turbine speed, the higher the torque needed to rotate the blades.

Due to limitation of time, this project could be improvised by using other software such as MATLAB and ADAMS to get more accurate and detailed results. This is because the SolidWorks Motion Analysis has a limited variable and parameter in the software.

REFERENCES

[1] D. A. Spera, *Wind Turbine Technology*, 1994.

[2] A. R. Jha, *Wind Turbine Technology*: CRC press, 2010.

[3] G. P. Corten, *Flow Separation on Wind Turbines Blades*, 2001.

[4] R. Vijay, "*Pitch Control of Horizontal Axis Wind Turbine*," National Institute of Technology, Rourkela, 2011.

[5] B. Wu, Y. Lang, N. Zargari, and S. Kouro, *Power Conversion and Control of Wind Energy Systems*: John Wiley & Sons, 2011.

[6] T. Shi, Z. Wu, R. Gao, Z. Song, and C. Xia, "*Study on independent blade pitch control for huge wind turbines*," in Electrical Machines and Systems (ICEMS), 2011 International Conference on, 2011, pp. 1-6.

[7] M. O. Hansen, *Aerodynamics of Wind Turbines*: Routledge, 2015.

[8] T. Wei, *Wind Power Generation and Wind Turbine Design*, WIT Press , 2010

[9] A. Ibrahim, *Wind Turbines*, InTech, 2011

[10] K. Arkadiusz, "*Pitch and Torque Control of Variable Speed Wind Turbines*", Chalmers University of Technology, Goteborg, 2004

[11] Griffin, Dayton A., and Thomas D. Ashwill. "*Alternative composite materials for megawatt-scale wind turbine blades: design considerations and recommended testing*." ASME 2003 Wind Energy Symposium. American Society of Mechanical Engineers, 2003.

[12] MacPhee, David, and Asfaw Beyene. "*A flexible turbine blade for passive blade pitch control in wind turbines.*" Power Engineering and Automation Conference (PEAM), 2011
IEEE. Vol. 1. IEEE, 2011.

[13] Marin, J. C., et al. "*Study of fatigue damage in wind turbine blades*." Engineering failure analysis 16.2 (2009): 656-668.

[14] Abdulhadi, Fadi Omar. "*Design and Characterization of a Small Wind Turbine Model equipped with a Pitching System*." CU Theses (2012).