**PROJECT COMPLETION REPORT
FOR
SHORT TERM RESEARCH GRANT**

Study and Design of Multi-blade Wind Energy Conversion System

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ABSTRACT

This project was performed to study and design a VAWT rotor blade and the gearbox to produces 5 kW of electrical power. This project mainly focuses on Savonius wind turbine. The wind speed distribution was observed and the wind energy site was set at Melaka, Malaysia. The relevant design parameters for designing Savonius rotor blade were studied in this report.

The Savonius rotor was designed with the rotor diameter of 3.5 m and rotor height of 7 m. The rotor blade thickness was designed as 10 mm. SolidWorks was the design software used in this project. The material chosen for the rotor blade was E-glass fiber composite. Pressure difference between the concave and convex blade surface of Savonius rotor induced to drag force that turn the blade. The pressure difference was obtained by implement Computational Fluid Dynamics (CFD) analysis on SolidWorks Flow Simulation. The two flow types in this project were external flow and internal flow analysis. Both analyses were static analysis. Aerodynamic analysis was performed in manually to obtain the resultant drag force on the rotor blade. The resultant drag force obtained was 595.98 N and this value was used in Finite Element Analysis (FEA) to test the structural reliability. The FEA was performed by SolidWorks Simulation and the result was interpreted in three aspects: stress, deformation and Factor of Safety (FoS). The model with blade thickness of 10 mm was found to be able to withstand the load from wind speed of 7 m/s.

The wind turbine gearbox has been designed in three stages which are one stage of planetary gear and two stages of parallel gears. Some theories regarding to the machine element design and structural design have been applied to determine the shaft diameter, number of teeth of the gear, module of the gear, gear ratio and the number gear stages. The wind turbine gearbox has been designed to increase the speed from 60 rpm to 1280 rpm with the gear ratio of 1:21.

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CHAPTER 1
INTRODUCTION

1.1   Introduction to the Research

This project is concern about the design and analysis of wind turbine system applicable to the UTeM Durian Tunggal Campus, Melaka which capable to generate 5 kW electricity.

1.2   Background

As the awareness of people toward global warming issues, pollution issues, and the natural resource depletion issues had increased, people are kept continued finding another more suitable way to solve those problems. One of the solutions for those problems is to use renewable energy instead of keep using fossil fuel that will finish one day. The examples of renewable energy are solar energy, hydropower, and wind energy. Wind energy is one of the useful renewable energy because the wind is free of charge and it exists everywhere on the earth. Everyone can utilize wind to help them to do something they need. For example, sailor use wind for sailing, people use windmill for grinding and water pumping, and the modern wind turbine is used to generate electricity.

In Malaysia, wind turbine is seldom used to generate electricity power in commercialize way. This is because wind speed in peninsular Malaysia is low. The low wind speed is due to the reason where the wind is blocked by both Titiwangsa Mountains and Sumatra Mountains. Besides that, other issues such as the high installation cost and the wind farm location also are the causes that inhibit the use of wind turbine in Malaysia.

There are two main types of wind turbine, which is vertical axis wind turbine (VAWT) and horizontal axis wind turbine (HAWT). This project focused on the design and analysis of VAWT rotor blade the wind turbine gearbox.

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1.3   Problem Statement

Since, the wind speed in Malacca is low and it is not suitable to set up large scale wind turbine. In this project, the wind turbine blade is designed for the use of small scale wind turbine which capable to generate 5 kW power.

1.4   Objective

The objectives of the research are as follows:
- To study the existing design and the design parameters of VAWT rotor blade.
- To design VAWT rotor blade in order to generate 5 kW power.
- To design a gearbox for the VAWT.
- To analyze the structural of VAWT.

1.5   Scope and Key Assumptions

This report only focused on the design and the structural analysis of VAWT rotor blade. There is no prototyping of the VAWT rotor blade and the gearbox been done considering the cost to manufacture of a rotor blade is not included in this research. On the other hand, any cost that involved in the design such as installation cost and material cost with the design of rotor blade are not considered in this report.

CHAPTER 2
APPROACH

2.1. Wind Turbine Design Parameter

2.1.1. Power and Power Coefficient

Wind power, P_w is defined as the multiplication of mass flow rate, $\rho A V$ and the kinetic energy per unit mass, $\frac{1}{2} V^2$ (Musgrove, 2010). The wind power is denoted by the equation of

$$= \frac{1}{2}$$

From the wind power equation, wind power is also proportional to the cube of the wind velocity, V^3. This mean that the power output will increase by factor of eight if the wind speed increased by a factor of two. The ρ in wind power equation represent the air density which is 1.225 kg/m^3 for standard condition (Manwell *et al.*, 2009). Besides that, the A represent the swept area of wind turbine. Swept area is depended on the type of wind turbine. Hayashi *et al.* (2004) found that the swept area for Savonius Wind Turbine is calculated by multiplication of rotor diameter, D and the rotor height, H. The larger the swept area, the larger the power generated.

$$= \quad .$$

The wind power in the above equation represents the ideal power of wind turbine, as in case of no aerodynamic or other losses during the energy conversion processes. However, as state by Manwell *et al.* (2009), there is not possible for all energy being converted into useful energy. The ideal efficiency of a wind turbine is known as Betz limit. According to the Betz limit, as supported by Musgrove (2011) there is at most only 59.3 % of the wind power can be converted into useful power. Some of the energy may lose in gearbox, bearings, generator, transmission and others (Jain, 2011). However, most wind turbine failed to achieve the 59.3 % of efficiency and thus it is normally referred to as power coefficient, C_p. A power coefficient is defined as the ratio of power output to power available in the wind (Johnson, 2004). The maximum power coefficient, C_p for Savonius rotor is 0.30. Hence, the C_p value used in this project is 0.30.

$$= \frac{\qquad}{0.5}$$

$$= 0.30$$

Thus the power output, *P* with considering the power efficiency is

$$= \frac{1}{2}$$

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2.1.2. Power Performance Curve

Power performance curve define the relationship between wind speed and power output. Manwell *et al*. (2009) realize that each type of wind turbine has their own characteristic for power performance curve and is varied with wind speed. The function of power curve is to predict the energy production of a wind turbine. Jain (2011) explains that the theoretical power performance curves are derived from field testing.

Both Manwell *et al*. (2009) and Jain (2011) agree that the three wind speed parameters related to the power performance are as follow:

- **Cut-in speed.**

  Cut-in speed is the minimum wind speed for the wind turbine to start produce power. Cut-in speed is counted as 50 % of the average wind speed. Most wind turbines begin to produce power at wind speeds in the range of 3 to 5 m/s. The lower the wind speeds, the lower the power can be produce. An important point stated by Jain (2011) is the torque produce at low wind speed is too small to overcome the inertia of the turbine system and thus failed to generate power.

$$= 0.50$$

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- **Rated wind speed.**

  This is a wind speed at which the rated power is reached. Gipe (2004) defines the rated power as the maximum power output of the electrical generator. The rated power defines the shape of the power curve. The wind speed is reached on its rated when it is 50 % more than the average wind speed. Normally the rated wind speed is in the range of 11.5 to 15 m/s (Jain, 2011). Wind turbine produce more energy at wind speeds between cut-in and rated, therefore power curved with low rated wind speed will produce more energy overall.

$$= 1.5$$

- **Cut-out speed.**

  Cut-out speed indicates the maximum wind speed at which the turbine is allowed to deliver power. Most turbine stop produce power at wind speed of 25 m/s. Wind turbines are usually stop operating for the reason of engineering and safety constraints (Jain, 2011).

$$= 3$$
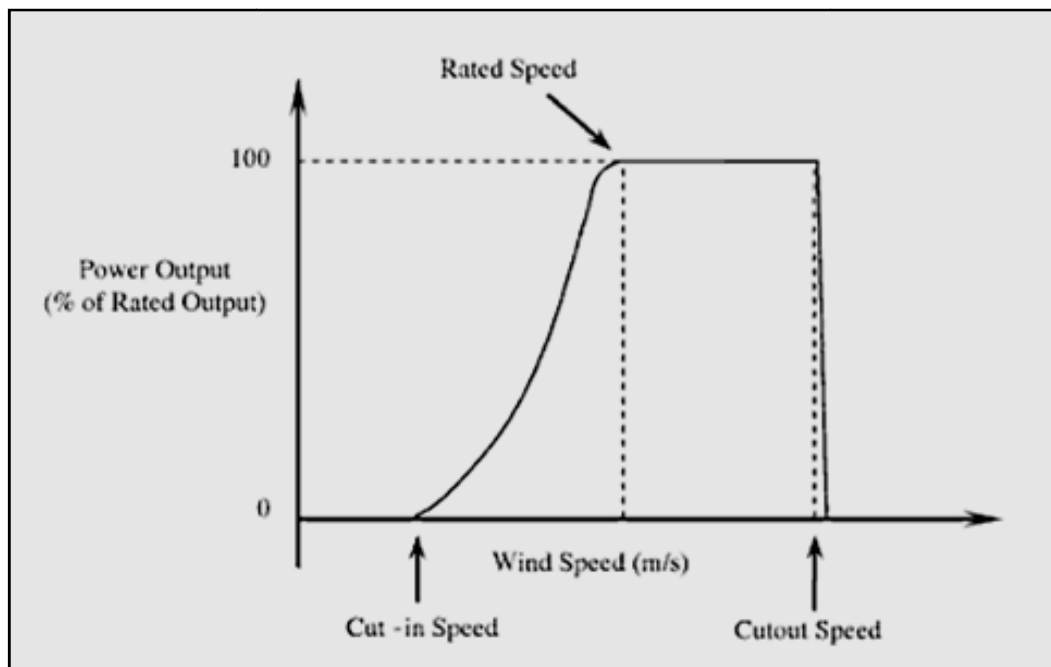
Figure 1 Typical wind turbine power curve (Source: Tong, 2010).

2.1.3. Tip Speed Ratio

Tip speed ratio, λ is defined as the ratio of the linear speed of rotor blade, $\omega.R$ to the undisturbed wind speed, V (Solanki, 2009). ω is the angular velocity and R represent the radius revolving part of the turbine. The maximum tip speed ratio that Savonius rotor can reach is 1.0. Manwell *et al*. (2009) write that high tip speed ratio improves the performance of wind turbine and this could be obtained by increasing the rotational rate of the rotor. However, this induces to great aerodynamic noise and lead to structural problem (Strong, 2008).

$$\lambda = \frac{\omega.R}{V}$$

2.1.4. Solidity

According to Manwell *et al*. (2009), solidity is related to tip speed ratio. A high tip speed ratio will result in a low solidity. Musgrove (2010) defines solidity as the ratio of blade area to the turbine rotor swept area. For VAWT, the solidity is defined as

$$\sigma = \frac{nd}{R}$$

Where n is the number of blades, d is the chord length or can be defined as the diameter of each half cylinder, and R is radius of wind turbine, as shown in Figure **2**. Solanki (2009) founds that the value of solidity will affect the starting torque. The higher the solidity, the higher is the starting torque.
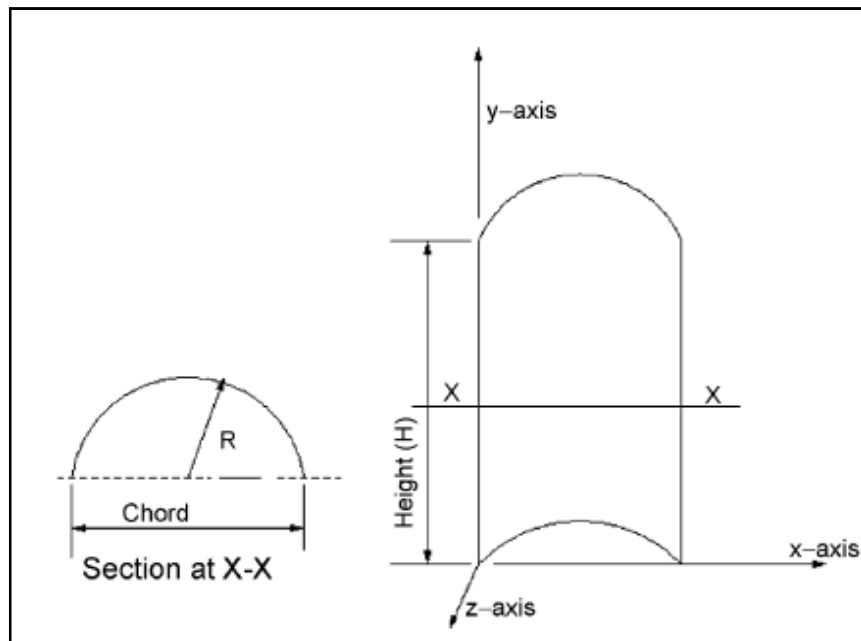
Figure 2 Schematic diagram of a Savonius rotor blade (Source: Saha *et al*., 2008).

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2.1.5. Aspect Ratio

Aspect ratio is a crucial criterion to evaluate the aerodynamic performance of Savonius rotor. Menet (2004) defines aspect ratio, *AR* as the ratio of rotor height, *H* to the rotor diameter, *D*. Iqbal and Alam (2010) found that the turbine efficiency can be improved by design a rotor blade that has higher aspect ratio. Saha *et al*. (2008) agree on this and write that the value of aspect ratio around 4.0 lead to the best power coefficient for Savonius rotor. However, most of the wind turbine is failed to achieve AR of 4.0. Therefore, Johnson (1998) suggests the Savonius rotor is designed with rotor height twice of rotor diameter and this lead to better stability with proper efficiency.

$$= -$$

2.1.6. Overlap Ratio

The overlap ratio represents the overlap distance relative to its chord length. Menet and Bourabaa (2004) declare that overlap ratio will influence the flow structure inside the rotor and consequently its aerodynamic performance. Akwa *et al*. (2011) writes that the smaller the overlap between the rotor blades, the higher the rotor performance. A study shows that the values of overlap ratio in range of 20 % and 30 % of the length chord provide better efficiency for wind turbine (Manet, 2004). Blackwell and Feltz (1977) state that the overlap ratio of 0.10 to 0.15 gives optimum performance.

$$= -$$

2.1.7. Reynolds Number

Kamoji *et al*. (2008) have mentioned that Reynolds number, *Re* for Savonius rotor is mainly based on the rotor diameter.

$$= \overline{}$$

The ρ in the equation represent the density of air, *V* is the wind speed, *D* is the rotor diameter, and μ is the absolute viscosity of air. Paraschivoiu (2002) founds that the turbine performance can be improved by increasing the Reynolds number. Cengel

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and Ghajar (2011) state that the absolute viscosity of air at standard condition (T= 20˚C, P= 1 atm) is 1.825 x 10^{-5} kg/m.s, as shown in **Appendix** . They also write that the flow is considered as laminar if the Reynolds number is below 2 x 10^5 and start becomes turbulent for Reynolds number greater than or equal to 2 x 10^5.

2.1.8. Diameter of the End Plates

Diameter of the end plates, D_f also play an important role to the turbine performance. As stated by Manet (2004), Fujisawa has conducted some experimentally studies and concludes that the higher value of power coefficient can be obtained by designing the diameter of rotor end plates, D_f 10% more than the diameter of the rotor, D.

$$= 1.10$$

2.1.9. Number of Blades

Zhao *et al*. (2009) have studied the effect of number of blades on the performance of Savonius rotor. Many researchers have proved that the higher the number of blades, the higher the performance for most wind turbine. However, Saha *et al*. (2008) and Zhao *et al*. (2009) found that the two-bladed Savonius rotor has higher performance than three-bladed Savonius rotor.

From experiments that done by Zhao *et al*. (2009), the power coefficient of Savonius rotor decreases when the number of blades gets increased from two to three. Figure **3** show the experimental result obtained by Zhao *et al.* (2009).
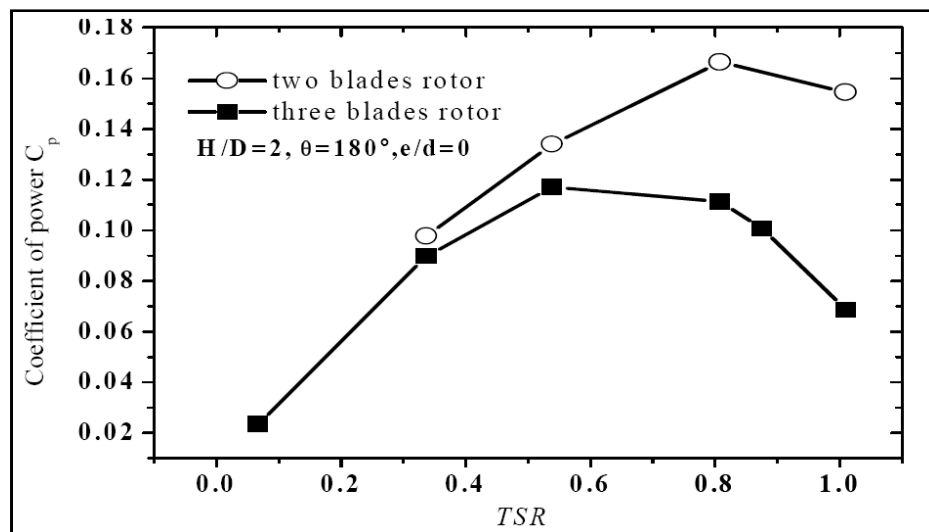
Figure 3 The performance curves of the two and three blades rotor (Source: Zhao *et al.*, 2009).

From _{Figure} **3**, it is obvious that the coefficient of power, C_p for two blades rotor is much higher than three blades rotor in the tip speed ratio of 0.8. Zhao *et al*. (2009) make their result more clearly by conduct the simulation. The simulation results for both two blades and three blades Savonius rotor are shown in _{Figure} **4**. From the figure, it is obviously the downwind pressure surface is bigger for the two blades rotor than the three blades rotor. Meanwhile, the upwind pressure surface gets bigger in three blades rotor because of the following blade existing. Zhao *et al*. (2009) state that to obtain better rotor performance, the rotor should be designed in big downwind surface and the smaller upwind surface. Therefore, two blades Savonius rotor is better than three blades rotor.
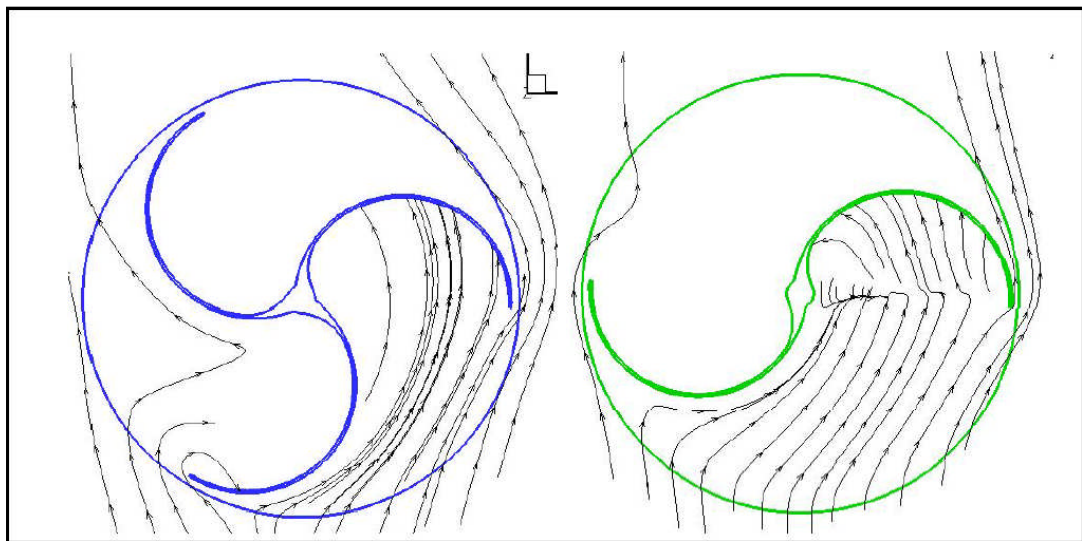
Figure 4 The fluid field of two and three blades rotor (Source: Zhao et al., 2009).

The results of Zhao *et al*. (2009) is supported by Saha *et al*. (2008) that doing the similar experiment before. Saha *et al*. (2008) explain their founding using the phenomenon of air flow: when the number of blades was increased to three, the air strike on one blade get reflected back on the following blade so that the following blade rotates in negative direction as compared to the succeeding blade.

2.1.10. Rotor Blade Material

Manwell *et al*. (2009) found that the reasons damaging the wind turbine blades are aerodynamic loads, moisture absorption, fatigue, and lightning strikes. Therefore, the choice of the material is crucial to determine the performance and cost of the wind turbine.

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2.1.11. Required Properties of Blade Materials

Tangler (2009) and Burton *et al.* (2011) found that the blades must be made from high strength-to-weight ratio and stiffness materials to maintain optimum aerodynamic performance. Other properties are further added by Islam *et al.* (n.d.) such as the following:

- Low cost.
- Corrosion resistant.
- Easy to manufacture.
- Lightweight to minimize loads effect to blade fatigue.
- Provide long term mechanical performance per unit cost.
- Low density for reduced amount of gravity and normal force component.
-

2.1.12. Prospective Material

Many materials have ever been used to manufacture the wind turbine blades, as list out by Tangler (2000) included wood, steel, aluminium, fiberglass, and carbon fibers.

Islam *et al.* (n.d.) reveal that in 1977, woods are used as the major material for wind turbine blade because it is a cheap material. Furthermore, since wood is a nature composite material, it has high strength-to-weight ratio and good stiffness. However, the use of woods in this area is hindered because it's unstable characteristic when deals with moisture.

Manwell *et al.* (2009) propose using aluminium for VAWT blades since VAWT have a constant chord with no twist. However, Tangler (2000) argues that composite such as fiberglass should be used instead of aluminium because aluminium has low fatigue life relative to composite.

Manwell *et al.* (2009) write that fiberglass is the most popular materials used for wind turbine blades construction. The fiberglass composite normally composed of polyester, vinyl ester or epoxy matrix to increase its strength (Tangler, 2000).

Carbon fiber is a competitive material to fiberglass because it posses highest strength-to-weight ratio and stiffness than fiberglass. However, Tangler (2000) founds that the cost of carbon fiber is very high compares to other blade materials. Its difficulty in handling also inhibits its use for wind turbine blades.

2.1.13. Wind Turbine Loads

Manwell *et al*. (2009) define loads as the forces or moments that may act upon the turbine. The loads are the primary elements concerning in wind turbine blades design. According to Manwell *et al*. (2009), there are five types of wind turbine loads as shown in Table **1**.

Table 1   Wind turbine loads (Source: Manwell *et al*., 2009).

No.	Load	Definition	Sources
1.	Steady (Static and rotating)	Static loads are loads that react on a non-moving structure whereas rotating loads react with the moving structure. For example, a wind blowing on a stationary wind turbine would induce static loads whereas a wind blowing on a rotating wind turbine rotor while it is generating power would induce steady rotating loads on the blades.	• Mean wind. • Rotation of the rotor.
2.	Cyclic	Cyclic loads refer to the loads which arise due to the rotation of the rotor.	• Wind shear. • Gravity. • Rotation of the rotor.
3.	Stochastic	Stochastic loads are time varying, as are cyclic, transient, and impulsive loads.	• Turbulence. • Rotation of the rotor.
4.	Transient	Transient loads only occur in occasionally and are associated with	• Wind gusts. • Change in

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		starting and stopping.	wind direction • Starting / stopping. • Pitch motion. • Teetering.
5.	Resonance-induced	Resonance-induced loads are cyclic loads that result from the dynamic response of some part of the wind turbine being excited at one of its natural frequencies. Resonance-induced loads should be avoided. However, it may occur under unusual operating circumstances or due to poor design.	• Structure. • Excitation. • Turbulence. • Rotation of the rotor.

2.2. Design of the Savonius Rotor Blade

2.2.1 Wind Speed Data Analysis

Wind speed is the major element that affects the power output. The wind speed data is gathered from a reliable website, which is Weather Underground from November 2010 to October 2011 (12 months). Table **2** shows the data collected in that period. The location is set at Melaka, Malaysia.

Table 2 Wind speed distribution from November 2010 to October 2011 (12 months) at Melaka, Malaysia (Source: Weather Underground, 2011).

Year	Month	Wind Speed Observation	Wind Speed (m/s)		
			Min	Max	Avg
2010	November	1	0	6.38	1.67
	December	2	0	7.22	1.67
2011	January	3	0	7.22	2.5
	February	4	0	7.22	2.78
	March	5	0	6.39	1.94
	April	6	0	5.83	1.94
	May	7	0	6.39	1.39
	June	8	0	5.83	1.67
	July	9	0	5.83	1.67
	August	10	0	6.39	1.67
	September	11	0	5.83	1.67
	October	12	0	5.28	1.39
		$\sum$	0	75.81	21.96

The wind speed distribution is presented graphically in Figure **5**. Form the data collected above, the average wind speed is generally in the range of 1.39 m/s to 2.78 m/s.
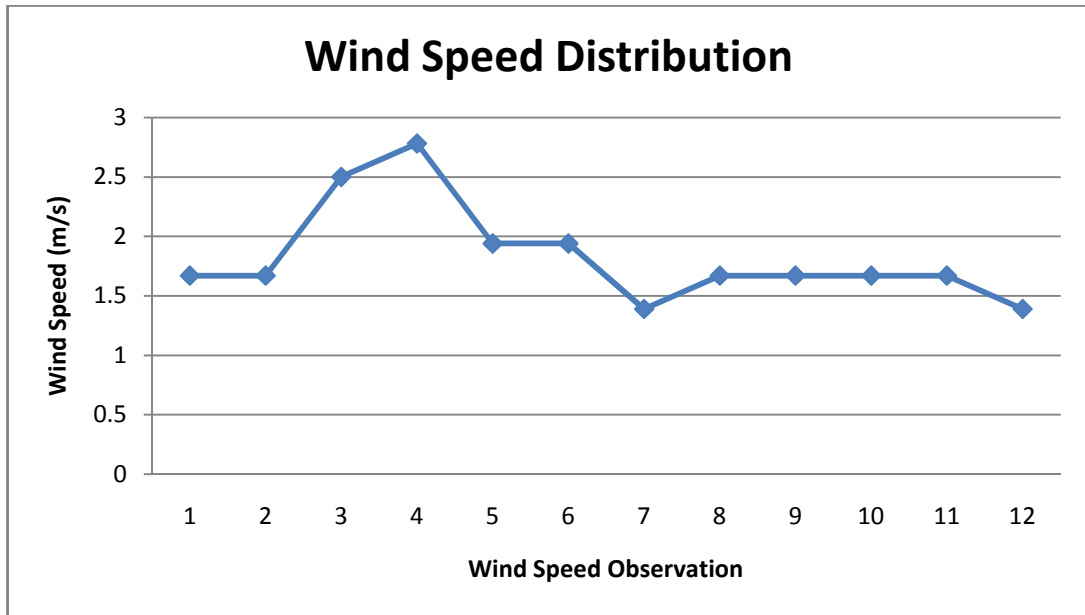
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Figure 5 Wind speed distribution from November 2010 to October 2011 (12 months) at Melaka, Malaysia

According to Manwell *et al*. (2009), the average wind speed V_{avg}, over the total period of a year data collection is:

$$V = \frac{1}{N} \sum V_i$$

$$= \frac{1}{12}(21.96)$$

$$= 1.83 \ m/s$$

Where,

V_{avg} = Average wind speed of a year

$V_{i,}$ = Average wind speed of a month

N = Number of wind speed observation

Based on the result above, the average wind speed of a year is 1.83 m/s. According to Vanek and Albright (2008), the minimum wind speed required for wind turbine to operate is 4 m/s. Hence, the average wind speed of Melaka is too small to generate wind power. Otherwise, the wind turbine must be build with very high tower.

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However, Aziz, (2011) found that the wind speed of Malaysia could reach up to 15 m/s during the monsoon season. To proceed for the design stage, the wind speed of 7 m/s is used as average wind speed in this project.

2.2.2 Wind Speed Parameters

The three wind speed parameters involve in this project is cut-in speed, rated wind speed and cut-out speed. All these parameters are depended on the value of average wind speed. The average wind speed, V_{avg} is 7 m/s. Table **3** summarizes the value of these three wind speed parameters.

Table 3 Value of cut-in speed, rated wind speed, and cut-out speed.

Wind Speed Parameter	Equation	Calculation
Cut-in speed,	= 0.5	= 0.5 (7 /) = 3.5 /
Rated wind speed,	= 1.5	= 1.5 (7 /) = 10.5 /
Cut-out speed,	= 3	= 3 (7 /) = 21 /

The three wind speed parameters are used to construct the power curve, which is to characterize the response of the wind turbine. Different model of wind turbine has different response. This is important for user to predict the power production and efficiency over long periods of time. Figure 4.2 display the power curve of the Savonius wind turbine for this project. The power curve performance data is shown in **Appendix**. From Figure **6**, the Savonius rotor start produces power at wind speed of 3.5 m/s and stop operating when the wind speed reached 21 m/s. Figure **6** has verified the statement of power is proportional to the cube of wind speed, $P\alpha V^{3}$, if the wind speed is lower than the rated speed. The power output reached maximal at the rated wind speed of 10.5 m/s and become constant at the wind speed in range of rated speed and cut-out speed. Since the power output reached maximum at rated speed, thus the wind speed of 10.5 m/s is used in the coming calculation.
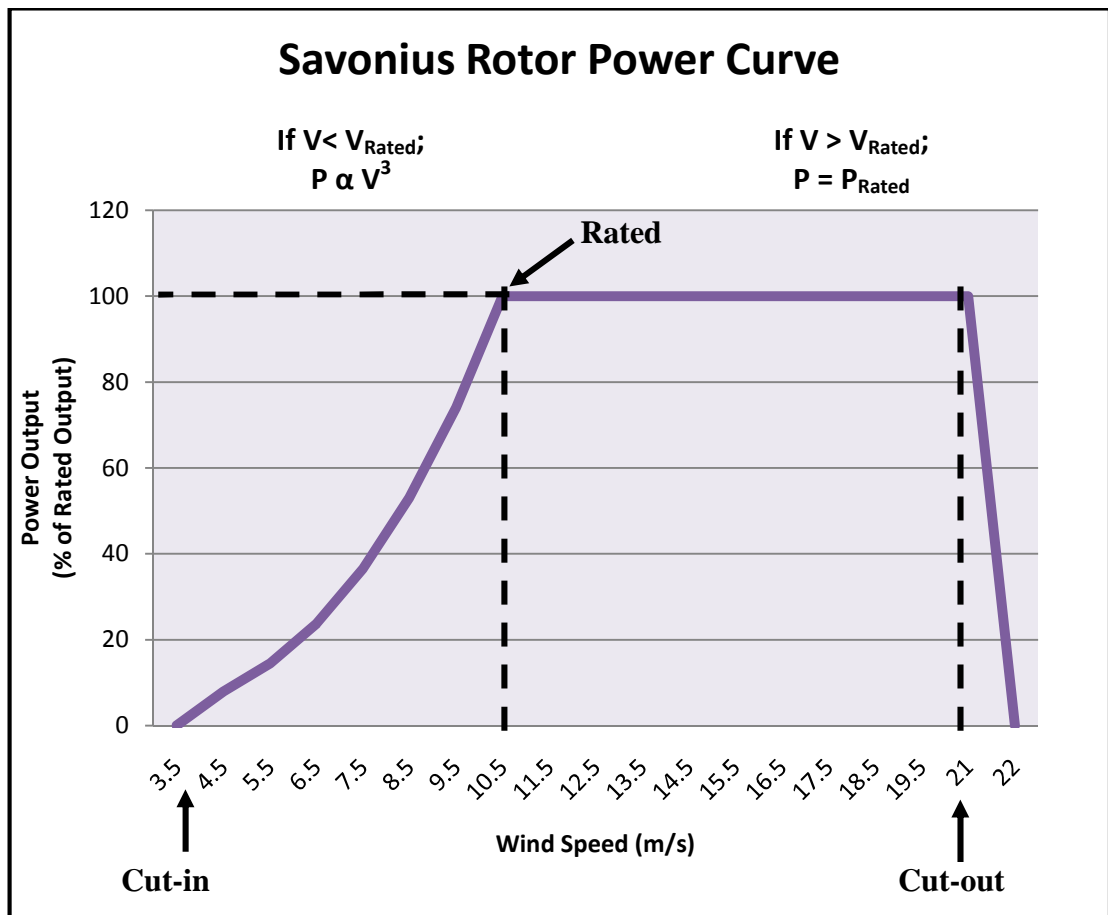
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Figure 6 Savonius rotor power curve at average wind speed of 7 m/s.

2.2.3 Detail Design

To determine the diameter and height of the Savonius rotor blade, the swept area, *A* is first determined from the equation of output power. In this project, the power coefficient C_p value used is 0.30, which is the maximum power coefficient for Savonius wind turbine. The air density is 1.225 kg/m^3 for standard condition and the rated wind speed is 10.5 m/s.

$$= \frac{1}{2}$$

$$5000 = \frac{1}{2}(0.30)(1.225 \quad / \quad) \quad (10.5 \quad / \ )$$

$$= 23.5058$$

The swept area for Savonius wind turbine is multiplication of rotor diameter, *D* and the rotor height, *H*. Both rotor diameter and rotor height is unknown in this equation.

Trial and error method is used to define the rotor diameter and rotor height and the value is rounded up. The value of rotor diameter and rotor height is verified by Aspect Ratio. This means that the value of rotor diameter and rotor height only valid if the Aspect Ratio, *AR* is acceptable.

$$= .$$

Seven groups of data is created and calculated for the aspect ratio to see the possibility for used. Table **4** summarizes the aspect ratio for each combination of data.

Table 4 Value of rotor diameter, rotor height and aspect ratio.

Trial and Error Set	Rotor Diameter, D (m)	Rotor Height, H (m)	Aspect Ratio, = /
1	2.0	12.0	6.00
2	2.5	9.5	3.80
3	3.0	8.0	2.67
4	3.5	7.0	2.00
5	4.0	6.0	1.50
6	4.5	5.5	1.22
7	5.0	4.5	0.90

According to Iqbal and Alam (2010) and Saha *et al.* (2008), the higher the aspect ratio, the higher the starting torque and thus improve the turbine efficiency. From Table **4**, Set 1 has the highest value of aspect ratio, which is 6.00. However, the small rotor diameter makes smaller base support for a high rotor body. This induces to stability problem and hence this set of data is not chosen. Johnson (1998) suggests the Savonius rotor with rotor height twice of rotor diameter lead to better stability and efficiency. From Table 4.3, data of Set 4 give the aspect ratio of 2. Therefore, the rotor diameter and rotor height are set as 3.5 m and 7 m respectively in this project.