ACKNOWLEDEMENTS

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LIST OF ABBREAVIATION

HAWT	: Horizontal Axis Wind Turbine
VAWT	: Vertical Axis Wind Turbine
PM	: Permanent Magnet
EDM	: Electron Discharge Machine
Cp	: Coefficient of Performance
NACA	: National Advisory Committee for Aeronautics
MMF	: Magneto Motive Force
AC	: Alternate Current
TSR	: Tip Speed Ratio
C_l	: Coefficient of Lift
C_d	: Coefficient of Drag
Re	: Reynolds's Number

PENGOPTIMUMAN KINCIR ANGIN BERPAKSI MENDATAR UNTUK HALAJU ANGIN RENDAH

ABSTRAK

Kebanyakan kincir angin komersial direka untuk halaju angin yang tinggi (>10 m/s). Ini menyebabkan ia tidak sesuai untuk digunakan di kebanyakan kawasan Asia Tenggara yang terletak dalam kawasan angin berhalaju rendah. Tujuan kajian ini adalah untuk mengoptimumkan kincir angin berskala kecil dan mesin janakuasa untuk kawasan angin berhalaju rendah terutamanya di Malaysia. Sebuah mesin janakuasa magnet kekal fluks jenis paksi telah direka dan dibangunkan. Mesin janakuasa ini mampu menghasilkan kuasa elektrik sebanyak 200W pada laju putaran 300 rpm. Kincir angin yang mempunyai 3 bilah berdiameter 4.6m ini dikaji melalui faktor sudut serangan bilah dan rintangan yang dikenakan. Bilah kayu kincir angin ini menggunakan profil NACA 4415. Sejumlah 16 kombinasi rintangan dan sudut serangan telah dijalankan. Kajian ini dijalankan di atas bumbung bangunan Pusat Pengajian Kejuruteraan Mekanik yang merupakan kawasan angin berhalaju rendah. Satu peranti perekod data telah digunakan untuk merekod data kuasa, suhu, halaju angin serta arah angin. Sepanjang tempoh kajian selama 2 bulan, purata halaju angin ialah 0.2 m/s dengan kuasa puncak pada halaju angin 3m/s serta halaju angin maksimum setinggi 9m/s direkodkan. Purata kuasa harian sebanyak 150Wh telah dicatatkan. Pada sudut serangan 9 darjah dan rintangan 6 ohm, kincir angin ini menghasilkan kuasa maksimum sebanyak 200W pada halaju angin 4.2m/s. Pekali prestasi kincir angin ini ialah 0.27.

OPTIMIZATION OF HORIZONTAL AXIS WIND TURBINE FOR LOW WIND SPEEDS

ABSRACT

Most commercial wind turbines are designed for high wind speeds (>10m/s) making them inappropriate for use in most areas of South East Asia which are located in a low wind speed region. The purpose of this work is to optimize a small wind turbine and generator for lower wind speeds prevalent in Malaysia. An axial flux permanent magnet generator was designed and developed. This generator was optimized to achieve high power at low rotational speeds. The generator is capable of producing 200W of electrical power at a rotational speed of 300rpm. Wind turbine is investigated as a function of angle of attack and load on a 4.6 m diameter 3–blade horizontal axis wind turbine. The wooden blades used a NACA (National Advisory Committee for Aeronautics) 4415 profile. A total of 16 various combinations of load and attack angle were carried out. These tests were performed with the turbine mounted atop of the Mechanical Engineering building which is located in a representative low wind speed region. A data logger was used to collect power, temperature, wind speed and wind direction data. In a 2 month study, the average wind speed was 0.2m/s with peak power wind speed of 3m/s and a maximum wind speed recorded was 9 m/s. Average daily energy production of 150Wh was recorded. A 9 degree angle attack and 6 ohm load produced the maximum power of 200W at 4.2m/s wind speed. The coefficient of performance of the wind turbine was measured to be 0.27.

CHAPTER ONE

INTRODUCTION

1.0 Background

Alternative energy such as wind power has started to gain more attention as crude oil production is climbing to its peak. From the Figure 1.1, we notice that the world oil production is near its peak at year 2007 and soon we will face a rapid decline (BEODOM,2006). Wind energy is free, clean and endless. Today, the cost of the electric produced from wind turbines is still not competitive with fossil based power in our country. However for the future, it will be a wise investment as soon the crude oil around the world will begin running out.

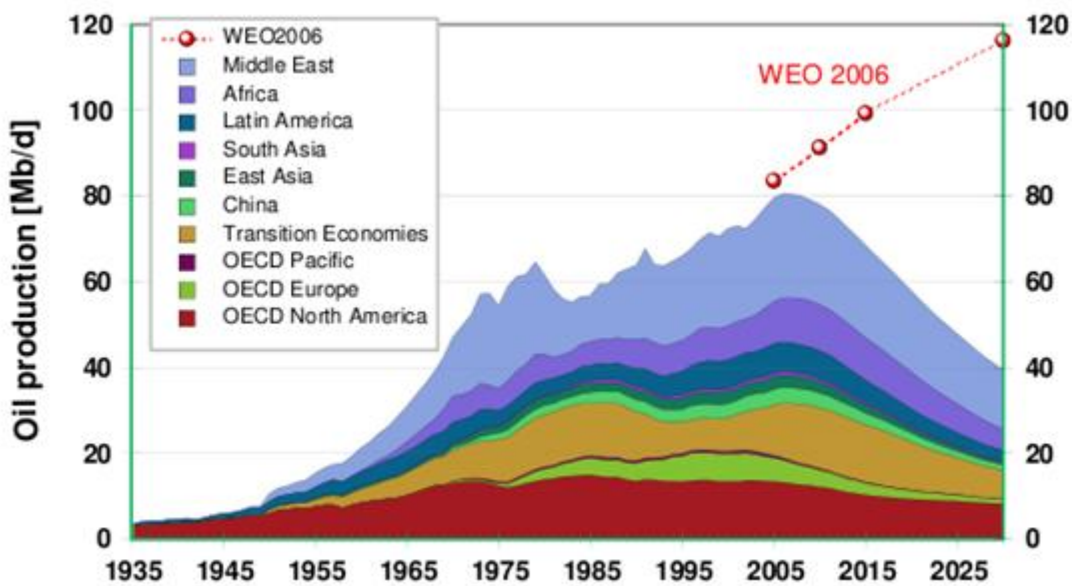

Figure 1.1 World Oil Productions 1935-2025 (BEODOM)

A wind turbine is a machine that converts the wind's kinetic energy into mechanical kinetic energy. In the old days, wind turbines were used for grain-grinding, water pumping, etc.

The first known electricity generating windmill operated was a battery charging turbine installed in 1887 by James Blyth in Scotland (Price, 2005). Ever since then, wind turbines have played a role in providing electric power.

There are 2 major types of turbines geometries; horizontal axis wind turbine (HAWT) and vertical axis wind turbine (VWAT). HAWT have their axis of rotation horizontal and parallel to the wind stream. Typically HAWTs will have lower cut in speed and higher power coefficient compared to VAWTs. These advantages make it the best choice for low wind speeds (Piggott, 2001). By optimizing the blade shape, higher efficiency is achievable when aerodynamic lift is exploited to a maximum degree. Most turbine blades use NACA airfoil shapes. A HAWT can be single bladed, 2 bladed, 3 bladed or even multi bladed. For VAWT, the axis of rotation is vertical and thus perpendicular to the wind direction.

In terms of power we can divide the wind turbines into 2 categories, utility scale wind turbines and small scale wind turbines (Hazen, 1996). For utility scale wind turbines, the rating of the turbines will be usually 100kW or more. While for small scale wind turbines, the rating of the turbines will be in the range below 100 kW. Most of the small wind turbines are designed with higher tip speed ratio compared to large wind turbines, thus their rotational speed become very high (Ameku et al., 2008). This makes them potentially noisy and dangerous under strong winds.

Malaysia generated around 21,817MW of electricity in 2009. 87% of the electricity was supplied by thermal generation while 13% was generated by hydro generation (Energy Commission Annual Report 2009). The cost of the electricity is expected to rise higher in the future along with crude oil price as most of our electricity are generated through burning coal, diesel and methane. Hydroelectric generation is an excellent option for electric generation. However, hydro plants may endanger large areas of eco system surrounding their dams. Hence non-hydroelectric renewable energy is becoming a new trend in the power generation field. Malaysia is located at the center of South East Asia. We are surrounded by Indonesia to the west, south and south east. Hence most of the places in Malaysia do not have high wind except certain spot located in east cost of peninsular like Pontian (mean wind speed is 3.31 m/s), Kuantan (mean wind speed is 2.42m/s and Kuala Terengganu (2.41m/s) (Bawadi, 2005).

1.1 Problem Statements

In order to utilize wind power in Malaysia, a low wind speed wind turbine is needed. Most commercial wind turbines are designed for high wind speeds (>10m/s) making them inappropriate for use in Malaysia. A new blade profile and suitable generator need to be designed and developed to produce a high efficiency of low wind speed wind turbine. Figure 1.2 shows power output of various brands of commercial wind turbine operating at Malaysia wind conditions. It clearly shows that these turbines are not able to capture a majority amount of the wind energy at low wind speeds. These turbines start producing higher power at higher wind speed as the power output is proportional to the ${V_{wind}}^3$. A special low wind speed turbine is proposed in order to produce significant power even at low wind speeds. The proposed wind turbine is predicted to produce 80W of power at wind speed of 3 m/s compare to BWC XL.1 (20W), Cyclone (27 W) and Navitron (36W). The proposed wind turbine won't be able to produce power as high as the other turbines at higher wind speeds (e.g. 10m/s) as the blades of the low wind speed wind turbines are designed to cut in at low speeds and will therefor stall at lower speeds than the high speed turbines.

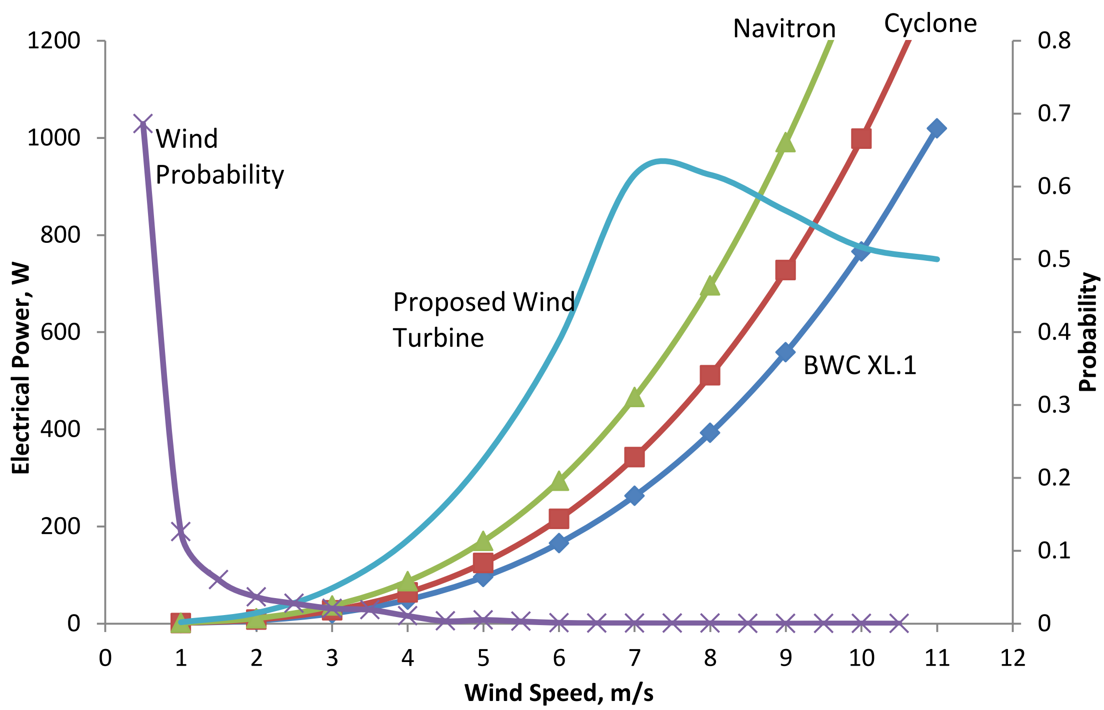

Figure 1.2 Wind Turbine Power and Wind Speed Probability vs Wind Speed at Wind Test Site

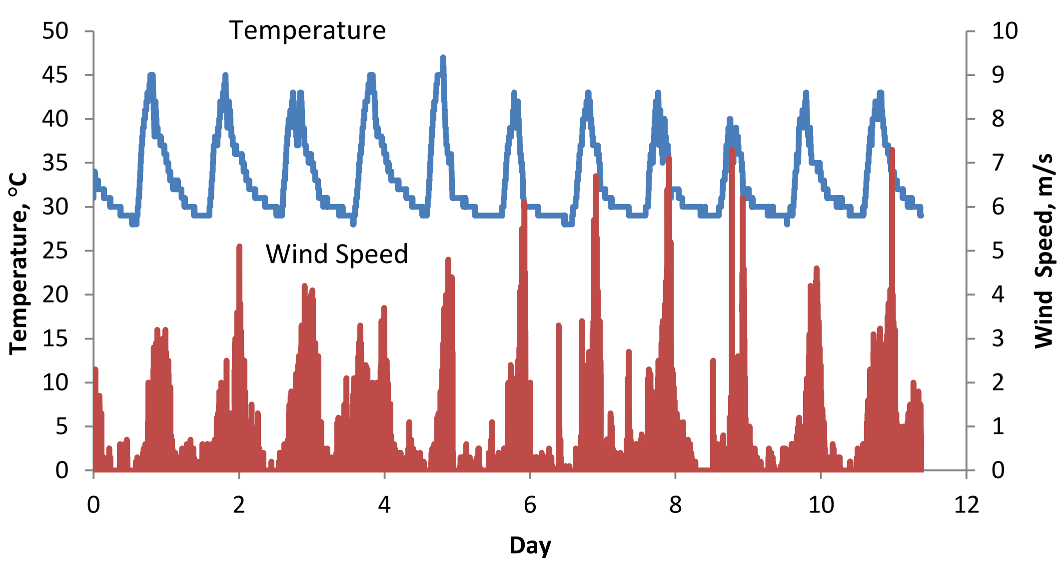

Figure 1.3 Temperature and Wind Speeds at the USM Mechanical School

Over Several Days

Figure 1.3 shows the peak temperature is 45℃ during day time and minimum temperature is 29℃ at night. Most of the time the wind speeds is below 2m/s. Due to the small variation in temperature, the atmosphere thermal pumping is low. This contributes to the low wind speeds atop the Mechanical School building at USM.

1.2 Scope of Work

The ideal wind turbine should be small, save cost and have better efficiency at low wind speeds then existing design. To design and develop a good performance low speed wind turbine, studies and good works need to be focus in the following areas:

I. Study the available wind data

II. Choose the proper wind turbine's blade profile

III. Generator design and performance optimization

IV. Tower assembly, data logger and controller set up for overall system optimization testing and verifications

1.3 Research Objectives

The objectives of this research are:

I. To analyze the wind data from USM's wind test site which is located on Banjaran Relau at an altitude of 400m above sea level (shows in Figure 1.4 and Figure 1.5)

II. Design and verify low wind speed turbine blades.

III. Design a generator which is optimized for a low wind speed wind turbine.

IV. Commercial analysis and economic comparison between optimized wind turbine and commercial high wind speed turbine.

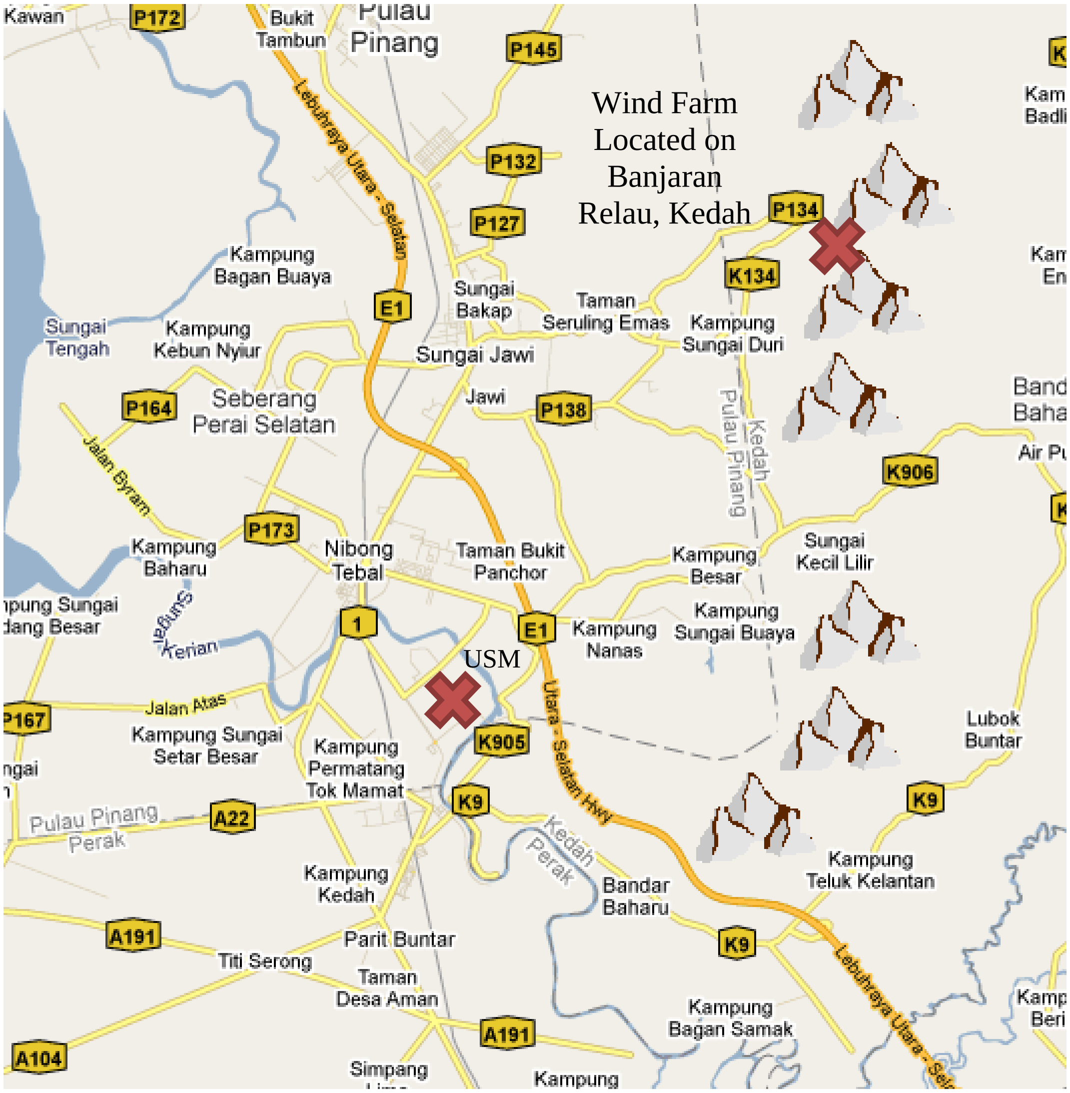

Figure 1.4 Wind Farm Location

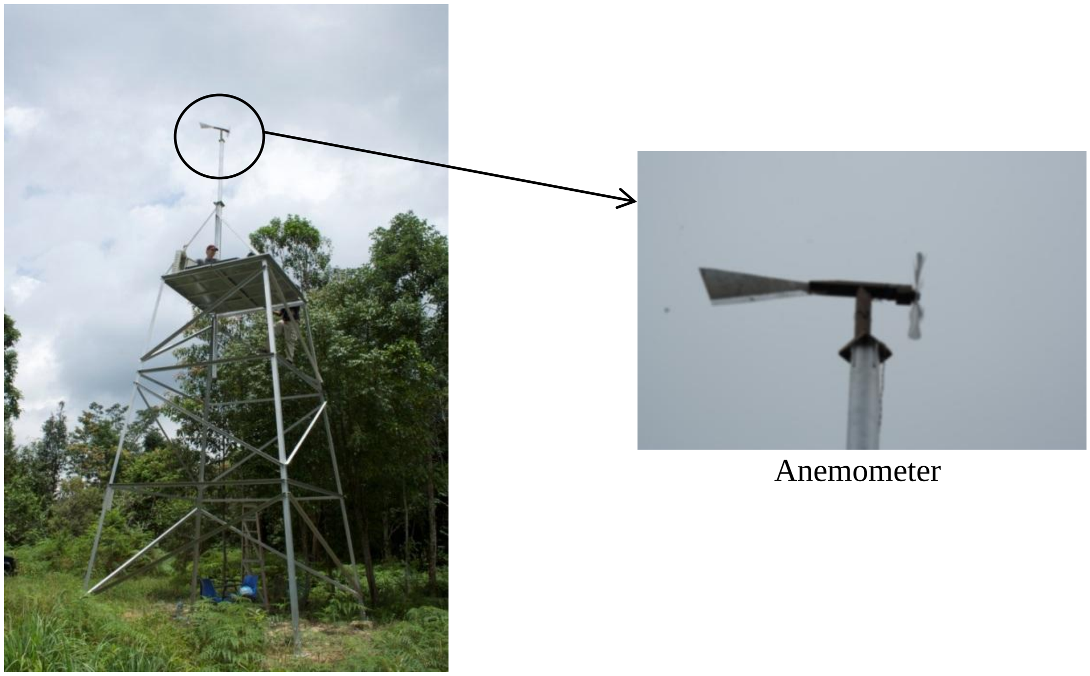

Figure 1.5 Turbine Tower at Wind Test Site Located at Banjaran Relau

1.4 Thesis Scope

This thesis is organized in 6 primary chapters which included introduction, literature review, methodology, results and discussion and finally is conclusions. The first chapter has introduced briefly on the wind situation in Malaysia and the problem. The objectives and thesis outline are also included in this chapter.

In chapter 2, literature on the history of wind turbines and wind speeds in Malaysia are reviewed. The types of wind turbines and blade profiles are also discussed. The types of generators and the potential problems of the generator are included in this chapter.

In chapter 3, the methodology of modeling the generator and wind turbine are explained. This part is also includes the steps in fabricating blades, generator and the support structure of the wind turbine.

In chapter 4, the results of generator and wind turbine studies are shown. Additionally the detail discussion of the results is presented.

In chapter 5, conclusions and future works for this project are presented

CHAPTER TWO

LITERATURE REVIEW

2.0 Introduction

In this chapter, a review of the wind turbines is presented based on published data. The review focuses on both the angel attack of the wind turbine blade and the research on the generator. The optimization of the generator will be briefly discussed at the end of this chapter.

2.1 Wind Energy

The first turbine was built in Sistan, region between Afghanistan and Iran during 7th century [Hassan & Hill, 1996]. Wind turbine had started to gain more attention as the crude oil production is near its peak. From Figure 2.1, we notice that the world oil production is on its peak and soon we will face a rapid decline (Chefurka, 2007). Wind energy is free, clean and endless. Today, the cost of the electric produced from wind turbines is higher than fossil based power in most of the countries. However for future, it will be a good investment as soon the crude oil price is running high around the world as crude oil will be running out.

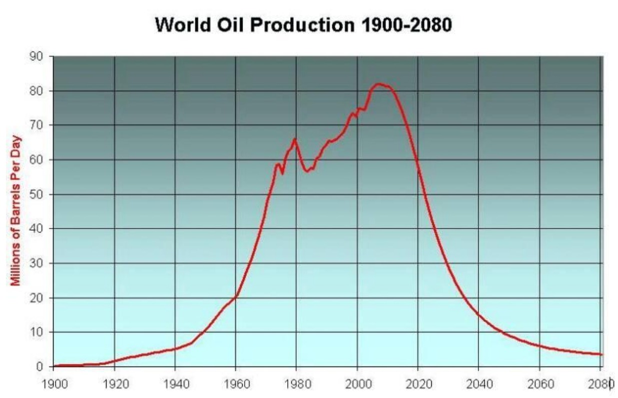

Figure 2.1 World Oil Productions 1900-2080 (Chefurka, 2007)

The energy in wind comes in the form of kinetic energy of large masses of air moving over the earth's surface. The turbine is used to transform wind's kinetic energy into shaft power. The air density and the air velocity determine the amount of the energy in the wind. The equation of the wind energy is given in Equation 2.1.

$$E_{wind} = \frac{1}{2} m V_{wind}^2 \qquad (2.1)$$

Where m is the mass of the air in kg and V is the wind speed in m/s.

The power that the turbine is able to capture depends directly on the blade sweep area, A. The equation of air volume, Vol, interacting with the rotor at velocity, V_{wind}

$$Vol = A \cdot V_{wind} \qquad (2.2)$$

Hence the equation of wind power that passing through an area, A is

$$Wind\ power = \frac{1}{2} \rho A V_{wind}^3 \qquad (2.3)$$

Due to inefficiency of wind turbine, a power coefficient, Cp needs to be added into the above equation. The actual power output equation will then become

$$Turbine\ Power = \frac{1}{2} C_p \rho A V_{wind}^3 \qquad (2.4)$$

2.2 Betz Theory

When the air is passing through a rotating wind turbine, the air must be slowed down. If we extract 100% of energy, the air will be stopped. This will cause pile-up of stationary air at the wind turbine blocking further wind from reaching the turbine (Johnson, 2006; Piggott, 2001). So air must escape with some speed causing some loss in energy. According Betz theory, a wind turbine is only able to capture 59.3% of the total wind kinetic energy; this value also represents the maximum power coefficient of a wind turbine, Cp (Hau, 2006; Lee & Flay, 1999).

$$c_p = \frac{power\ output\ from\ wind\ turbine}{power\ available\ in\ wind} \tag{2.5}$$

2.3 Wind Turbine Introduction

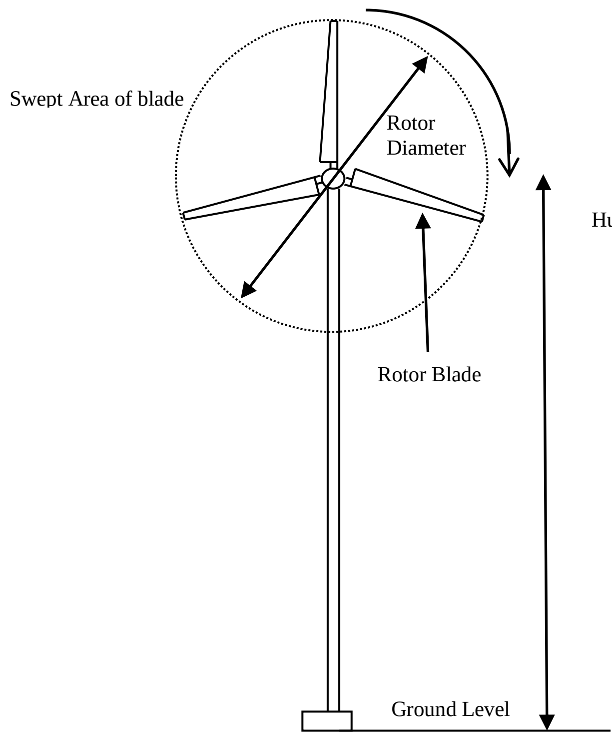

Figure 2.2 Wind Turbine Structure

Figure 2.2 shows the common structure of wind turbine. Normally a wind turbine consists of a set of blades, a generator and a tail. The blades are to capture the kinetic energy in the wind and change it become shaft power. The generator transforms the shaft power into electric power. The tail's function is to make sure that the wind turbine is always oriented toward the wind direction and maybe used to steer it away if there is a big gust. The number of blades is related to the wind turbine functions as shown in the Table 2.1(Piggott, 2001). When the number of blades is increased, the rotational speed will decreased but the mechanical torque will increased.

Table 2.1 Table of No. of Blades and Functions [Piggott ,2001]

Tip Speed Ratio (TSR)	No. of Blades	Common Applications
1	6-20	Slow pumps
2	4-12	Faster pumps
3	3-6	Mechanical pumps
4	2-4	Slow generator
5-8	2-3	Generators
8-15	1-2	Fastest possible

The TSR (tip speed ratio) is defined as the ratio between linear speed of the tip of the speed of turbine and wind velocity (Erich, 2006; Mathew, 2006; Rahim et al.)

$$TSR = \frac{Linear\ Speed\ of\ Tip}{WInd\ Velocity} \qquad (2.6)$$

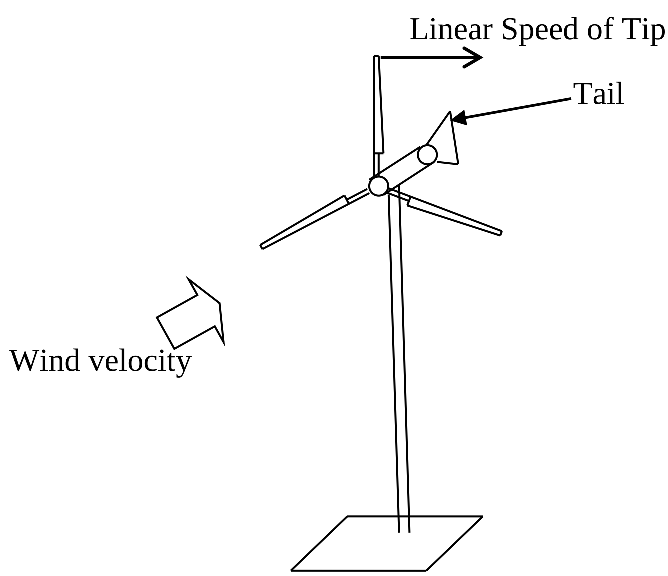

Figure 2.3 Wind Turbine

The value of TSR will directly affect the coefficient of performance (C_p) of the wind turbine. From the Figure 2.4, we can see that the power increases with TSR and reaches a peak at TSR of around 8 with C_p 0.4 and then it starts decreasing. When the TSR value is increasing, the ability of the wind turbine to capture more wind in a time increases, so the efficiency increased. As the TSR value increases past 6, the C_p starts to drop as the blades are spinning at a very high rotational speed. Blade will act like a fan pulling the wind in rather than being driven by it. Hence the efficiency will drop. For a high efficiency horizontal axis wind turbine (HAWT), the optimum TSR value will typically be around 6-7 (Johnson, 2006).

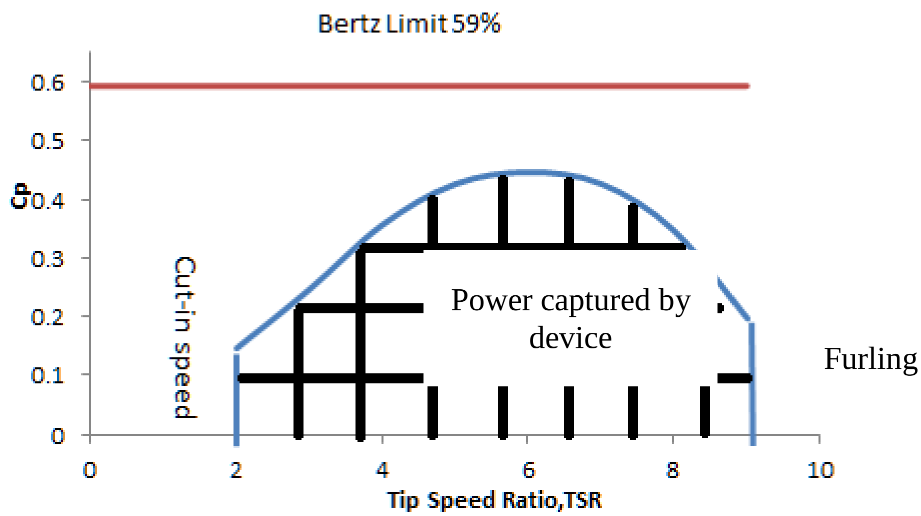

Figure 2.4 C_p vs TSR Value

2.4 Wind Sources

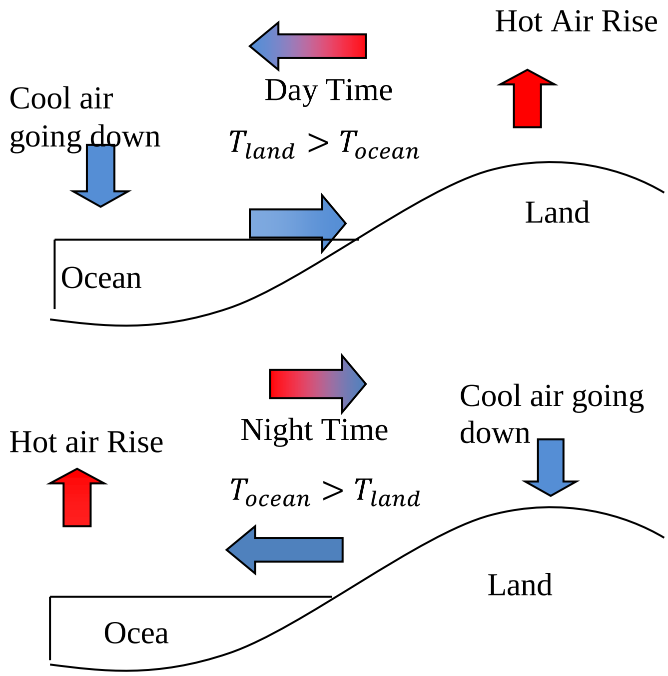

Figure 2.5 Marine Layers Pumping during Day Time and Night Time

Wind is large scale movement of air from one place to another place. Often high velocity wind sites are located near the sea and the mountain. Figure 2.5 shows the marine layers pumping during day time and night time. During the day time, the temperature of the earth rises and causes some low pressure region. As a result, the cooler breeze from the sea is blown to the coast area. At night, due to specific heat values, the earth cools faster than the sea. Hence the temperature of sea is higher than the earth and causing low pressure regime at the sea. This makes the wind blow from earth to the sea.

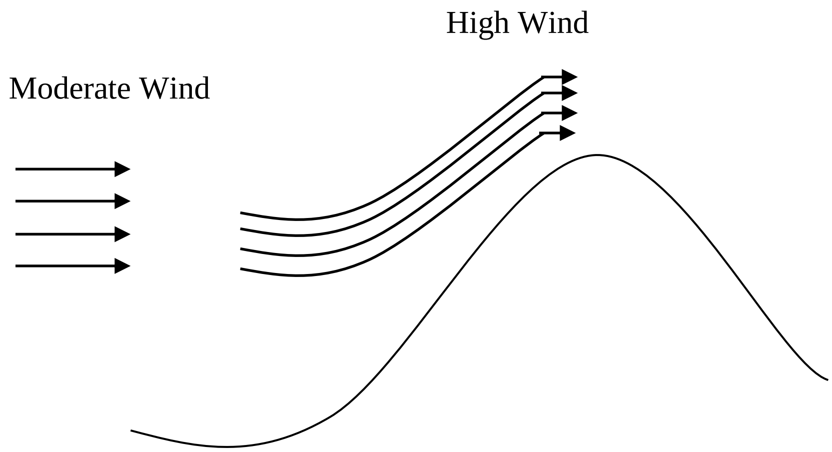

Figure 2.6 Winds Concentration Passing Over a Mountain

Mountains create a wind concentration as the air passed over the peak which is shown in Figure 2.6.

Wind speeds at heights 50m to 250m above ground level are suitable for conversion into electrical power (Jarass et al, 1981). Wind turbines typically produce energy only when the wind speed between 3m/s and 25 m/s. (Kurtulmus et al, 2007). Most of the annual average wind speeds in America are higher than 4m/s. (US Department of Energy). While for Europe countries, their wind speed lies between 3.5m/s and 5m/s. (Troen & Petersen, 1989). For Asia, most of the countries are having average 4m/s wind speed except for certain coast in Shanghai, Japan, India and Jakarta as they are facing the ocean and will have higher wind speed. Most of the wind turbines manufacturers are from America, Europe and China. Hence the wind turbines that they produce are suit mostly for the high wind speed in their countries.

Figure 2.7 shows the monsoon phenomena Malaysia is located in the center of the South East Asia. Malaysia is surrounded by the Sumatera Island and face directly to the South China Sea. There are 2 monsoon seasons throughout the year. From June until September Malaysia face the South West monsoon. At this period the area around Australia is in winter season while the Asian countries are facing the summer season. The high pressure air at area near of Australia move to the Asia through the Khastulistiwa line and head toward Asia mainland. Malaysia doesn't face any high speed wind as we are surrounded by Sumatera and Jawa Islands. From November until February, the North Asian faces winter season especially at the Siberia area. This breeze blow from Siberia to the mainland of China and were turned to become North East monsoon to Australia. At this time, as the east coast of the Malaysia is facing directly to the South China Sea and receives a lot of wind compare to the South West monsoon. Hence, the east coast of Peninsular Malaysia, Sabah and Sarawak are having higher wind speed compare to the west coast of Peninsular Malaysia (Troen, I. and Petersen.E.L.1989).

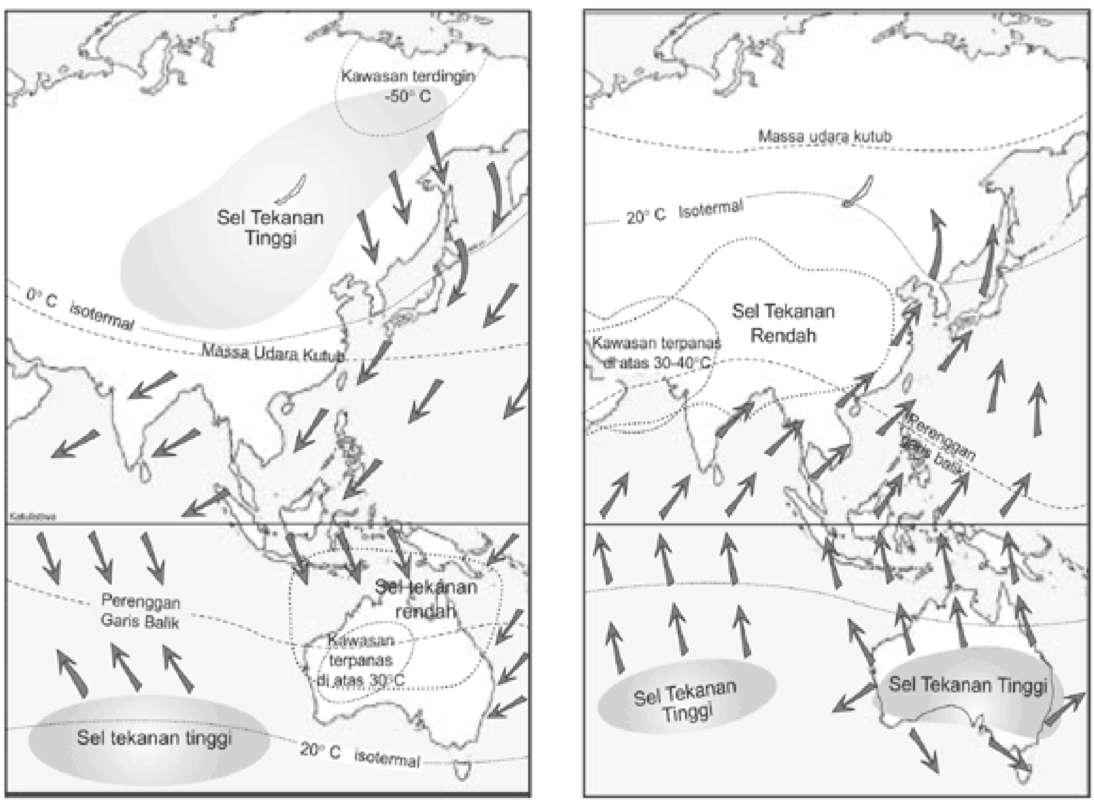

Figure 2.7 North East Monsoon (left) and South West Monsoon (right) in Malaysia. (Australia-Indonesia Institute)

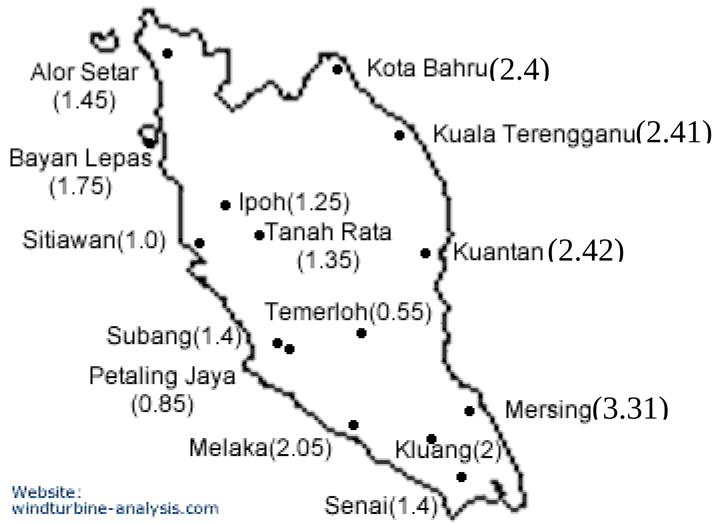

Figure 2.8 Annual wind speed at 18 meteorological stations in Peninsular Malaysia (windturbine-analysis.com)

Extensive researches have been carried out to determine the most suitable wind site in Malaysia (Phd Bawadi, 2005). Those analyses have taken about 7 to 8 years' to collect hundreds thousands of data points. Figure 2.8 shows the annual wind speed at 18 meteorological stations located in Peninsular Malaysia. There is little wind in the west coast of Malaysia due to geographical constrains, hence most of the stations chosen will be on the east coast of peninsular Malaysia and Sabah. The wind speeds at these locations are shown in the below table.

Table 2.2 Location of Wind Station

Station	Altitude	Mean Wind Speed, m/s	Mode Wind Speed, m/s
Cameron Highland	1545m	3.08	0.00
Kota Bharu	4.6m	2.40	0.00
Kota Kinabalu	2.3m	2.40	2.47
Kuala Terengganu	5.2m	2.41	0.00
Kuantan	15.3m	2.42	0.00

Mersing	43.6m	3.31	3.08
Pulau Labuan	29.3m	3.00	0.00

From the Table 2.2, wind speeds in most of the places in Malaysia are lower than the wind turbine manufacturing countries. Hence, the wind turbine that manufactured by those countries may not suit to our wind conditions.

2.5 Rotor Design

Wind turbines are mechanical devices designed to convert a portion of the kinetic energy in the wind into mechanical energy which is then converted into electrical power with the help of a generator. There are 2 major types of turbine geometries, horizontal axis wind turbine (HAWT) and vertical axis wind turbine (VWAT).

2.5.1Horizontal Axis Wind Turbine (HAWT)

These types of wind turbines have their axis of rotation horizontal to the ground and almost parallel to the wind stream. Typically HAWTs will have lower cut in speed and higher power coefficient compared to VAWTs. These advantages make it the best choice for low wind speed (Piggott, 2001). By optimizing the blade shape, higher efficiency is achievable when aerodynamic lift is exploited to a maximum degree. Most turbine blades use NACA airfoil shape. A HAWT can be single bladed, 2 bladed, 3 bladed or even multi bladed. The numbers of blades are depending on the wind turbine function just as stated in Table 2.1.

Single bladed turbines are less common in wind turbines as they are prone to have balancing and stability problems although these types of turbines are cheaper. Most of the time, a counter weight has to be placed at the opposite to the blade to counter balance the centrifugal force. Unbalanced blades will cause unwanted vibration and increase stress on the bearing and the shaft of the turbine. Two bladed rotors will have less vibration compare to the single bladed. When the blades are in vertical position, the unbalance force between blades become more critical as there is different in wind speed between the top and the bottom of the turbine swept area. Besides, when the turbines are heading wind direction, the turbine tends to swivel. This happen as turbine need to overcome higher inertia as it is spinning fast. Hence, most of the time a 3 bladed rotor is more preferable as the aerodynamic loading is more uniform.

2.5.2 Vertical Axis Wind Turbine (VAWT)

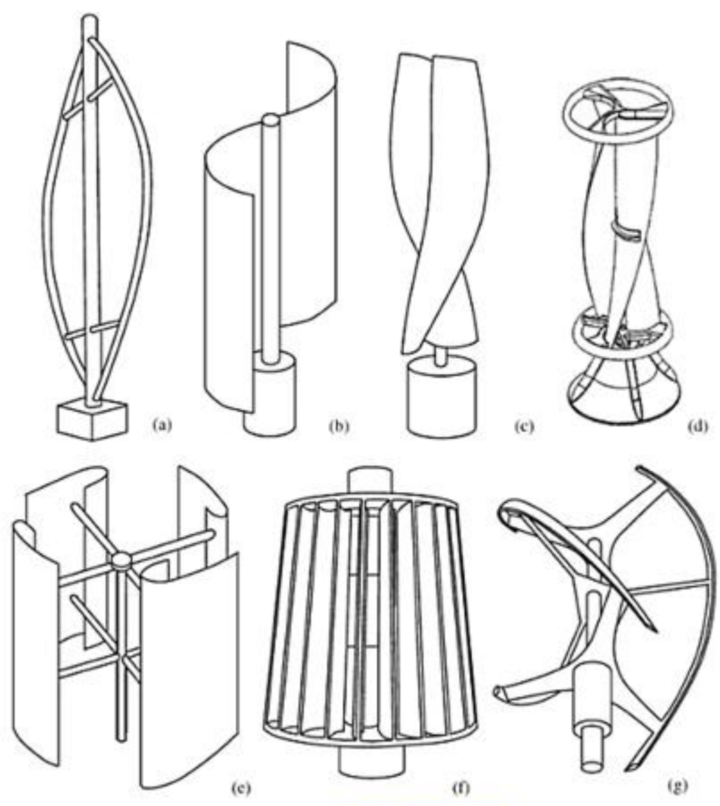

Figure 2.9 Several Types of HAWT. (a) Darrius; (b) Savonius; (c) Solarwind; (d) Helical; (e) Noguchi; (f) Maglev; (g) Cochrane (Wei Tong, 2010)

Figure 2.9 shows several types of common VAWT which are available in market. For VAWT, the axis of rotation is vertical to the ground and almost perpendicular to the wind direction. This type of turbines can receive wind from any direction although it doesn’t have yaw devices. Yaw device is a device that normally used in HAWT to make sure that the turbine is always faces to the wind direction. This type of turbine has several characteristics that problematic.

- VAWT need an additional mechanism to start turbine
- Poor efficiency compare to HAWT. Maximum efficiency is around 0.15 while for HAWT efficiency normally around 0.30
- Subject to bending effects of centrifugal and lift force cause fatigue failure.

2.5.3 Large and small wind turbine

In terms of power we can divide the wind turbines into 2 categories, utility scale wind turbines and small scale wind turbines (Hazen, 1996). For utility scale wind turbines, the rating of the turbines will usually be 100kW or more. While for small scale wind turbines, the rating of the turbines will be in the range below 100 kW. Most of the small wind turbines are designed with higher tip speed ratio compared to large wind turbines, thus their rotational speed become very high (Ameku et al, 2008). This makes them potentially noisy and dangerous under strong winds.

According to Bernoulli's principle, a pocket of low pressure forms on the leeward edge of the moving blade as it passes through the wind and this will pull the blades causing the turbine to rotate against the counter-torque induced by the drag force, the generator and by system losses (Shenck). Fixed speed generators are not suitable for small wind system as wind speed is variable so it would be best if able to design a system that varies the operating speed of the turbine with wind speed so that turbines are always extracting maximum power from the wind. The weak point of a synchronous system is that the interface between the slips rings and brushes on the synchronous generator's rotor create wear point which need periodic inspection.

Some protections as below are needed to prevent the system from over loads:

1. Stall control: During the periods of high winds, the blades are pitched or loaded to stall angel which will completely depower and stall the rotor.

2. Pitch control: This system is just like stall control except the blades are adjusted to reduce turbine power and the control is able to slow down the rotation speed without stalling.

3. Yaw or Tilt control: System which shifts the rotor axis out of the wind in case of high winds.

4. No control: both mechanical and electrical systems are designed robust enough to withstand all wind conditions.

Most of the small wind turbines were designed to be affordable, reliable and almost maintenance free by sacrificing optimal performance and most likely installed in low and unsteady wind speed regime (Wright & Wood, 2004). Small wind turbines rely solely on the torque produced by wind acting on the blades to overcome the frictional torque in the gear box and drive train and also the cogging torque in the generator. Hence, the difficulties to overcome this torque and friction increase as the size of the turbines decrease. Unsteadiness wind speed at site cause the rotor to stop frequently during the lulls in the wind and hence subsequently require a starting sequence during subsequence gusts. The aerodynamic torque is initially required to accelerate the blades, rather than extract kinetic energy from wind.

A few actions need to be taken to increase up the usage of wind turbines throughout the world market (Tavner, 2008):

1. Lowering the installation and capital cost of the wind turbine so that return on investment period (ROI) will be reduced.

2. Improving the reliability and quality of the wind turbine to prolong the life of the wind turbine.

3. More wind turbine power should be penetrated into the existing and future electrical systems.

Small wind turbines are easier to implement technically but difficult to predict successful economic outcome than those large scale wind turbine, but small wind turbine are accessible to individual consumers and within their disposable incomes. Offshore utility grade turbines can be larger and able to located in higher wind speed areas but expose to the onerous aerodynamic, hydrodynamic, ambient and connection condition which in turn increase the technical and financial risk.

It is evident that the best utilization of the energy in the wind can be obtained when the turbine efficiency reaches its highest value at a point close to the maximum of the power density function of wind (Khalfallah and Koliub, 2007). Hence the aerodynamic efficiency curve of wind turbine should fit the wind speed distribution well. The Cp of a wind turbine can be improved simply by increasing the rotational speed of the wind turbine at low speeds. By changing the angle of attack, the power captured and the efficiency of the wind turbine also varies. Increasing the angle of attacks is likely to increase the captured power and also the efficiency at low speeds while causing stalling at a lower rotational speed.

2.5.4 Turbine Blades

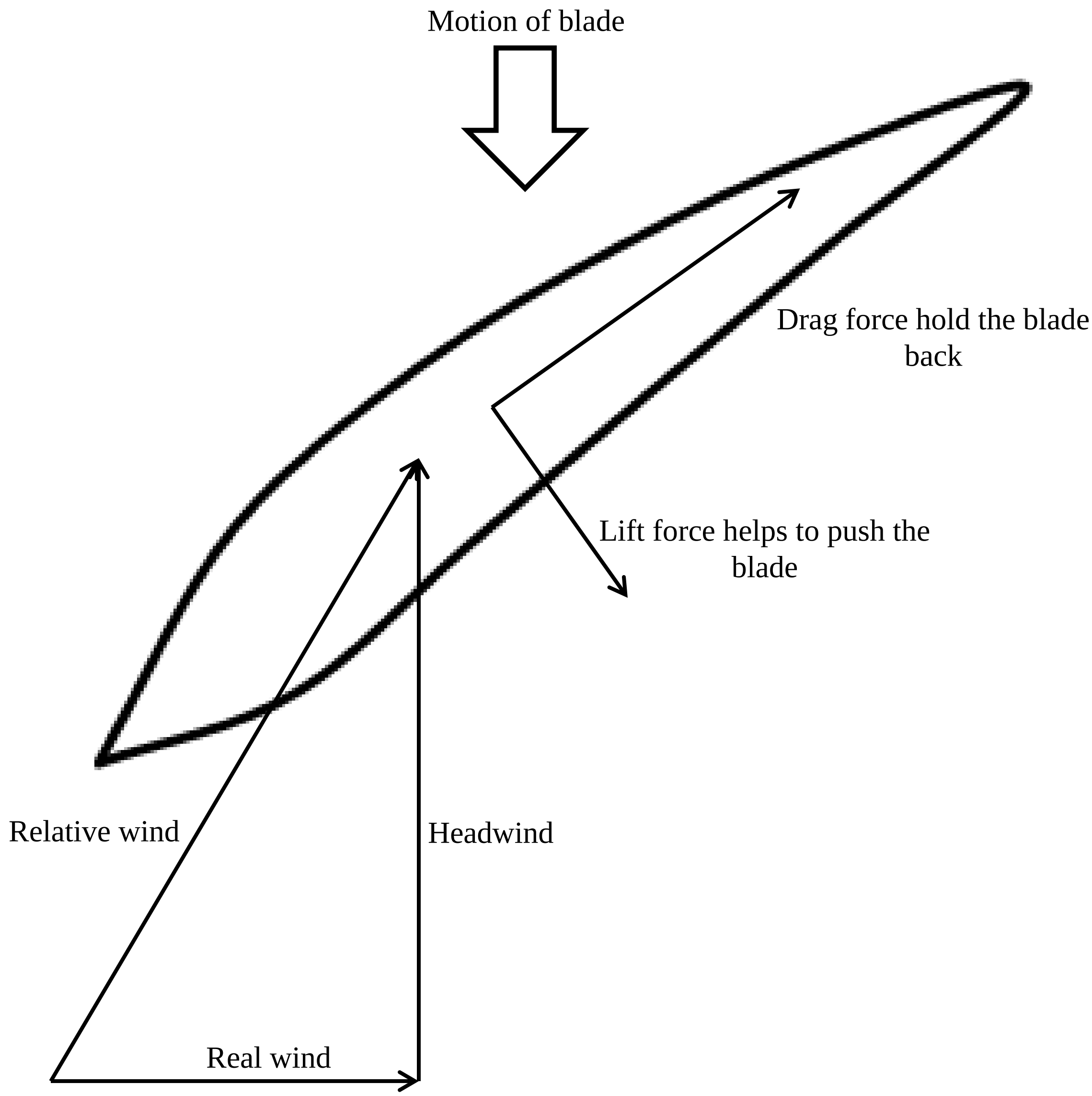

Figure 2.10 Forces Acting on a Blade Element

As the wind passes, the curve side of the blade will have lower pressure and this produces a net force perpendicular to the direction of air flow. This force is called the lift force. There will be another force which acts parallel to the direction of flow. This force is called drag force. To achieve higher coefficient of power (Cp), we desire higher lift force and lower drag force.

From Figure 2.10 at low angles of attack, the flow is attached to the upper surface of the air foil where lift increases with the angles of attack while drag is increase relatively slow. At a stall point lift reaches the maximum lift force and then it starts dropping while the drag force continues increasing. Wind tunnel studies show that the drag to lift ratio of a blade is not constant as it varies as the wing section is tilted. Usually, the best lift and drag ratio occurs at an angle of attack of around 4 °(Piggott,2001). The coefficient of lift and drag depend on the profile shape. For high wind speed HAWTs, it is advised that the blade be a narrow, laminar aero foil section with tip speed ratios (TSR) between 6 and 8. (Yurdusev et al., 2005).

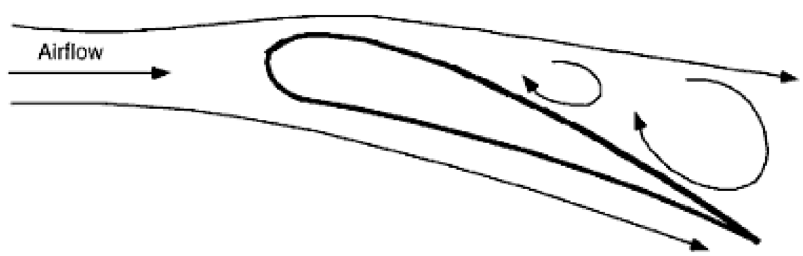

Figure 2.11 Illustration of Airfoil Stall [James et al., 2009]

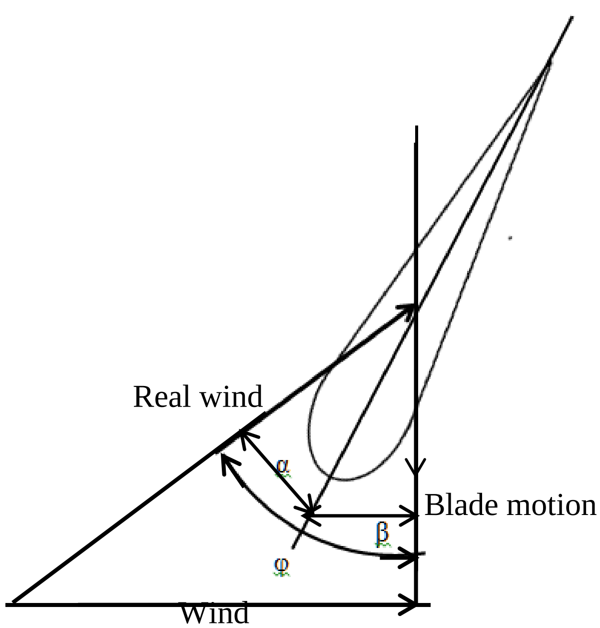

Figure 2.12 The Setting Angle, β, Flow Angle, φ, Angle of Attack,α

The setting of the blade, angle β, is such that the lift force causes the blade to move in the direction of rotation, and so power is transmitted via the root of the blade to the turbine shaft. Note that the direction of the relative wind, as experienced by the blade because of its own motion is in a different direction from the wind. In Figure 2.7, this direction is at angle φ to the plane of rotation, where φ is the flow angle, equal to the sum of the angle of attack, α, and the blade setting angle β. The design of the blade profile allows optimum values of angle of attack and blade setting, both of which should remain constant regardless of the speed of the wind. Because the relative wind speed increases in amplitude from the blade root to the blade tip, blade section design has improved from standard airplane shapes to specialist wind turbine designs via "twisting" (Twidell, 2007).

[Kurtulmus et al, 2007] use computer software, Snack 2.0 to analyses lift, drag, moment and minimum pressure of coefficients for 4 various blade profiles including NACA 4412, NACA4415, NACA 0012 and NACA 23012.

Sliding angel was defined as

$$Sliding\ angel = \frac{C_l}{C_d} \quad (2.7)$$

Where C_l= Coefficient of lift

C_d=coefficient of drag

As the sliding angel is higher, the efficiency of the blade will increase. By using the Reynolds's number formula

$$Re = 68500 \cdot C \cdot v \quad (2.8)$$

The C is the chord value while v is the wind speed.

$$C = \frac{4D}{TSR^2 \cdot B} \quad (2.9)$$