Development of a Low Cut-In Speed Wind Turbine

By

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Declaration

This is to certify that the project work entitled " **Development of a Low Cut-In Speed Wind Turbine**" carried by Mausumi Ferdous in Department of Mechanical Engineering, Khulna University of Engineering & Technology, Bangladesh. The above research work or any-part of the work has not been submitted anywhere for the award of any degree or diploma.

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ABSTRACT

Wind energy systems have become a focal point in the research of renewable energy sources. In this research provides a new concept of high performance, low cut-in speed wind turbine blade. To design the wind turbine blade, SG6043 airfoil profile has been chosen and wind tunnel experiments were performed at various Reynolds numbers. The pressure distribution, C_P, the lift and drag coefficients, C_L and C_D, were used for varying angles of attack, α. The conventional wind turbine blades have performed generally above $2.5ms^{-1}$ wind velocity at least. But our wind turbine blades can rotate well below the usual minimum wind velocity of $2.5ms^{-1}$ and in this lower velocity ($< 2.5ms^{-1}$) we have got the maximum 100 W power output and voltage of 12V.

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Nomenclature

a	= Axial interference or induction factor
a'	= Angular induction factor
A	= Projected airfoil area (chord_span), surface area, rotor swept area
B	= Number of blades
C	= Airfoil chord length
C_d	= Drag coefficient
C_l	=Lift coefficient
C_p	= Pressure coefficient
C_P	=Power coefficient
dr	=Thickness
F	=Tip loss correction factor
F_D	= Drag force
F_L	= Lift force
F_N	= Normal force, force normal to plane of rotation (thrust)
F_T	= Force tangential to circle swept by blade section
$\dot{m}$	= Mass flow rate per unit height
N	= Number of blade elements
p	= Pressure
P	= Power
r	= Radius
r_h	= Rotor radius at the hub
R	= Outer blade radius
Re	= Reynolds number
C_p	= Pressure Coefficient
L	= Lift
D	= Drag
U_∞	= Free Stream Velocity

C	= Chord Length
α	= Angle of Attack
η_{mech}	=Mechanical efficiency
η_{out}	=Overall output efficiency
$\eta_{overall}$	= Overall efficiency
θ_p	=Section pitch angle
$\theta_{p,0}$	=Blade pitch angle at the tip
θ_T	=Blade twist angle
λ	=Tip speed ratio
λ_h	=Local speed ratio at the hub
λ_r	=Local speed ratio
ρ	=Air density
σ	=Rotor solidity
σ'	= Local rotor solidity
φ	=Angle of relative wind
ω	=Angular velocity of the wind
Ω	= Angular velocity of the wind turbine rotor

CHAPTER I

INTRODUCTION

1.1 General

Wind is a vast energy resource which is clean and renewable. By its inherent nature, wind power has the potential to reduce the environmental impact on wildlife and human health. Improvements in power electronics, materials, and wind turbine designs allow production to continually lower the cost of wind generated electricity making it today economically viable compared with most other fossil fuels. Last decade, among the publications on wind energy, many interesting works on the characteristics and the performance of small wind turbines are reported and this is the result of the augmented interest in this new area of wind energy technology, compared to medium and large wind power systems. The small WTs can be of horizontal or vertical rotor axis and their maximum power and dimensions must be taken into consideration in their applications. In horizontal axis WTs (HAWT) the tracking of the wind direction is necessary, which could be considered as a major disadvantage of this type WTs. Alternatively, stationary mounted HAWT systems have been suggested for several applications, including the modified type of wind concentrator. Vertical axis WTs (VAWT) are practical, as they use a fixed rotation axis and the turbine at the bottom, but they are still of higher cost compared to HAWTs.

An extended research of small wind turbines as long as development issues have been presented in a number of articles [1-4]. The modified type of wind concentrator has been proposed and studied for the improvement of system output [5,6]. The starting behavior of a small horijuzontal-axis wind turbine is a very important issue which may have a great effect on its performance and has been thoroughly examined by scientists [7,8]. Vertical Axis WTs (VAWT) are more practical, because of the fact that they use a fixed rotation axis and also due to the low position of their motorgenerator. However, they are still of higher cost compared to HAWTs. The Savonius and Darrieus Wind turbine types are the most usual

VAWT systems, a combination of these two types has also been suggested [9] and small commercial models are already out in the market.

During the last decade, more and more scientists and researchers have taken under consideration the prospects of using small wind turbines for energy supply in various applications. In other words, small wind turbines, may change radically the philosophy of modern world's energy system. The most important concern of small wind turbine industry is to construct systems that are cost effective and yet well designed so that they can withstand 20 or 30 years of operation in weather that is often severe. Because of the need for simplicity and high reliability, small wind turbines are still a difficult field for wind energy technology. Important issues such as the furling behavior, the thrust measurements, the yaw behavior, the blade and tower loads of small wind turbines remain subjects that need further research. Despite this, small wind turbines have already entered the commercial world and the practical aspects of their applications can only make optimistic, the people who range themselves with wind energy technology.

However, in comparison with the overall demand for energy, the wind power usage is still small: The level of development in Bangladesh is extremely few. For this reasons, various causes are conceivable. For example, suitable area is limited for wind power plants, the complies terrain compared to that in European or North American countries and turbulent nature of the local wind are pointed out. Therefore, the introduction of new wind power system that produces higher power output even in areas where lower wind speeds and complex wind patterns are expected is strongly desired. On the other hand, in this new research, turbine blades have some advantages: high utilization of wind energy which contributes to the annual energy output and also important factor is that the blades are rotating below 2.5 m/sec. So the wind turbine, we have developed, can improve the higher power output in spite of various obstacles of our country in the past.

Figure 1.1: Designed Wind Turbine with Three Blades.

1.2 Objectives of the Research Work:

The objectives of this project work are as follows:

i) To design a high performance, low cut-in speed wind turbine blade.

ii) To construct a wind turbine using the designed blade which generate power even when the wind velocity is less than 2.5 ms^{-1}.

iii) To reduce the turbine noise and to save blades from damp and breakage.

1.3 Historical Background

Wind power has been used as long as humans have put sails into the wind. For more than two millennia wind-powered machines have ground grain and pumped water. Wind power was widely available and not confined to the banks of fast-flowing streams, or later, requiring sources of fuel. Wind-powered pumps drained the polders of the Netherlands, and in arid regions such as the American mid-west or the Australian outback, wind pumps provided water for live stock and steam engines.

With the development of electric power, wind power found new applications in lighting buildings remote from centrally-generated power. Throughout the 20th century parallel paths developed distributed small wind plants suitable for farms or residences, and larger utility-scale wind generators that could be connected to electricity grids for remote use of power. Today wind powered generators operate in every size range between tiny plants for battery charging at isolated residences, up to near-gigawatt sized offshore wind farms that provide electricity to national electrical networks.

1.3.1 Antiquity:

Sailboats and sailing ships have been using wind power for at least 5,500 years, and architects have used wind-driven natural ventilation in buildings since similarly ancient times. The use of wind to provide mechanical power came somewhat later in antiquity.

The Babylonian emperor Hammurabi planned to use wind power for his ambitious irrigation project in the 17th century BC. [11]

The windwheel of the Greek engineer Heron of Alexandria in the 1st century AD is the earliest known instance of using a wind-driven wheel to power a machine. [10][12] Another early example of a wind-driven wheel was the prayer wheel, which was used in ancient Tibet and China since the 4th century. [13]

1.3.2 Early Middle Ages:

The first practical windmills were in use in Sistan, a region in Iran and bordering Afghanistan, at least by the 9th century and possibly as early as the 7th century. These "Panemone windmills" were vertical-axle windmills, which had long vertical driveshafts with six to twelve rectangular sails covered in reed matting or cloth. [14] These windmills were used to grind corn and pump water, and in the gristmilling and sugarcane industries. [14] The use of windmills became widespread use across the Middle East and Central Asia, and later spread to China and India.[15] Horizontal-axle windmills were later used extensively in Northwestern Europe to grind flour beginning in the 1180s, and many Dutch horizontal-axle windmills still exist. [15] By 1000 AD, windmills were used to pump seawater for salt-making in China and Sicily. [16]

A wind-powered automata is known from the mid-8th century: wind-powered statues that "turned with the wind over the domes of the four gates and the palace complex of the Round City of Baghdad". The "Green Dome of the palace was surmounted by the statue of a horseman carrying a lance that was believed to point toward the enemy. This public spectacle of wind-powered statues had its private counterpart in the 'Abbasid palaces where automata of various types were predominantly displayed." [15]

1.3.3 Late Middle Ages:

The first windmills in Europe appear in sources dating to the twelfth century. These early European windmills were horizontal-axle sunk post mills. The earliest certain reference to such a horizontal-axle windmill dates from 1185, in Weedley, Yorkshire, although a number of earlier but less certainly dated twelfth century European sources referring to windmills have also been adduced.[17] While it is sometimes argued that crusaders may have been inspired by windmills in the Middle East, this is unlikely since the European horizontal-axle windmills were of significantly different design than the vertical-axle windmills of Afghanistan. Lynn White Jr., a specialist in medieval European technology, asserts that the European windmill was an "independent invention;" he argues that it is unlikely that the Afghanistan-style vertical-axle windmill had spread as far west as the Levant during the Crusader period [17]. In medieval England rights to waterpower sites were often confined to nobility and clergy, so wind power was an important resource to a new middle class.[17] In addition, windmills, unlike water mills, were not rendered inoperable by the freezing of water in the winter.

By the 14th century Dutch windmills were in use to drain areas of the Rhine River delta.

18th century:

Windmills were used to pump water for salt making on the island of Bermuda, and on Cape Cod during the American revolution.[16]

19th century:

In Denmark there were about 2,500 windmills by 1900, used for mechanical loads such as pumps and mills, producing an estimated combined peak power of about 30 MW.

In the American midwest between 1850 and 1900, a large number of small windmills, perhaps six million, were installed on farms to operate irrigation pumps.[17] Firms such as Star, Eclipse, Fairbanks-Morse and Aeromotor became famed suppliers in North and South America.

The first windmill used for the production of electricity was built in Scotland in July 1887 by Prof James Blyth of Anderson's College, Glasgow (the precursor of Strathclyde University).[18] Blyth's 33-foot (10 m) high, cloth-sailed wind turbine was installed in the garden of his holiday cottage at Marykirk in Kincardineshire and was used to charge accumulators developed by the Frenchman Camille Alphonse Faure, to power the lighting in the cottage,[18] thus making it the first house in the world to have its electricity supplied by wind power.[19] Blyth offered the surplus electricity to the people of Maykirk for lighting the main street, however, they turned down the offer as they thought electricity was "the work of the devil."[18] Although he later built a wind machine to supply emergency power to the local Lunatic Asylum, Infirmary and Dispensary of Montrose the invention never really caught on as the technology was not considered to be economically viable.[18] Across the Atlantic, in Cleveland, Ohio a larger and heavily engineered machine was designed and constructed in 1887-1888 by Charles F. Brush,[20] this was built by his engineering company at his home and operated from 1886 until 1900.[21] The Brush wind turbine had a rotor 56 feet (17 m) in diameter and was mounted on a 60 foot (18 m) tower. Although large by today's standards, the machine was only rated at 12 kW; it turned relatively slowly since it had 144 blades. The connected dynamo was used either to charge a bank of batteries or to operate up to 100 incandescent light bulbs, three arc lamps, and various motors in Brush's laboratory. The machine fell into disuse after 1900 when electricity became available from Cleveland's central stations, and was abandoned in 1908.[22]

In the 1890s a Danish scientist, Poul la Cour, constructed wind turbines to generate electricity, which was then used to produce hydrogen [18]for experiments and light and the Askov Highschool. His last windmill of 1896 later became the local powerplant of the village of Askov.

20th century:

Development in the 20th century might be usefully divided into the periods:

- 1900–1973, when widespread use of individual wind generators competed against fossil fuel plants and centrally-generated electricity
- 1973–onward, when the oil price crisis spurred investigation of non-petroleum energy sources.

1900–1973

Danish development:

In Denmark wind power was an important part of a decentralized electrification in the first quarter of the 20th century, partly because of Poul la Cour from his first practical development in 1891 at Askov. By 1908 there were 72 wind-driven electric generators from 5 kW to 25 kW. The largest machines were on 24 m (79 ft) towers with four-bladed 23 m (75 ft) diameter rotors.[23] In 1957 Johannes Juul installed a 24 m diameter wind turbine at Gedser, which ran from 1957 until 1967. This was a three-bladed, horizontal-axis, upwind, stall-regulated turbine similar to those now used for commercial wind power development.[23]

A giant change took place in 1978 when the world's first multi-megawatt wind turbine was constructed. It pioneered many technologies used in modern wind turbines and allowed Vestas, Siemens and others to get the parts they needed. Especially important was the novel wing construction using help from German aeronautics specialists. The power plant was capable of delivering 2MW, had a tubular tower, pitch controlled wings and three blades. It was built by the teachers and students of the Tvind school. Before completion these "amateurs" were much ridiculed. The turbine still runs today and looks almost identical to the newest most modern mills.

Danish commercial wind power development stressed incremental improvements in capacity and efficiency based on extensive serial production of turbines, in contrast with development models requiring extensive steps in unit size based primarily on theoretical extrapolation. A practical consequence is that all commercial wind turbines resemble the Danish model, a light-weight three-blade upwind design.[24]

1.3.4 Farm power and isolated plants:

In 1927 the brothers Joe Jacobs and Marcellus Jacobs opened a factory, Jacobs Wind in Minneapolis to produce wind turbine generators for farm use. These would typically be used for lighting or battery charging, on farms out of reach of central-station electricity and distribution lines. In 30 years the firm produced about 30,000 small wind turbines, some of which ran for many years in remote locations in Africa and on the Richard Evelyn Byrd expedition to Antarctica.[25] Many other manufacturers produced small wind turbine sets for the same market, including companies called Wincharger, Miller Airlite, Universal Aeroelectric, Paris-Dunn, Airline and Winpower.

In 1931 the Darrieus wind turbine was invented, with its vertical axis providing a different mix of design tradeoffs from the conventional horizontal-axis wind turbine. The vertical orientation accepts wind from any direction with no need for adjustments, and the heavy generator and gearbox equipment can rest on the ground instead of atop a tower.

By the 1930s windmills were widely used to generate electricity on farms in the United States where distribution systems had not yet been installed. Used to replenish battery storage banks, these machines typically had generating capacities of a few hundred watts to several kilowatts. Beside providing farm power, they were also used for isolated applications such as electrifying bridge structures to prevent corrosion. In this period, high tensile steel was cheap, and windmills were placed atop prefabricated open steel lattice towers.

The most widely-used small wind generator produced for American farms in the 1930s was a two-bladed horizontal-axis machine manufactured by the Wincharger Corporation. It had a peak output of 200 watts. Blade speed was regulated by curved air brakes near the hub that deployed at excessive rotational velocities. These machines were still being manufactured in the United States during the 1980s. In 1936, the U.S. started a rural electrification project that killed the natural market for wind-generated power, since network power distribution provided a farm with more dependable usable energy for a given amount of capital investment.

In Australia, the Dunlite Corporation built hundreds of small wind generators to provide power at isolated postal service stations and farms. These machines were manufactured from 1936 until 1970.[26]

1.3.5 Utility-scale turbines:

A forerunner of modern horizontal-axis utility-scale wind generators was the WIME-3D in service in Balaklava, near Yalta, USSR from 1931 until 1942. This was a 100 kW generator on a 30 m (100 ft) tower, connected to the local 6.3 kV distribution system. It had a three-bladed 30 metre rotor on a steel lattice tower.[28] It was reported to have an annual load factor of 32 per cent,[29] not much different from current wind machines.[30]

In 1941 the world's first megawatt-size wind turbine was connected to the local electrical distribution system on the mountain known as Grandpa's Knob in Castleton, Vermont, USA. It was designed by Palmer Cosslett Putnam and manufactured by the S. Morgan Smith Company. This 1.25 MW Smith-Putnam turbine operated for 1100 hours before a blade failed at a known weak point, which had not been reinforced due to war-time material shortages. No similar-sized unit was to repeat this "bold experiment" for about forty years.[27]

1.3.6 Fuel-saving turbines:

During the Second World War, small wind generators were used on German U-boats to recharge submarine batteries as a fuel-conserving measure. In 1946 the lighthouse and residences on the island Insel Neuwerk were partly powered by an 18 kW wind turbine 15 metres in diameter, to economize on diesel fuel. This installation ran for around 20 years before being replaced by a submarine cable to the mainland.[31]

The Station d'Etude de l'Energie du Vent at Nogent-le-Roi in France operated an experimental 800 KVA wind turbine from 1956 to 1966.[32]

1973–2000

US development:

From 1974 through the mid-1980s the United States government worked with industry to advance the technology and enable large commercial wind turbines. The NASA wind turbines were developed under a program to create a utility-scale wind turbine industry in the U.S. With funding from the National Science Foundation and later the United States Department of Energy (DOE), a total of 13 experimental wind turbines were put into operation, in four major wind turbine designs. This research and development program pioneered many of the multi-megawatt turbine technologies in use today, including: steel tube towers, variable-speed generators, composite blade materials, partial-span pitch control, as well as aerodynamic, structural, and acoustic engineering design capabilities. The large wind turbines developed under this effort set several world records for diameter and power output. The MOD-2 wind turbine cluster of three turbines produced 7.5 megawatts of power in 1981. In 1987, the MOD-5B was the largest single wind turbine operating in the world with a rotor diameter of nearly 100 meters and a rated power of 3.2 megawatts. It demonstrated an availability of 95 percent, an unparalleled level for a new first-unit wind turbine. The MOD-5B had the first large-scale variable speed drive train and a sectioned, two-blade rotor that enabled easy transport of the blades. The 4 megawatt WTS-4 held the world record for power output for over 20 years. Although the later units were sold commercially, none of these two-bladed machines were ever put into mass production. When oil prices declined by a factor of three from 1980 through the early 1990s,[33] many turbine manufacturers, both large a small, left the business. The commercial sales of the NASA/Boeing Mod-5B, for example, came to an end in 1987 when Boeing Engineering and Construction announced they were "planning to leave the market because low oil prices are keeping windmills for electricity generation uneconomical."[34]

Later, in the 1980s, California provided tax rebates for wind power. These rebates funded the first major use of wind power for utility electricity. These machines, gathered in large wind parks such as at Altamont Pass would be considered small and un-economic by modern wind power development standards.

1.3.7 Self-sufficiency and back-to-the-land:

In the 1970s many people began to desire a self-sufficient life-style. Solar cells were too expensive for small-scale electrical generation, so some turned to windmills. At first they built ad-hoc designs using wood and automobile parts. Most people discovered that a reliable wind generator is a moderately complex engineering project, well beyond the ability of most amateurs. Some began to search for and rebuild farm wind generators from the 1930s, of which Jacobs Wind Electric Company machines were especially sought after. Hundreds of Jacobs machines were reconditioned and sold during the 1970s.

All major horizontal axis turbines today rotate the same way (clockwise) to present a coherent view. However, early turbines rotated counter-clockwise like the old windmills, but a shift occurred from 1978 and on. The individualist-minded blade supplier Økær made the decision to change direction in order to be distinguished from the collective Tvind and their small wind turbines. Some of the blade customers were companies that later evolved into Vestas, Siemens, Enercon and Nordex. Public demand required that all turbines rotate the same way, and the success of these companies made clockwise the new standard.[35]

Following experience with reconditioned 1930s wind turbines, a new generation of American manufacturers started building and selling small wind turbines not only for battery-charging but also for interconnection to electricity networks. An early example would be Enertech Corporation of Norwich, Vermont, which began building 1.8 kW models in the early 1980s.

In the 1990s, as aesthetics and durability became more important, turbines were placed atop tubular steel or reinforced concrete towers. Small generators are connected to the tower on the ground, then the tower is raised into position. Larger generators are hoisted into position atop the tower and there is a ladder or staircase inside the tower to allow technicians to reach and maintain the generator, while protected from the weather.

21st century:

As the 21st century began, fossil fuel was still relatively cheap, but rising concerns over energy security, global warming, and eventual fossil fuel depletion led to an expansion of interest in all available forms of renewable energy. The fledgling commercial wind power industry began expanding at a robust growth rate of about 30% per year, driven by the ready availability of large wind resources, and falling costs due to improved technology and wind farm management.

The steady run-up in oil prices after 2003 led to increasing fears that peak oil was imminent, further increasing interest in commercial wind power. Even though wind power generates electricity rather than liquid fuels, and thus is not an immediate substitute for petroleum in most applications (especially transport), fears over petroleum shortages only added to the urgency to expand wind power. Earlier oil crisis had already caused many utility and industrial users of petroleum to shift to coal or natural gas. Natural gas began having its own supply problems, and wind power showed potential for replacing natural gas in electricity generation.

1.3.8 Floating wind turbine technology:

Offshore wind power began to expand beyond fixed-bottom, shallow-water turbines beginning late in the first decade of the 2000s. The world's first operational deep-water *large-capacity* floating wind turbine, Hywind, became operational in the North Sea off Norway in late 2009 [36][37] at a cost of some 400 million kroner (around US$62 million) to build and deploy.[38]

These floating turbines are a very different construction technology—closer to floating oil rigs rather—than traditional fixed-bottom, shallow-water monopile foundations that are used in the other large offshore wind farms to date.

By late 2011, Japan announced plans to build a multiple-unit floating wind farm, with six 2-megawatt turbines, off the Fukushima coast of northeast Japan where the 2011 tsunami and nuclear disaster has created a scarcity of electric power.[39] After the evaluation phase is complete in 2016, "Japan plans to build as many as 80 floating wind turbines off Fukushima by 2020"[39] at a cost of some 10-20 billion Yen.[40]

1.4 Wind Energy in Bangladesh:

Government has recognized the importance of renewable energy in our energy planning programme and a draft Renewable Energy Policy is on the verge of being approved. In the context of Bangladesh, renewable energy consists mainly of biomass, solar energy and wind power. Hydropower potential appears very limited. Studies could be made for microhydropower which could meet some of the local needs of electricity. This would, however, be seasonal and other forms of power generation may be required during some months of the year. There is little chance of geothermal power and further R&D would be needed to exploit wave/tidal power.

In Bangladesh, as in many other countries, wind energy has also been used to provide some motive force to boats with sails of various designs. Unfortunately, not much research has been conducted in these areas, although renewed interest have recently been generated in utilizing the energy of wind for wind pumps and sailing boats.

Wind electricity for decentralized system or hybrid generation of electricity using other energy sources as complementary to wind energy has now been given some attention and this could be suitable in low wind regimes for localized small grid systems or battery charging. For low wind speed, wind pumps could also be a viable option.

Bangladesh is situated between 20034'-26038 North Latitude and 88001'-92041' East Longitude. The country has a 724 km long coast line and many small islands in the Bay of Bengal, where strong south-westerly tradewind and sea-breeze blow in the summer months and there is gentle north-easterly tradewind and land breeze in winter months.

In Bangladesh, little systematic wind speed study has been made. Data collected by the meteorology department are usually meant for weather forecasting and are insufficient for determining wind energy potential. In an early study report in 1982, a 30-year meteorological data from a number stations throughout the country were considered. It was found that wind speeds in the districts of Chittagong and Cox's Bazar were the only ones which showed promise. Extending the idea, only coastal area and the bay islands showed promise for possible electricity generation from wind.

Recently, some measurements were made by F. Rahman in some coastal areas followed by a year's measurement in Patenga (Chittagong) at a height of 20 m in 1995. It was found that wind speed is higher than the values obtained by the meteorological department. This led to a year-long systematic wind speed study at seven coastal sites in 1996-97 at a height of 25 m by Bangladesh Centre for Advanced Studies (BCAS), in collaboration with Local Government and Engineering Department (LGED) and Energy Technology & Services Unit (ETSU), UK which was financially supported by the British Government (DFID). A parallel study was also conducted by another Group (REVB1 GTZ).

The BCAS study first made an analysis of available meteorological data and established the following worthwhile information:

Wind speeds are higher in coastal areas.

Wind speeds exhibit strong seasonal cycle, lower in the September to February period and higher in summer (March to August).

Wind speeds exhibit a diurnal cycle, generally peaking in the afternoon and weakest at night (the trends are also similar in West Bengal, India).

The wind speed measurements by BCAS Group and GTZ group confirmed that wind speed is much higher in summer months (due to monsoon wind) than in winter months. Actual wind speed found by GTZ was slightly higher than those of BCAS Group; but the frequency distribution was similar. Diurnal variation confirmed the trend observed by the meteorological department.

Power curves of wind turbines with two different installed capacities from two different manufacturers have been used to calculate energy generation. The estimated annual energy outputs for Kutubdia and Kuakata are 133 MWh and 160 MWh for a 150 KW wind turbine; while the outputs are about 200 MWh and 230 MWh respectively from a 250 KW station at these places.

Some of the specific projects that could be undertaken were pointed out by the WEST study as follows:

- A pilot wind turbine plant may be set up and be linked with the existing 250 KW diesel power station at Kutubdia, to study the overall performance of a hybrid wind-diesel system in an isolated local grid.
- A demonstration wind power generating plant at Kuakata may be set up and connected to the existing grid to study the performance and efficiency of such a system.

A study may be undertaken to assess the performance of wind pumps for lifting water for drinking (Kutubdia) and irrigation for crop production (Chittagong).

Some wind-pv generators (100 W to 2KW) may be set up at remote locations to charge battery systems for specific users.

It is necessary to continue the present effort of collecting, processing and analysis of wind-data from the existing monitoring sites for at least three years for developing realistic plans and projects on wind energy.

In addition, other monitoring sites should also be selected for proper assessment of the wind-regime of the country. The proposed sites may include different terrain conditions including the coastal region.

As an initial step, demonstration and pilot plants may be set up to examine the technical, operational and economic viability of wind energy in the country.

Recently, several small wind generators have been installed by BRAC (11 small wind turbines in various coastal sites) and Grameen Shakti (two wind generators of 300 W and 1 KW at its Chakoria Shrimp Farm). These are small DC operation type systems supplying power to target groups to improve their quality of life. Their results are not well documented. Grameen Shakti has recently installed 4 small wind generators (3xl.5KW + ONE 10 KW) in Barguna district (coastal south). They are planning to develop these stations into hybrid systems later, first with diesel and then with solar pv, to maximize the energy output and then study the cost economics. Their final quantitative results would be awaited with great interest.

While the Government is yet to undertake extensive wind mapping followed by wind monitoring, a research Group of Bangladesh University of Engineering and Technology (BUET) is now conducting a wind speed study at Chandana, Gazipur (near Dhaka) at a height of about 60ft and, as expected from previous meteorological studies, the speed is between 2-3 m/see. Wind speed measurements are also being taken at St. Martin Island on top of a lighthouse by BCSIR. Extensive study is likely to discover wind pockets in the country, especially in the hilly areas (e.g. Chittagong Hill Tracts) and in coastal islands.

As for mechanical power from the wind, recently two groups have worked in such projects. The first one, form LGED, has set up a number of 27 ft high windpumps at Tangail, Kuslitia, Cox's Bazar and other places. Theoretically, these indigenously made windpumps have a power of 0.5 h.p. (385W) at a windspeed of 4m/ see. The pump outlet is narrow and the output was found to be 25 liter/minute at windspeed of 3.2 m/see. No quantitative results are, however, available. The second Group from BCAS installed a windpump designed by the IT (Intermediate Technology) Group of the UK and made in Karachi (Pakistan). The windpump was located in an agricultural field in Patenga (Chittagong). The Tower height was 40 ft and the rotor consisted of 12 blades. Daily water output has been varying and the average water output between November and January was about 8000 liters/day. It appears that suitability designed wind pumps can be extensively used for irrigation of vegetables in winter months in the coastal region. It should also be possible to draw fresh underground water for drinking purposes in the coastal islands.

The potential of wind energy has not been fully explored in Bangladesh, mainly due to lack of reliable wind speed data. It appears that the wind speed will not be high but wind energy can be put to a variety of uses, especially for wind pumps, hybrid electricity generating systems with wind as one of the energy sources, small battery chargers at isolated places and electricity inputs to local grids in some coastal areas or the bay islands. To mention some practical applications, wind energy in Bangladesh could be used in shrimp production, fish/poultry firming, salt/ ice production, fish-mill industries, hatcheries, domestic applications and vegetable irrigation - all using decentralized electricity (hybrid or mechanical energy from wind). Wind energy is a clean renewable energy source cheaper to maintain, saves fuel and can give decentralized energy. We should make maximum use of it (including more efficient boat sails where wind energy is directly used). This needs creation of necessary data and manpower base, setting up some demonstration plants at appropriate locations and carrying out research and studies for indigenization of technology.

1.4.1 Wind Energy Resource Assessment

In Bangladesh, adequate information on the wind speed over the country and particularly on wind speeds at hub heights of wind machines is not available. A previous study (1986) showed that for the wind monitoring stations of Bangladesh Meteorological Department (BMD) the wind speed is found to be low near the ground level at heights of around 10 meter. Chittagong – Cox's Bazar seacoast and coastal off-shore islands appeared to have better wind speeds. Measurements at 20m and 30m heights have been made later on by BCAS, GTZ and BCSIR. WERM project of LGED for measurements at the height of 20 and 30m have been going on for 20 locations all over Bangladesh. However, the speed at a higher height of 50m which is often used for wind generators has not been available. This SWERA Program provides predictions for wind speed and wind energy density at different heights including 50m height to look for the possibility of wind power generation. For
prediction of wind speed at different heights and for assessment of wind energy in the coastal part of Bangladesh, Wind Atlas Analysis and Application Program (WAsP), a micro-scale modeling software has been used. WAsP develops models for obstacles, roughness and terrain surrounding a measuring station and then generates a regional wind climate or a wind atlas for the region around 100km2 in area.

Wind resource assessment over Bangladesh has been done independently by RISOE National Laboratory, Denmark using KAMM (Karlsruhe Atmospheric Meso-scale) model. The model uses upper atmosphere wind speed data and satellite information. Based on a comparison between KAMM (done by RISOE) and WAsP results (done by RERC) the wind resource map for Bangladesh has been developed. The maps are given at the following pages.

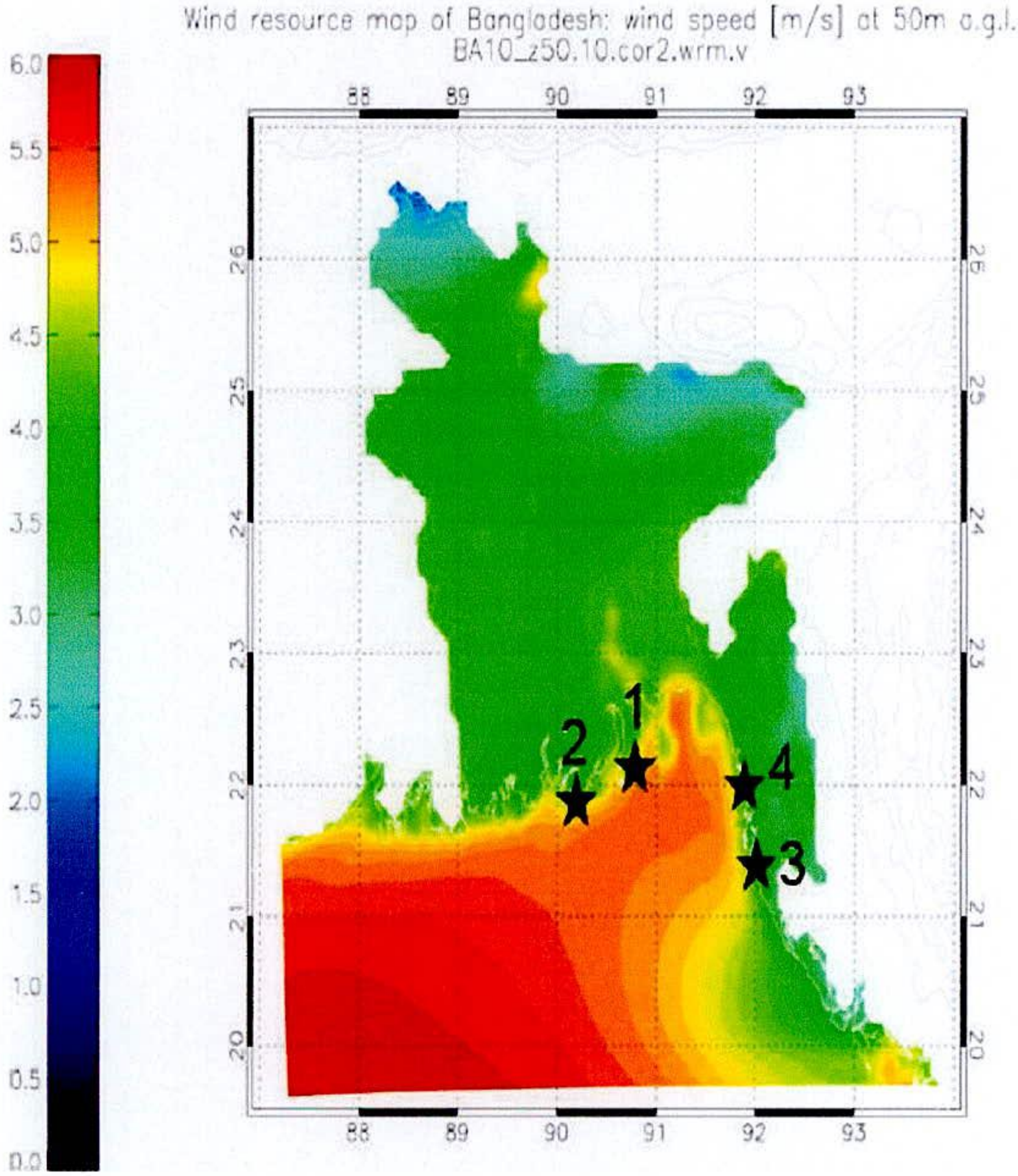


Figure 1.2: Annual mean simulated wind speed at 50 m a.g.l.

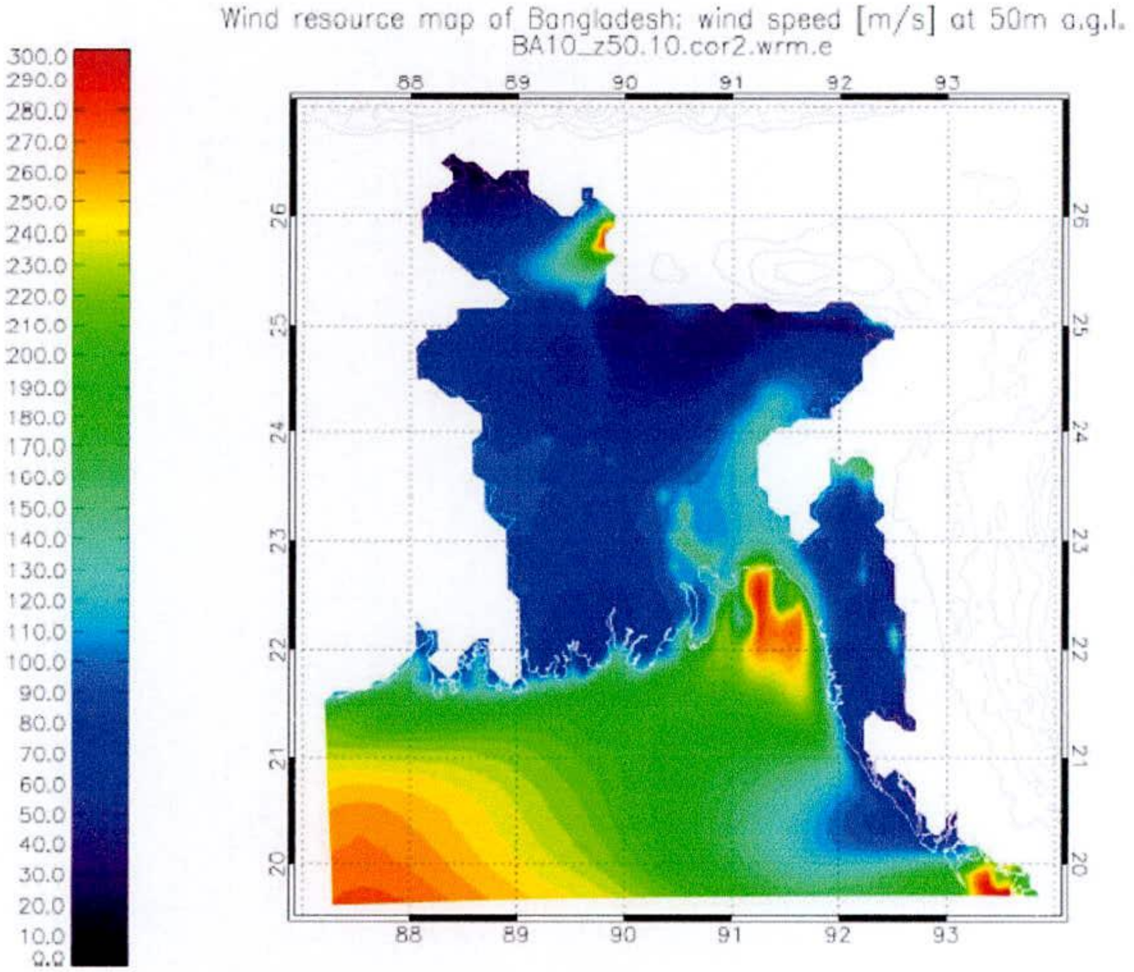


Figure 1.3: Annual mean simulated wind power density at 50 m a.g.l.

1.4.2 Production of electricity from renewable sources:

Globally renewable generate 3.47% of total electricity demand; while in Bangladesh, it is only about 0.45%. The renewable energy policy approved in December 2008 aims at exploring the country's electricity generating potential from renewable energy resources to meeting the nagging electricity crisis across the country. The policy encourages the private and public sectors to develop alternative sources of energy to meet up to 10 % of total electricity demand through renewable energy such as solar, wind, biomass and hydropower by 2020 at a cost of about $1.5 billion. Present production of electricity under renewable energy is at Table 1.1.

Table 1.1: RENEWABLE ENERGY

Solar Home System	IDCOL: 2,80.000 (14 MW) REB and Others: 50,000 (2.5 MW)
Wind Turbine (BPDB)	2.0 MW
Biomass Plant (IDCOL)	0.25 MW
Total Renewable	Around 19 MW

Source: Power Cell

The renewable could reach electricity to the rural people and help in poverty reduction. However, it cannot meet the ever growing demand for more power by the industries, service sectors, and the growing urban population economically.

CHAPTER II

THEORY

2.1 One-dimensional Momentum Theory and the Betz Limit

A simple model, generally attributed to Betz (1926), can be used to determine the power from an ideal turbine rotor, the thrust of the wind on the ideal rotor, and the effect of the rotor operation on the local wind field. This simple model is based on a linear momentum theory developed over 100 years ago to predict the performance of ship propellers.

The analysis assumes a control volume, in which the control volume boundaries are the surface of a stream tube and two cross-sections of the stream tube (see Figure 2.1). The only flow is across the ends of the stream tube. The turbine is represented by a uniform 'actuator disc' which creates a discontinuity of pressure in the stream tube of air flowing through it. Note that this analysis is not limited to any particular type of wind turbine.

This analysis uses the following assumptions:

. homogenous, incompressible, steady state fluid flow;

. no frictional drag;

. an infinite number of blades;

. uniform thrust over the disc or rotor area;

. a non–rotating wake;

. the static pressure far upstream and far downstream of the rotor is equal to the undisturbed ambient static pressure

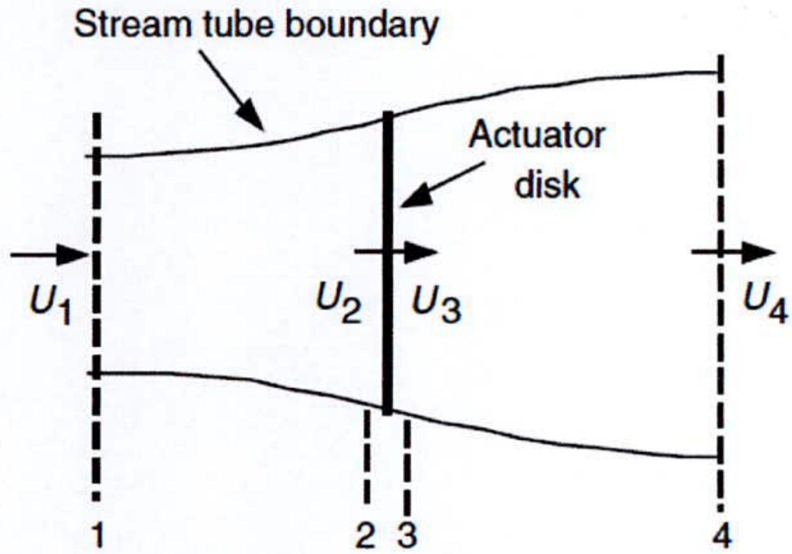


Figure 2.1: Actuator disc model of a wind turbine; U, mean air velocity; 1, 2, 3, and 4 indicate locations

Applying the conservation of linear momentum to the control volume enclosing the whole system, one can find the net force on the contents of the control volume. That force is equal and opposite to the thrust, T, which is the force of the wind on the wind turbine. From the conservation of linear momentum for a one-dimensional, incompressible, time-invariant flow, the thrust is equal and opposite to the rate of change of momentum of the air stream:

$$T = U_1(\rho AU)_1 - U_4(\rho AU)_4 \longrightarrow \quad (2.1)$$

where ρ is the air density, A is the cross-sectional area, U is the average air velocity, and the subscripts indicate values at numbered cross-sections in Figure 2.1.

For steady state flow, $(\rho AU)_1 = (\rho AU)_4 = \dot{m}$, where $\dot{m}$ is the mass flow rate. Therefore:

$$T = \dot{m}(U_1 - U_4) \longrightarrow \quad (2.2)$$

The thrust is positive so the velocity behind the rotor, U_4, is less than the free stream velocity, U_1. No work is done on either side of the turbine rotor. Thus the Bernoulli function can be used in the two control volumes on either side of the actuator disc. In the stream tube upstream of the disc:

$$p_1 + \tfrac{1}{2}\rho U_1^2 = p_2 + \tfrac{1}{2}\rho U_2^2 \longrightarrow \quad (2.3)$$

In the stream tube downstream of the disc:

$$p_3 + \tfrac{1}{2}\rho U_3^2 = p_4 + \tfrac{1}{2}\rho U_4^2 \longrightarrow \quad (2.4)$$

where it is assumed that the far upstream and far downstream pressures are equal ($p_1 = p_4$) and that the velocity across the disc remains the same ($U_2 = U_3$).

The thrust can also be expressed as the net sum of the forces on each side of the actuator disc:

$$T = A_2(p_2 - p_3) \longrightarrow \quad (2.5)$$

If one solves for (p_2 - p_3) using Equations (2.3) and (2.4) and substitutes that into Equation (2.5), one obtains:

$$T = \tfrac{1}{2}\rho A_2(U_1^2 - U_4^2) \longrightarrow \quad (2.6)$$

Equating the thrust values from Equations (2.2) and (2.6) and recognizing that the mass flow rate is also $\rho A_2 U_2$, one obtains:

$$U_2 = \frac{U_1 + U_4}{2} \longrightarrow \quad (2.7)$$

Thus, the wind velocity at the rotor plane, using this simple model, is the average of the upstream and downstream wind speeds.

If one defines the axial induction factor, a, as the fractional decrease in wind velocity between the free stream and the rotor plane, then

$$a = \frac{U_1 - U_2}{U_1} \qquad (2.8)$$

$$U_2 = U_1(1 - a) \qquad (2.9)$$

and

$$U_4 = U_1(1 - 2a) \qquad (2.10)$$

The quantity U_1a is often referred to as the induced velocity at the rotor, in which case the velocity of the wind at the rotor is a combination of the free stream velocity and the induced wind velocity. As the axial induction factor increases from 0, the wind speed behind the rotor slows more and more. If a =1/2, the wind has slowed to zero velocity behind the rotor and the simple theory is no longer applicable.

The power out, P, is equal to the thrust times the velocity at the disc:

$$P = \frac{1}{2}\rho A_2(U_1^2 - U_4^2)U_2 = \frac{1}{2}\rho A_2 U_2(U_1 + U_4)(U_1 - U_4) \qquad (2.11)$$

Substituting for U_2 and U_4 from Equations (2.9) and (2.10) gives:

$$P = \tfrac{1}{2}\rho A U^3 4a(1-a)^2 \longrightarrow \tag{2.12}$$

where the control volume area at the rotor, A_2, is replaced by A, the rotor area, and the free stream velocity U_1 is replaced by U.

Wind turbine rotor performance is usually characterized by its power coefficient, C_P:

$$C_P = \frac{P}{\frac{1}{2}\rho U^3 A} = \frac{\text{Rotor power}}{\text{Power in the wind}} \longrightarrow \tag{2.13}$$

The non-dimensional power coefficient represents the fraction of the power in the wind that is extracted by the rotor. From Equation (2.12), the power coefficient is:

$$C_P = 4a(1-a)^2 \longrightarrow \tag{2.14}$$

The maximum C_P is determined by taking the derivative of the power coefficient (Equation (2.14)) with respect to a and setting it equal to zero, yielding a=1/3. Thus:

$$C_{P,\max} = 16/27 = 0.5926 \longrightarrow \tag{2.15}$$

when a=1/3. For this case, the flow through the disc corresponds to a stream tube with an upstream cross-sectional area of 2/3 the disc area that expands to twice the disc area downstream. This result indicates that, if an ideal rotor were designed and operated such that the wind speed at the rotor were 2/3 of the free stream wind speed, then it would be operating at the point of maximum power production. Furthermore, given the basic laws of physics, this is the maximum power possible.

From Equations (2.6), (2.9) and (2.10), the axial thrust on the disc is:

$$T = \tfrac{1}{2}\rho A U^2 \left[4a(1-a)\right] \longrightarrow \tag{2.16}$$

Similarly to the power, the thrust on a wind turbine can be characterized by a non-dimensional thrust coefficient:

$$C_T = \frac{T}{\frac{1}{2}\rho U^2 A} = \frac{\text{Thrust force}}{\text{Dynamic force}} \longrightarrow \tag{2.17}$$

From Equation (2.16), the thrust coefficient for an ideal wind turbine is equal to $4a(1\text{-}a)$. C_T has a maximum of 1.0 when $a=0.5$ and the downstream velocity is zero. At maximum power output (a=1/3), C_T has a value of 8=9. A graph of the power and thrust coefficients for an ideal Betz turbine and the non-dimensionalized downstream wind speed are illustrated in Figure 2.2.

As mentioned above, this idealized model is not valid for axial induction factors greater than 0.5. In practice (Wilson et al., 1976), as the axial induction factor approaches and exceeds 0.5, complicated flow patterns that are not represented in this simple model result in thrust coefficients that can go as high as 2.0.

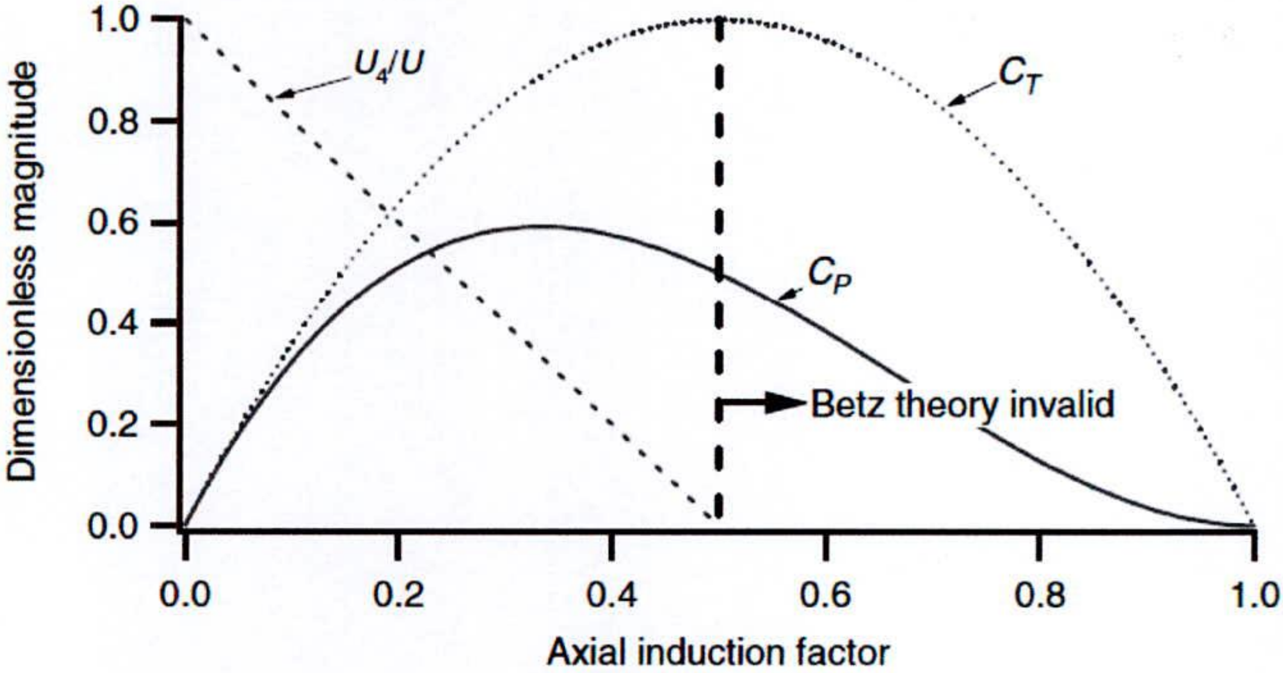


Figure 2.2: Operating parameters for a Betz turbine; U, velocity of undisturbed air; U_4, air velocity behind the rotor; C_P, power coefficient; C_T , thrust coefficient

The Betz limit, CP;max ¼ 16=27, is the maximum theoretically possible rotor power coefficient. In practice, three effects lead to a decrease in the maximum achievable power coefficient:

. rotation of the wake behind the rotor;

. finite number of blades and associated tip losses;

. non-zero aerodynamic drag.

Note that the overall turbine efficiency is a function of both the rotor power coefficient and the mechanical (including electrical) efficiency of the wind turbine:

$$\eta_{overall} = \frac{P_{out}}{\frac{1}{2}\rho A U^3} = \eta_{mech} C_P \longrightarrow \quad (2.18)$$

Thus:

$$P_{out} = \frac{1}{2}\rho A U^3(\eta_{mech} C_P) \longrightarrow \tag{2.19}$$

2.2 Momentum Theory and Blade Element Theory

A wind turbine rotor consists of airfoils that generate lift by virtue of the pressure difference across the airfoil, producing the same step change in pressure seen in the actuator disc type of analysis. The flow field around a wind turbine rotor, represented by an actuator disc, was determined using the conservation of linear and angular momentum. That flow field, characterized by axial and angular induction factors that are a function of the rotor power extraction and thrust, will be used to define the air flow at the rotor airfoils.

Momentum theory refers to a control volume analysis of the forces at the blade based on the conservation of linear and angular momentum. Blade element theory refers to an analysis of forces at a section of the blade, as a function of blade geometry. The results of these approaches can be combined into what is known as strip theory or blade element momentum (BEM) theory. This theory can be used to relate blade shape to the rotor's ability to extract power from the wind. The analysis in this and the following sections covers:

. Momentum and blade element theory.

. The simplest 'optimum' blade design with an infinite number of blades and no wake rotation.

. Performance characteristics (forces, rotor air flow characteristics, power coefficient) for a general blade design of known chord and twist distribution, including wake rotation, drag, and losses due to a finite number of blades.

. A simple 'optimum' blade design including wake rotation and a finite number of blades. This blade design can be used as the start for a general blade design analysis.

2.2.1 Momentum Theory

The forces on a wind turbine blade and flow conditions at the blades can be derived by considering conservation of momentum since force is the rate of change of momentum. The necessary equations have already been developed in the derivation of the performance of an ideal wind turbine including wake rotation. The present analysis is based on the annular control volume shown in Figure 3.4. In this analysis, the axial and angular induction factors are assumed to be functions of the radius, r.

Applying the conservation of linear momentum to the control volume of radius r and thickness dr is an expression for the differential contribution to the thrust:

$$dT = \rho U^2 4a(1-a)\pi r dr \longrightarrow \quad (2.20)$$

Similarly, the differential torque, Q, imparted to the blades (and equally, but oppositely, to the air) is:

$$dQ = 4a'(1-a)\rho U \pi r^3 \Omega dr \longrightarrow \quad (2.21)$$

Thus, from momentum theory one gets two equations, Equations (2.20) and (2.21), that define the thrust and torque on an annular section of the rotor as a function of the axial and angular induction factors (i.e. of the flow conditions).

2.2.2 Blade Element Theory

The forces on the blades of a wind turbine can also be expressed as a function of lift and drag coefficients and the angle of attack.As shown in Figure 2.3, for this analysis, the blade is assumed to be divided into N sections (or elements). Furthermore, the following assumptions are made:

. There is no aerodynamic interaction between elements (thus, no radial flow).

. The forces on the blades are determined solely by the lift and drag characteristics of the airfoil shape of the blades.

In analyzing the forces on the blade section, it must noted that the lift and drag forces are perpendicular and parallel, respectively, to an effective, or relative, wind. The relative wind is

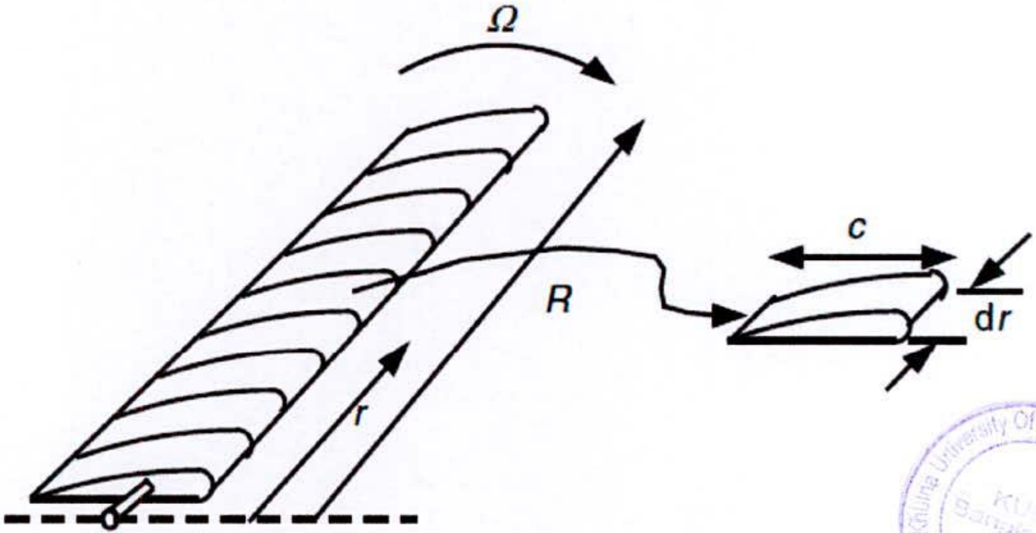


Figure 2.3: Schematic of blade elements; c, airfoil chord length; dr, radial length of element; r, radius; R, rotor radius; O, angular velocity of rotor

the vector sum of the wind velocity at the rotor, $U(1\text{-}a)$, and the wind velocity due to rotation of the blade. This rotational component is the vector sum of the blade section velocity, Ωr , and the induced angular velocity at the blades from conservation of angular momentum, $\omega r/2$, or

$$\Omega r + (\omega/2)r = \Omega r + \Omega a' r = \Omega r(1 + a') \longrightarrow \quad (2.22)$$

The overall flow situation is shown in Figure 2.4 and the relationships of the various forces, angles, and velocities at the blade, looking down from the blade tip, are shown in Figure 2.5. Here, θ_p is the section pitch angle, which is the angle between the chord line and the plane of rotation; $\theta_{p,0}$ is the blade pitch angle at the tip; θ_T is the blade twist angle; α is the angle of attack (the angle between the chord line and the relative wind); φ is the angle of relative wind; dF_L is the incremental lift force; dF_D is the incremental drag force;
dF_N is the incremental force normal to the plane of rotation (this contributes to thrust); and dF_T is the incremental force

tangential to the circle swept by the rotor. This is the force creating useful torque. Finally, U_{rel} is the relative wind velocity.

Note also that, here, the blade twist angle, θ_T, is defined relative to the blade tip (it could be defined otherwise). Therefore:

$$\theta_T = \theta_p - \theta_{p,0} \longrightarrow \quad (2.23)$$

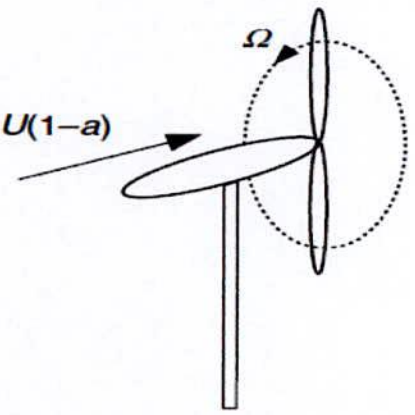


Figure 2.4: Overall geometry for a downwind horizontal axis wind turbine analysis; a, axial induction factor; U, velocity of undisturbed flow; Ω, angular velocity of rotor

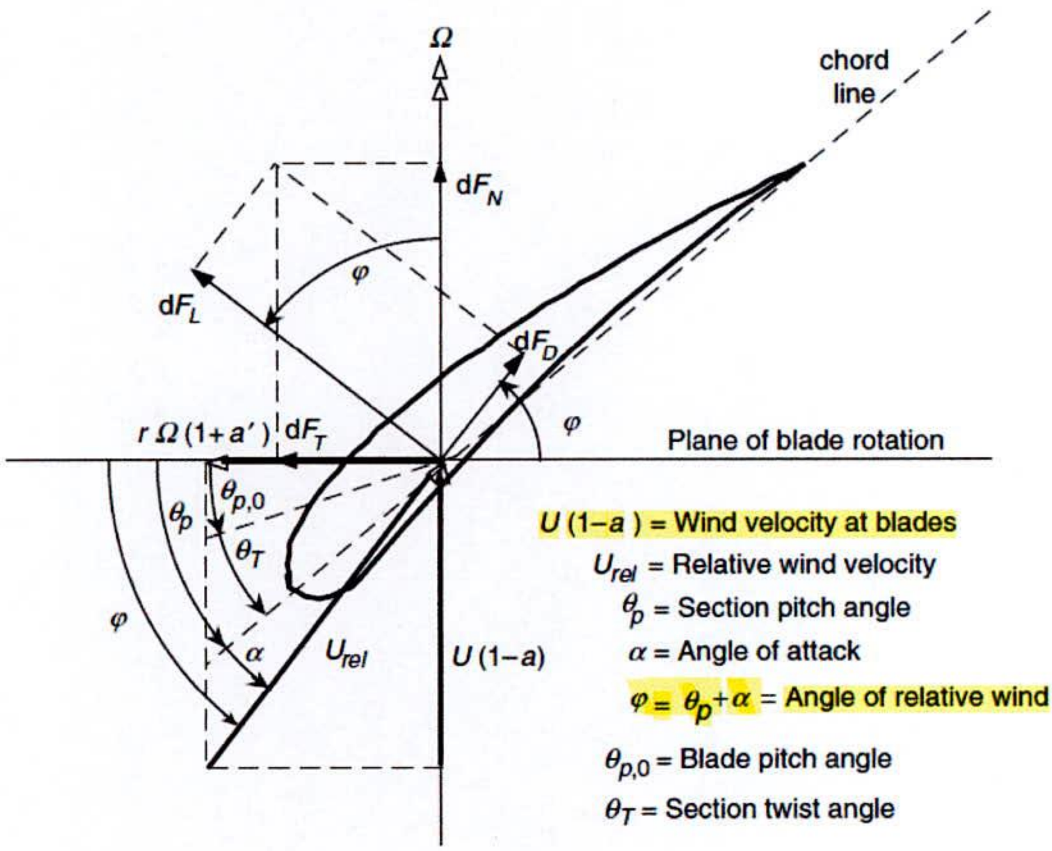


Figure 2.5 Blade geometry for analysis of a horizontal axis wind turbine.

where $\theta_{p,0}$ is the blade pitch angle at the tip. The twist angle is, of course, a function of the blade geometry, whereas θ_p changes if the position of the blade, $\theta_{p,0}$, is changed. Note, also, that the angle of the relative wind is the sum of the section pitch angle and the angle of attack:

$$\varphi = \theta_p + \alpha \qquad (2.24)$$

From Figure 2.5, one can determine the following relationships:

$$\tan\varphi = \frac{U(1-a)}{\Omega r(1+a')} = \frac{1-a}{(1+a')\lambda_r} \longrightarrow \quad (2.25)$$

$$U_{rel} = U(1-a)/\sin\varphi \longrightarrow \quad (2.26)$$

$$\mathrm{d}F_L = C_l \tfrac{1}{2}\rho U_{rel}^2 c\mathrm{d}r \longrightarrow \quad (2.27)$$

$$\mathrm{d}F_D = C_d \tfrac{1}{2}\rho U_{rel}^2 c\mathrm{d}r \longrightarrow \quad (2.28)$$

$$\mathrm{d}F_N = \mathrm{d}F_L\cos\varphi + \mathrm{d}F_D\sin\varphi \longrightarrow \quad (2.29)$$

$$\mathrm{d}F_T = \mathrm{d}F_L\sin\varphi - \mathrm{d}F_D\cos\varphi \longrightarrow \quad (2.30)$$

If the rotor has B blades, the total normal force on the section at a distance, r, from the center is:

$$\mathrm{d}F_N = B\tfrac{1}{2}\rho U_{rel}^2(C_l\cos\varphi + C_d\sin\varphi)c\mathrm{d}r \longrightarrow \quad (2.31)$$

The differential torque due to the tangential force operating at a distance, r, from the center is given by:

$$dQ = Br\,dF_T \longrightarrow \tag{2.32}$$

So

$$dQ = B\tfrac{1}{2}\rho U_{rel}^2(C_l \sin\varphi - C_d \cos\varphi)cr\,dr \longrightarrow \tag{2.33}$$

Note that the effect of drag is to decrease torque and hence power, but to increase the thrust loading.

Thus, from blade element theory, one also obtains two equations (Equations (2.31) and (2.33)) that define the normal force (thrust) and tangential force (torque) on the annular rotor section as a function of the flow angles at the blades and airfoil characteristics.

2.3 Blade Shape for Ideal Rotor without Wake Rotation

The maximum possible power coefficient from a wind turbine, assuming no wake rotation or drag, was determined to occur with an axial induction factor of 1/3. If the same simplifying assumptions are applied to the equations of momentum and blade element theory, the analysis becomes simple enough that an ideal blade shape can be determined. The blade shape approximates one that would provide maximum power at the design tip speed ratio of a real wind turbine. This will be called the 'Betz optimum rotor.'

In this analysis, the following assumptions will be made:

. There is no wake rotation; thus $a' = 0$.

. There is no drag; thus $C_d = 0$.

. There are no losses due to a finite number of blades (i.e. no tip loss).

. The axial induction factor, a, is 1/3 in each annular stream tube.

First, a design tip speed ratio, λ , the desired number of blades, B, the radius, R, and an airfoil with known lift and drag coefficients as a function of angle of attack need to be chosen. An angle of attack (and, thus, a lift coefficient at which the airfoil will operate) is also chosen. This angle of attack should be selected where C_d/C_l is minimal in order to most closely approximate the assumption that $C_d = 0$. These choices allow the twist and chord distribution of a blade that would provide Betz limit power production (given the input assumptions) to be determined. With the assumption that a=1/3, one gets from momentum theory (Equation (2.20)):

$$\mathrm{d}T = \rho U^2 4\left(\frac{1}{3}\right)\left(1-\frac{1}{3}\right)\pi r\,\mathrm{d}r = \rho U^2\left({}^{8}/_{9}\right)\pi r\,\mathrm{d}r \longrightarrow \tag{2.34}$$

and, from blade element theory (Equation (2.31)), with C_d=0:

$$\mathrm{d}F_N = B\frac{1}{2}\rho U_{rel}^2(C_l \cos\varphi)c\mathrm{d}r \longrightarrow \tag{2.35}$$

A third equation, Equation (2.26), can be used to express U_{rel} in terms of other known variables:

$$U_{rel} = U(1-a)/\sin\varphi = \frac{2U}{3\sin\varphi} \longrightarrow \tag{2.36}$$

BEM theory or strip theory refers to the determination of wind turbine blade performance by combining the equations of momentum theory and blade element theory. In this case, equating Equations (2.34) and (2.35) and using Equation (2.36), yields:

$$\frac{C_l B c}{4\pi r} = \tan\varphi \sin\varphi \longrightarrow \quad (2.37)$$

A fourth equation, Equation (2.25), which relates a, a', and φ based on geometrical considerations, can be used to solve for the blade shape. Equation (2.25), with a' = 0 and a =1/3, becomes:

$$\tan\varphi = \frac{2}{3\lambda_r} \longrightarrow \quad (2.38)$$

Therefore

$$\frac{C_l B c}{4\pi r} = \left(\frac{2}{3\lambda_r}\right)\sin\varphi \longrightarrow \quad (2.39)$$

Rearranging, and noting that $\lambda_r = \lambda(r/R)$, one can determine the angle of the relative wind and the chord of the blade for each section of the ideal rotor:

$$\varphi = \tan^{-1}\left(\frac{2}{3\lambda_r}\right) \longrightarrow \quad (2.40)$$

$$c = \frac{8\pi r \sin\varphi}{3BC_l\lambda_r} \longrightarrow \quad (2.41)$$

These relations can be used to find the chord and twist distribution of the Betz optimum blade. As an example, suppose: $\lambda = 7$, the airfoil has a lift coefficient of $C_l = 1$, C_d / C_l has a minimum at $\alpha = 7^\circ$ and, finally, that there are three blades, so B = 3. Then, from Equations (2.40) and (2.41) we get the results shown in Table 2.1. Here the chord and radius have been non-dimensionalized by dividing by the rotor radius. In this process, Equations (2.23) and (2.24) are also used to relate the various blade angles to each other (see Figure 2.5). The twist angle is assumed to start at 0 at the tip. The chord and twist of this blade are illustrated in Figures 2.6 and 2.7.

It can be seen that blades designed for optimum power production have an increasingly large chord and twist angle as one gets closer to the blade root. One consideration in blade design is the cost and difficulty of fabricating the blade. An optimum blade would be very difficult to manufacture at a reasonable cost, but the design provides insight into the blade shape that might be desired for a wind turbine.

Table 2.1: Twist and chord distribution for the example Betz optimum blade; r/R, fraction of rotor radius; c/R, Non- dimensionalized chord

r/R	c/R	Twist angle (deg)	Angle of rel. wind (deg)	Section pitch (deg)
0.1	0.275	38.2	43.6	36.6
0.2	0.172	20.0	25.5	18.5
0.3	0.121	12.2	17.6	10.6
0.4	0.092	8.0	13.4	6.4
0.5	0.075	5.3	10.8	3.8
0.6	0.063	3.6	9.0	2.0
0.7	0.054	2.3	7.7	0.7
0.8	0.047	1.3	6.8	−0.2
0.9	0.042	0.6	6.0	−1.0
1	0.039	0	5.4	−1.6

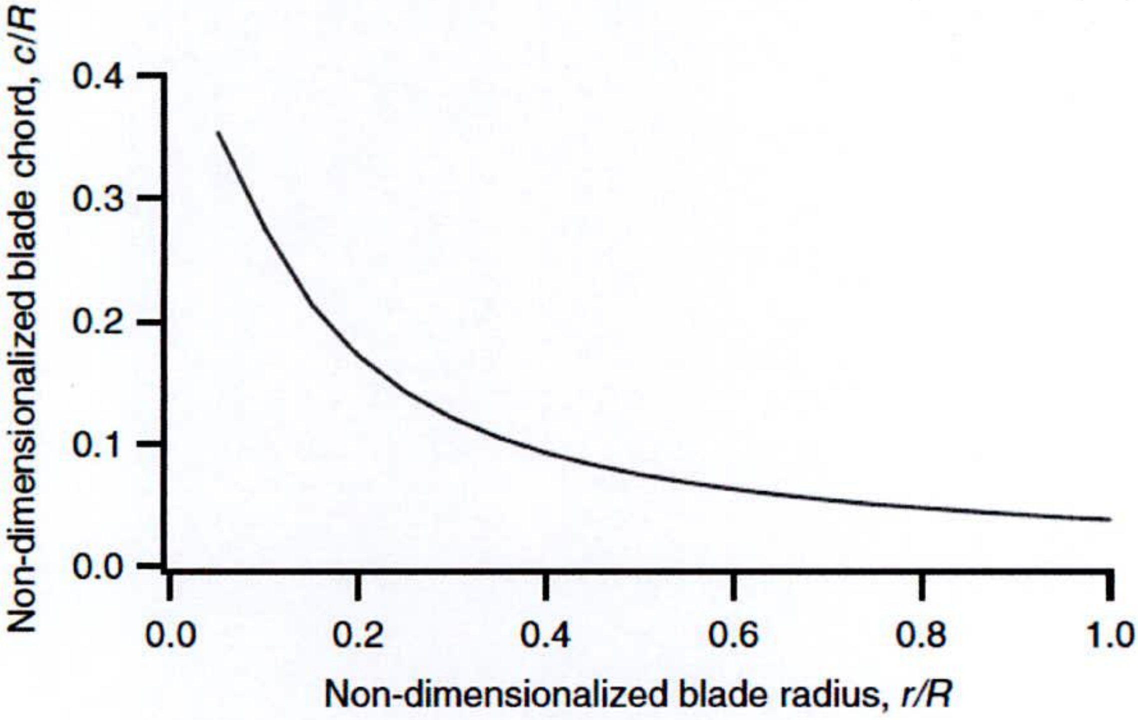


Figure 2.6: Blade chord for the example Betz optimum blade

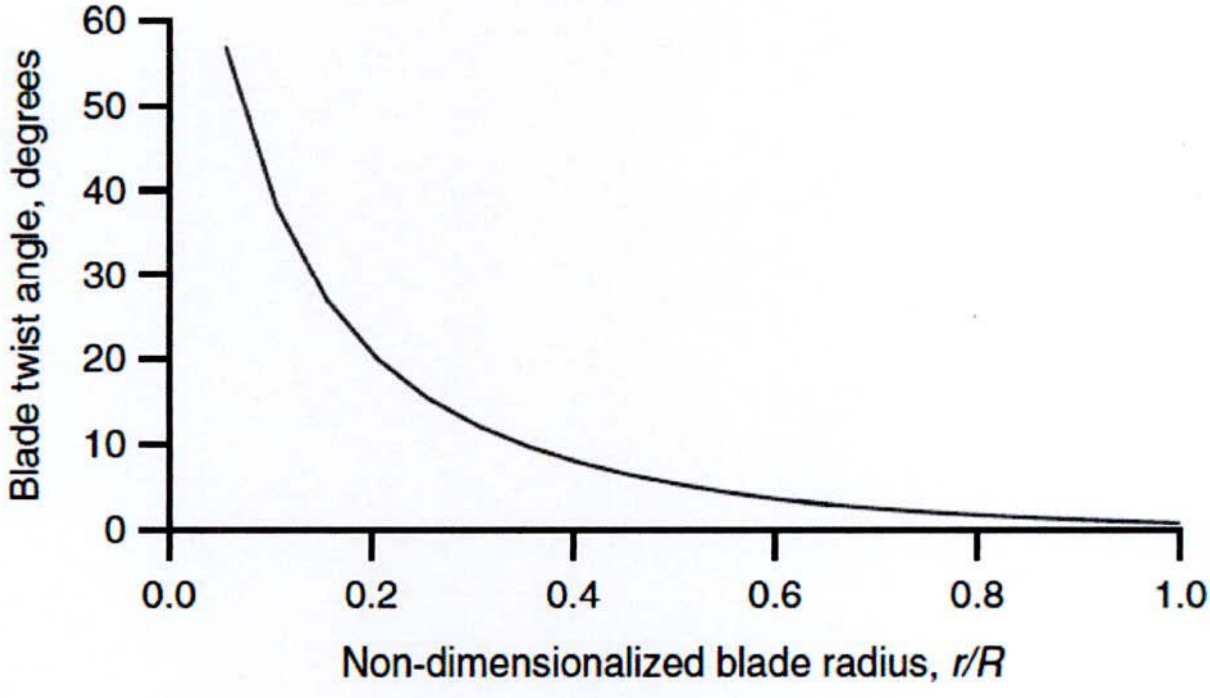


Figure 2.7: Blade twist angle for sample Betz optimum blade

2.4 General Rotor Blade Shape Performance Prediction

In general, a rotor is not of the optimum shape because of fabrication difficulties. Furthermore, when an 'optimum' blade is run at a different tip speed ratio than the one for which it is designed, it is no longer 'optimum'. Thus, blade shapes must be designed for easy fabrication and for overall performance over the range of wind and rotor speeds that they will encounter. In considering non-optimum blades, one generally uses an iterative approach. That is, one can assume a blade shape and predict its performance, try another shape and repeat the prediction until a suitable blade has been chosen.

So far, the blade shape for an ideal rotor without wake rotation has been considered. In this section, the analysis of arbitrary blade shapes is considered. The analysis includes wake rotation, drag, losses due to a finite number of blades, and off-design performance. In subsequent sections these methods will be used to determine an optimum blade shape,including wake rotation, and as part of a complete rotor design procedure.

2.4.1 Strip Theory for a Generalized Rotor, Including Wake Rotation

The analysis starts with the four equations derived from momentum and blade element theories. In this analysis, it is assumed that the chord and twist distributions of the blade are known. The angle of attack is not known, but additional relationships can be used to solve for the angle of attack and performance of the blade.

The forces and moments derived from momentum theory and blade element theory must be equal. Equating these, one can derive the flow conditions for a turbine design.

Momentum Theory

From axial momentum (Equation (2.20)) we already have:

$$dT = \rho U^2 4a(1-a)\pi r\, dr$$

From angular momentum (Equation (2.21)) we have:

$$dQ = 4a'(1-a)\rho U \pi r^3 \Omega\, dr$$

Blade Element Theory

From blade element theory (Equations (2.31) and (2.33)) we already have:

$$dF_N = B\tfrac{1}{2}\rho U_{rel}^2 (C_l \cos\varphi + C_d \sin\varphi) c dr$$

$$dQ = B\tfrac{1}{2}\rho U_{rel}^2 (C_l \sin\varphi - C_d \cos\varphi) cr dr$$

where the thrust, dT, is the same force as the normal force, dF_N. The relative velocity can be expressed as a function of the free stream wind using Equation (2.26). Thus, Equations (2.31) and (2.33) from blade element theory can be written as:

$$dF_N = \sigma' \pi\rho \frac{U^2(1-a)^2}{\sin^2\varphi}(C_l \cos\varphi + C_d \sin\varphi) r\, dr \longrightarrow \quad (2.42)$$

$$dQ = \sigma' \pi\rho \frac{U^2(1-a)^2}{\sin^2\varphi}(C_l \sin\varphi - C_d \cos\varphi) r^2 dr \longrightarrow \quad (2.43)$$

where σ' is the local solidity, defined by:

$$\sigma' = Bc/2\pi r \longrightarrow \quad (2.44)$$

Blade Element Momentum Theory

In the calculation of induction factors, a and a', accepted practice is to set C_d equal to zero . For airfoils with low drag coefficients, this simplification introduces negligible errors. So, when the torque equations from momentum and blade
element theory are equated (Equations (2.21) and (2.43)), with $C_d = 0$, one gets:

$$a'/(1-a) = \sigma' C_l/(4\lambda_r \sin\varphi) \longrightarrow \quad (2.45)$$

By equating the normal force equations from momentum and blade element theory (Equations (2.20) and (2.42)), one obtains:

$$a/(1-a) = \sigma' C_l \cos\varphi/(4\sin^2\varphi) \longrightarrow \quad (2.46)$$

After some algebraic manipulation using Equation (2.25) (which relates a, a', φ and λ_r, based on geometric considerations) and Equations (2.45) and (2.46), the following useful relationships result:

$$C_l = 4\sin\varphi \frac{(\cos\varphi - \lambda_r \sin\varphi)}{\sigma'(\sin\varphi + \lambda_r \cos\varphi)} \longrightarrow \quad (2.47)$$

$$a'/(1+a') = \sigma' C_l/(4\cos\varphi) \longrightarrow \quad (2.48)$$

Other useful relationships that may be derived include:

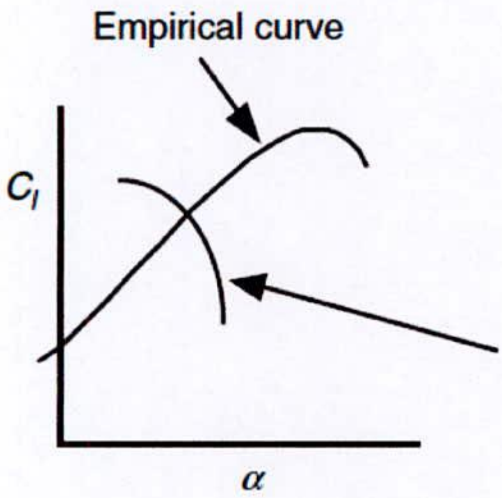
$$a/a' = \lambda_r/\tan\varphi \longrightarrow \quad (2.49)$$

$$a = 1/[1 + 4\sin^2\varphi/(\sigma' C_l \cos\varphi)] \longrightarrow \quad (2.50)$$

$$a' = 1/[(4\cos\varphi/(\sigma' C_l)) - 1] \longrightarrow \quad (2.51)$$

Solution Methods

Two solution methods will be proposed using these equations to determine the flow conditions and forces at each blade section. The first one uses the measured airfoil characteristics and the BEM equations to solve directly for C_l and a. This method can be solved numerically, but it also lends itself to a graphical solution that clearly shows the flow



$$C_l = \frac{4\sin\varphi}{\sigma'} \frac{(\cos\varphi - \lambda_r \sin\varphi)}{(\sin\varphi + \lambda_r \cos\varphi)}$$

Figure 2.8: Angle of attack – graphical solution method; C_l , two-dimensional lift coefficient; α , angle of attack; λ_r, local speed ratio; φ, angle of relative wind; σ', local rotor solidity

conditions at the blade and the existence of multiple solutions The second solution is an iterative numerical approach that is most easily extended for flow conditions with large axial induction factors.

Method 1 – Solving for Cl and a

Since $\varphi = \alpha + \theta_p$, for a given blade geometry and operating conditions, there are two unknowns in Equation (2.47), C_l and α at each section. In order to find these values, one can use the empirical C_l vs. α curves for the chosen airfoil . One then finds the C_l and α from the empirical data that satisfy Equation (2.47). This can be done either numerically or graphically (as shown in Figure 2.8). Once C_l and α have been found, a' and a can be determined from any two of Equations (2.48) through (2.51). It should be verified that the axial induction factor at the intersection point of the curves is less than 0.5 to ensure that the result is valid.

Method 2 – Iterative Solution for *a* and *a′*

Another equivalent solution method starts with guesses for a and a', from which flow conditions and new induction factors are calculated. Specifically:

1. Guess values of a and a'.
2. Calculate the angle of the relative wind from Equation (2.25).
3. Calculate the angle of attack from $\theta = \alpha + \theta_p$ and then C_l and C_d .
4. Update a and a' from Equations (2.45) and (2.46) or (2.50) and (2.51).

The process is then repeated until the newly calculated induction factors are within some acceptable tolerance of the previous ones. This method is especially useful for highly loaded rotor conditions .

2.4.2 Calculation of Power Coefficient

Once a has been obtained from each section, the overall rotor power coefficient may be calculated from the following equation (Wilson and Lissaman, 1974):

$$C_P = (8/\lambda^2)\int_{\lambda_h}^{\lambda} \lambda_r{}^3 a'(1-a)[1-(C_d/C_l)\cot\varphi]d\lambda_r \longrightarrow \tag{2.52}$$

where λ_h is the local speed ratio at the hub. Equivalently (de Vries, 1979):

$$C_P = (8/\lambda^2)\int_{\lambda_h}^{\lambda} \sin^2\varphi(\cos\varphi - \lambda_r\sin\varphi)(\sin\varphi + \lambda_r\cos\varphi)[1-(C_d/C_l)\cot\varphi]\lambda_r^2 d\lambda_r \longrightarrow \tag{2.53}$$

Usually these equations are solved numerically . Note that even though the axial induction factors were determined assuming $C_d = 0$, the drag is included here in the power coefficient calculation.

The derivation of Equation (2.52) follows. The power contribution from each annulus is

$$\mathrm{d}P = \Omega \mathrm{d}Q \longrightarrow \quad (2.54)$$

where Ω is the rotor rotational speed. The total power from the rotor is:

$$P = \int_{r_h}^{R} \mathrm{d}P = \int_{r_h}^{R} \Omega \mathrm{d}Q \longrightarrow \quad (2.55)$$

where r_h is the rotor radius at the hub of the blade.

The power coefficient, C_P, is

$$C_P = \frac{P}{P_{wind}} = \frac{\int_{r_h}^{R} \Omega \, \mathrm{d}Q}{\frac{1}{2}\rho \pi R^2 U^3} \longrightarrow \quad (2.56)$$

Using the expression for the differential torque from Equation (2.43) and the definition of the local tip speed ratio :

$$C_P = \frac{2}{\lambda^2}\int_{\lambda_h}^{\lambda} \sigma' C_l (1-a)^2 (1/\sin\varphi)[1-(C_d/C_l)\cot\varphi]\lambda_r^2 \mathrm{d}\lambda_r \longrightarrow \quad (2.57)$$

where λ_h is the local tip speed ratio at the hub.

From Equations (2.46) and (2.49):

$$\sigma' C_l(1-a) = 4a\sin^2\varphi/\cos\varphi \longrightarrow \quad (2.58)$$

$$a\tan\varphi = a'\lambda_r \longrightarrow \quad (2.59)$$

Substituting these into Equation (2.57), one gets the desired result, that is, Equation (2.52):

$$C_P = (8/\lambda^2)\int_{\lambda_h}^{\lambda} \lambda_r{}^3 a'(1-a)[1-(C_d/C_l)\cot\varphi]\mathrm{d}\lambda_r$$

Note that when $C_d = 0$, this equation for C_P is the same as the one derived from momentum theory, including wake rotation.

2.4.3 Tip Loss: Effect on Power Coefficient of Number of Blades

Because the pressure on the suction side of a blade is lower than that on the pressure side, air tends to flow around the tip from the lower to upper surface, reducing lift and hence power production near the tip. This effect is most noticeable with fewer, wider blades .

A number of methods have been suggested for including the effect of the tip loss. The most Straight forward approach to use is one developed by Prandtl . According to this method, a correction factor, F, must be introduced into the previously discussed equations. This correction factor is a function of the number of blades, the angle of relative wind, and the position on the blade.

Based on Prandtl's method:

$$F = \left(\frac{2}{\pi}\right)\cos^{-1}\left[\exp\left(-\left\{\frac{(B/2)[1-(r/R)]}{(r/R)\sin\varphi}\right\}\right)\right] \longrightarrow$$

(2.60)

where the angle resulting from the inverse cosine function is assumed to be in radians. If the inverse cosine function is in degrees, then the initial factor, $2/\pi$, is replaced by 1/90. Note, also, that F is always between 0 and 1. This tip loss correction factor characterizes the reduction in the forces at a radius r along the blade that is due to the tip loss at the end of the blade. The tip loss correction factor affects the forces derived from momentum theory. Thus Equations (2.20) and (2.21) become:

$$\mathrm{d}T = F\rho U^2 4a(1-a)\pi r\,\mathrm{d}r \longrightarrow$$

(2.20a)

And

$$\mathrm{d}Q = 4Fa'(1-a)\rho U\pi r^3\Omega\,\mathrm{d}r \longrightarrow$$

(2.21a)

Note that in this subsection, modifications of previous equations use the original equation numbers followed by an 'a' for easy comparison with the original equations.

Equations (2.23) through (2.33) are all based on the definition of the forces used in the blade element theory and remain unchanged. When the forces from momentum theory and from blade element theory are set equal, using the methods of strip theory, the derivation of the flow conditions is changed.

However, carrying the tip loss factor through the calculations, one finds these changes:

$$a'/(1-a) = \sigma' C_l / 4F\lambda_r \sin\varphi \tag{2.45a}$$

$$a/(1-a) = \sigma' C_l \cos\varphi / 4F \sin^2\varphi \tag{2.46a}$$

$$C_l = 4F \sin\varphi \frac{(\cos\varphi - \lambda_r \sin\varphi)}{\sigma'(\sin\varphi + \lambda_r \cos\varphi)} \tag{2.47a}$$

$$a'/(1+a') = \sigma' C_l / 4F \cos\varphi \tag{2.48a}$$

$$a = 1/[1 + 4F \sin^2\varphi / (\sigma' C_l \cos\varphi\}] \tag{2.50a}$$

$$a' = 1/[(4F \cos\varphi / (\sigma' C_l)) - 1] \tag{2.51a}$$

And

$$U_{rel} = \frac{U(1-a)}{\sin\varphi} = \frac{U}{(\sigma' C_l / 4F)\cot\varphi + \sin\varphi} \tag{2.61}$$

Note that Equation (2.49) remains unchanged. The power coefficient can be calculated from

$$C_P = 8/\lambda^2 \int_{\lambda_h}^{\lambda} F\lambda_r{}^3 a'(1-a)[1 - (C_d/C_l)\cot\theta] d\lambda_r \tag{2.52a}$$

$$\varphi = (^2/_3)\tan^{-1}(1/\lambda_r) \longrightarrow \quad (2.64)$$

$$c = \frac{8\pi r}{BC_l}(1 - \cos\varphi) \longrightarrow \quad (2.65)$$

Induction factors can be calculated from Equations :

$$a = 1/[1 + 4\sin^2\varphi/(\sigma' C_l \cos\varphi)]$$

$$a' = \frac{1 - 3a}{4a - 1}$$

These results can be compared with the result for an ideal blade without wake rotation, for which, from Equations (2.40) and (2.41):

$$\varphi = \tan^{-1}\left(\frac{2}{3\lambda_r}\right)$$

$$c = \frac{8\pi r}{BC_l}\left(\frac{\sin\varphi}{3\lambda_r}\right)$$

Note, that the optimum values for φ and c, including wake rotation, are often similar to, but could be significantly different from, those obtained without assuming wake rotation. Also, as before, select α where C_d / C_l is minimal.

Solidity is the ratio of the planform area of the blades to the swept area, thus:

$$\sigma = \frac{1}{\pi R^2}\int_{r_h}^{R} c\,\mathrm{d}r \longrightarrow \tag{2.66}$$

The optimum blade rotor solidity can be found from methods discussed above. When the blade is modeled as a set of N blade sections of equal span, the solidity can be calculated from:

$$\sigma \cong \frac{B}{N\pi}\left(\sum_{i=1}^{N} c_i/R\right) \longrightarrow \tag{2.67}$$

The blade shapes for three sample optimum rotors, assuming wake rotation, are given in Table 2.2. Here C_{l1} is assumed to be 1.00 at the design angle of attack. In these rotors, the blade twist is directly related to the angle of the relativewind because the angle of attack is assumed to be constant (see Equations (2.23) and (2.24)). Thus, changes in blade twist

Table 2.2 Three optimum rotors

r/R	$\lambda = 1$ $B = 1/2$		$\lambda = 6$ $B = 3$		$\lambda = 10$ $B = 2$	
	φ	c/R	φ	c/R	φ	c/R
0.95	31	0.284	6.6	0.053	4.0	0.029
0.85	33.1	0.289	7.4	0.059	4.5	0.033
0.75	35.4	0.291	8.4	0.067	5.1	0.037
0.65	37.9	0.288	9.6	0.076	5.8	0.042
0.55	40.8	0.280	11.2	0.088	6.9	0.050
0.45	43.8	0.263	13.5	0.105	8.4	0.060
0.35	47.1	0.234	17.0	0.128	10.6	0.075
0.25	50.6	0.192	22.5	0.159	14.5	0.100
0.15	54.3	0.131	32.0	0.191	22.5	0.143
Solidity, σ		0.86		0.088		0.036

Note: B, number of blades; c, airfoil chord length; r, blade section radius; R, rotor radius; λ, tip speed ratio; φ, angle of relative wind

would mirror the changes in the angle of the relative wind shown in Table 2.2. It can be seen that the slow 12-bladed machine would have blades that had a roughly constant chord over the outer half of the blade and smaller chords closer to the hub. The blades would also have a significant twist. The two faster machines would have blades with an increasing chord as one went from the tip to the hub. The blades would also have significant twist, but much less than the 12-bladed machine. The fastest machine would have the least twist, which is a function of local speed ratio

only. It would also have the smallest chord because of the low angle of the relative wind and only two blades (see Equations (2.64) and (2.65)).

CHAPTER III

METHODOLOGY

3.1 Blade design mechanism

Wind turbine blades must be designed to convert the kinetic energy in the wind into torque, while having structural properties that ensure the required static and fatigue strength for a long operational life. The starting point for wind turbine blade design assumes uniform axial flow upstream of the wind turbine two-dimensional flow over the blades and steady operating conditions, all under specific design aerodynamic conditions defined by the relationship between the rotor rotational speed and the incoming wind speed. Modern turbines evolved from the early designs and are typically classified as two or three blade rotors. Most of the turbines used today have three blades. The rotational speed is also a very important design factor. Turbines operating at a constant rotor speed have been fomenting up to now, but turbines with variable rotational speed are becoming increasingly more common with the desire to optimize the energy captured and to lower stress.

An important factor that determines the efficiency of a turbine is the profile of the blade, how effectively the Profile performs at various wind speeds and especially at high angles of attack that may exist locally on a wind turbine. Another factor is to have effective turbine startup and performance at low wind speeds. Blade designers employ the actual airfoil profile along the span of the blade (which is where power is produced) whereas the root is a shape between the airfoil profile and the circular section of the hub and thus does not contribute to power generation. The efficiency of the rotor largely depends on the blades profile in increasing the lift to generate sufficient torque. The airfoil is one of the fundamental parts of a rotor blade design. Its purpose is to induce suctionon the upper surface of the blade to generate lift. Drag is also generated perpendicular to the lift and its presence is highly undesirable. Typical aerodynamic characteristics of an airfoil used for wind turbine applications include a high C_L to C_D (L/D) ratio, a moderate to high C_L and trailing edge stall.

A high *L/D* ratio maximizes the energy produced by the turbine as well as reducing standstill loads, and it also contributes to higher values of torque. It is desirable that at favorable *L/D* ratios, there should be maximum C_L in order to have a small sized rotor. In order to maximize the power coefficient and the torque generated, the lift coefficient (C_L) and the lift to drag ratio (*L/D* ratio) for the airfoil must be maximized . The C_L value at maximum *L/D* should be approximately within 0.2 with respect to the maximum C_L value. In addition, low roughness sensitivity with respect to the maximum *L/D* and C_L value is desirable for optimum power production. Small wind turbines must also overcome separation bubbles associated with low Reynolds number airfoils as discussed by Lissaman. Power is decided which is needed at a particular wind velocity, *U* and included the effect of a probable C_P and efficiencies, η, of various other components. The radius, *R*, of the rotor may be estimated from: $P = C_P\eta(1/2)\pi\rho R^2 U^3$

Airfoil drag and tip losses that are a function of the total number of blades reduce the power coefficients of wind turbines. The maximum achievable power coefficient for turbines with an optimum blade shape but a finite number of blades and aerodynamic drag has been calculated by Wilson et al. (1976) [41-46]. Efficiency of a turbine is the important factor because it is the profile of the blade and effectively performs at various wind speeds, high angles of attack. Rotor efficiency largely depends on the blades profile in increasing the lift to generate sufficient torque. Assume η for your mechanical parts according to the state of your machines. In this project choose a tip speed ratio, λ, is 5. Choose the number of blades, B = 3. The airfoil is one of the fundamental parts of a rotor blade design. Its purpose is to induce suction on the upper surface of the blade to generate lift. Drag is also generated perpendicular to the lift and its presence is highly undesirable. A high *L/D* ratio maximizes the energy produced by the turbine as well as reducing standstill loads, and it also contributes to higher values of torque [47]. The SG6043 airfoil was selected based on their performance.

3.2 WIND TURBINE DESIGN AND CONSTRUCTION

3.2.1 Introducton

To design wind turbine, it is needed first to design the blades. Before that, we have observed the various wind speed at various cities and towns in our country.

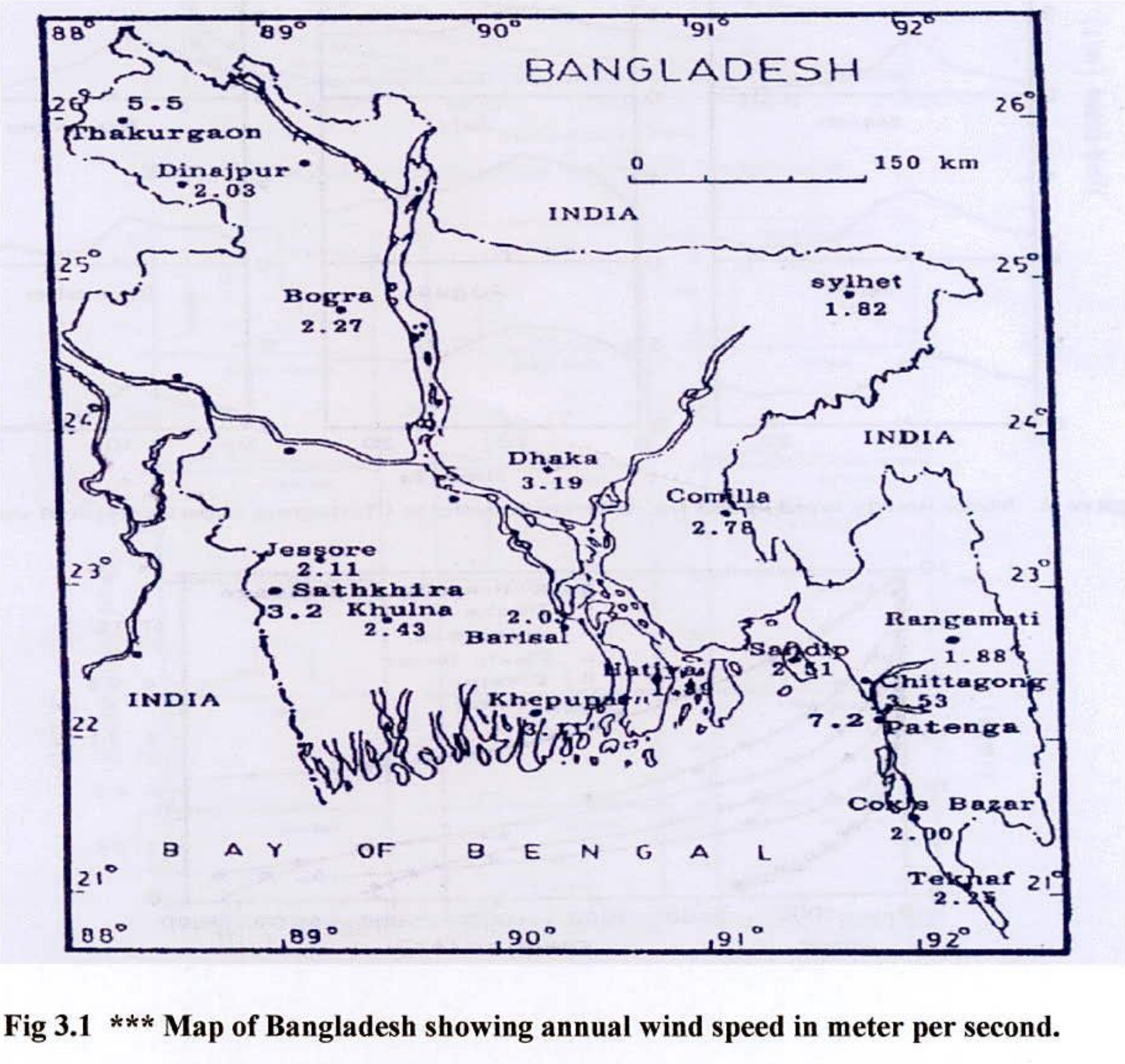


Fig 3.1 * Map of Bangladesh showing annual wind speed in meter per second.**

The above map shows the annual average wind speed (in ms^{-1}) of Bangladesh. This map says, the majority of the cities of Bangladesh have the wind speed above 2.0 ms^{-1} or equal to 2.0 ms^{-1} (except Sylhet =1.82 ms^{-1} & Rangamati=1.88 ms^{-1}). And basically the conventional blades rotate above 4.5 ms^{-1} wind speed. On the other hand, we have built our wind turbine in the city of Khulna that has 2.43 ms^{-1} wind speed. But we have built such type of blades that can rotate under 2.5ms^{-1} wind speed.

3.2.2 DESIGN OF WIND TURBINE:

The procedure begins with the choice of wind speed class, various rotor parameters and the choice of an airfoil. An initial blade shape is then determined using the optimum blade shape assuming wake rotation. The final blade shape and performance are determined iteratively considering drag, tip losses, and ease of manufacture. The steps in determining a blade design follow.

3.2.2.1 Selection of wind speed classses

One of the most important considerations in wind turbine design is the environment where it will be installed. Wind turbines can work in almost all the places, but the design dimensions shall be different depending on the design place. To classify those places, the IEC standards (International Electrotechnical Commission) provide four groups. These classifications are dependent on wind velocity and the intensity of the turbulence.

Table 3.1: wind turbine classes

Wind turbine class		**I**	**II**	**III**	**S**
Vref (m/s)		**50**	**42,5**	**37,5**	**-**
A	**Iref**	**0,16**			**-**
B	**Iref**	**0,14**			**-**
C	**Iref**	**0,12**			**-**

Vref is the reference wind speed average over 10 min.
A designates the category for higher turbulence characteristics.
B designates the category for medium turbulence characteristics.
C designates the category for lower turbulence characteristics.
Iref is the expected value of the turbulence intensity at 15 m/s.

For the fourth wind turbine class, the class S, the manufacturer shall describe the models used and provide values of design parameters in the design documentation (two examples of use are off-shore wind turbine and places with hurricanes).

The class we use for our 0.44 meter blade is class III. The wind turbine will be located in a place that doesn't have very strong winds. The wind speed average will be 3.5 $m.s^{-1}$. We will have a cut-in between 2 and 3 $m.s^{-1}$ and a Cut-out between 9 and 10 $m.s^{-1}$.

We want that our blade reaches its nominal power at the nominal wind speed which is 10 m.s-1. This is how my supervisor decided to make a 1.2 meter blade. We want to have 100 W of power, with an efficiency of 0.5 (this value is from average). The power formula is the following one:

$$\mathbf{P=0.5*1.24*0.5*(\pi*D^2/4)*V_{nom}^3}$$

1.24 is the air density, in $kg.m^{-3}$ and D is the rotor diameter (0.44*2 + 0.32 meters of hub).
V_{nom} is the nominal wind speed.
The loads and momentums may be the same for a class I, II or III. The class III wind turbines will start to produce power at lower wind speeds than classes I or II . It can be used more widely but it has the main disadvantage of being less cost effective that the class I ones.

3.2.2.2 Select Blade Profile

Two very important elements of a successful wind turbine are the blade and the power control system. In designing the blade, the most essential thing is to choose a good profile.A blade profile is typically similar to the wing of an aircraft. In fact, we used to choose a classical aircraft wing profile as a cross section in the past. We used them because there were not any other profiles available and the shape has a big similarity. In more recent times and thanks to new researches, engineers have begun to design profiles specific to wind turbines.

It is important to say here that a wind turbine blade use lift at all moment. The lift makes the rotor turn, even for low wind speed. If the wind is "pushing" the blade it means the blade turns because of drag. We can compare it to a sail boat. If the wind is pushing the boat from the rear, the boat will move thanks to the drag. If the boat moves perpendicularly to the wind it will use lift and will be ten times faster than the wind speed. That is why a blade is designed in order to use only the lift as a turning force.

When we select a profile we must check several important criteria: it should have a high coefficient of lift while maintaining a low coefficient of drag. Consequently the CL/CD coefficient should have a high value. Before designing the blade, a number of compromises including good lift and stall characteristics are also taken into consideration. The blades must be easy to produce and resistant to the weather. The profile must be still efficient for the blade stability according to dust and dirt accretion.

Based on the above criteria, we selected SG6043 airfoil.

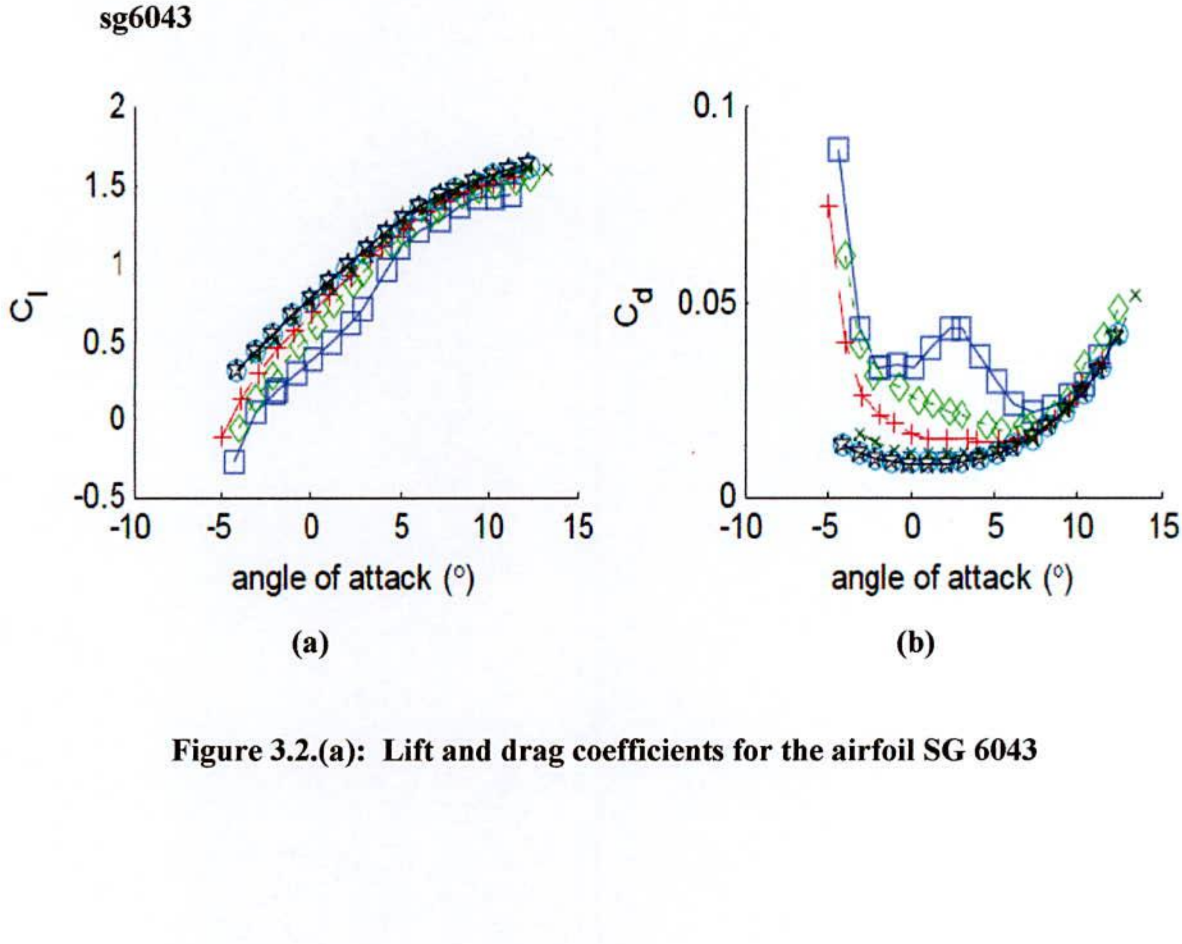
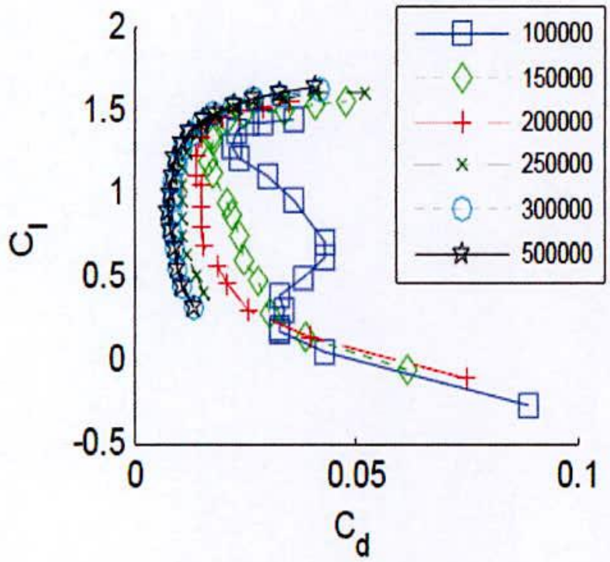
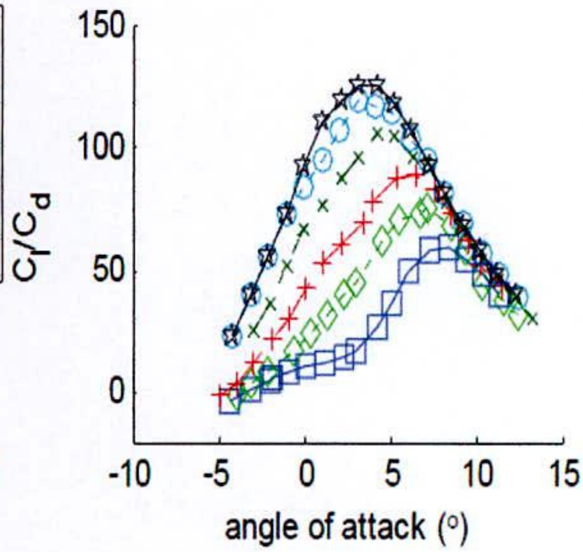


Figure 3.2.(a): Lift and drag coefficients for the airfoil SG 6043



(c)



(d)

Figure 3.2. (b) : Lift and drag coefficients for the airfoil SG 6043

3.2.2.3 Chord lengths

When the wind passes through the rotor plane and makes contact with the moving rotor, it provides the lift force on the blade. This force can be found using the equations below:

$$F_L = \frac{1}{2} C_L \, . \, \rho \, . \, c \, . \, W^2$$

The drag is force:

$$F_D = \frac{1}{2} C_D \, . \, \rho \, . \, c \, . \, W^2$$

Where,

C_L is the lift coefficient

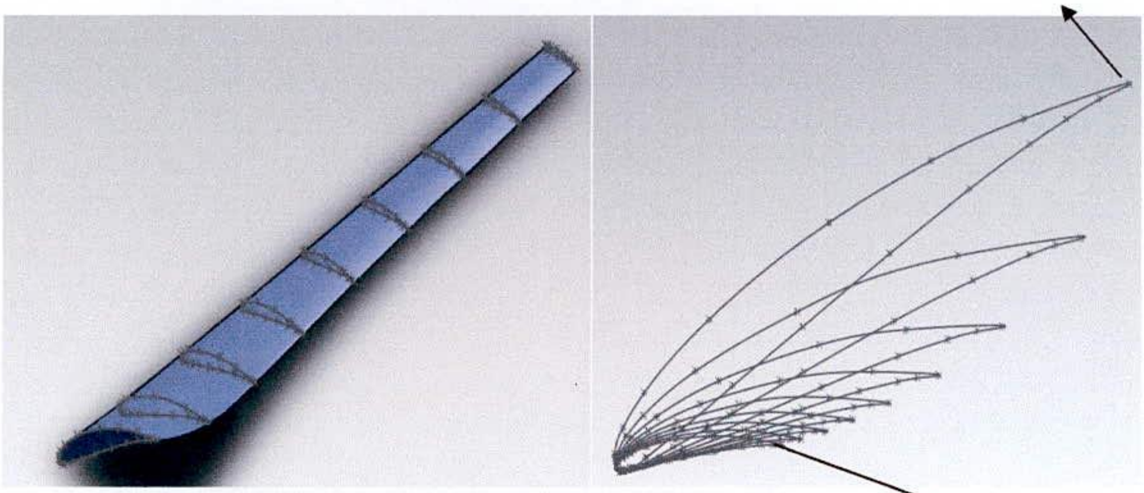
C_D is the drag coefficient

ρ is the density of the air

c is the chord length

W is the relative wind speed (Vrel)

If the chord length increases, the lift force also increases. We are not interested in the increase of the drag coefficient because it's applying bending moment at the blade. As we know, the force on the blade is related to the wind speed and the swept area (of the rotor). The forces within a blade are increasing with the radius and the loads in the root are higher than the loads on the tip. This is why the chord length must change from the root to the tip. Depending on the radius we can design different chord lengths in different sections, specifically bigger at the root and smaller at the tip.



(a) (b)

Figure 3.3: section of blade by solid work program

We calculated the chord lengths for 9 sections, from the very root to the very tip of the blade.The distance of every element is 0.12 m. The maximum chord equals 0.11 meters at the root and at the tip the chord length is 0.035 m. For a 1.2 meter blade, we design the blade section by solid work 2011 and calculate all the airfoil elements data by Matlab's program.

3.2.2.4. Angle of attack

The angle of attack, or angle between the chord line and the relative velocity, is calculated by this expression:

$$\alpha = \phi - (\beta + \theta_P)$$

Where,

ϕ is the flow angle

β is the twist of the blade

θ_P is the pitch angle

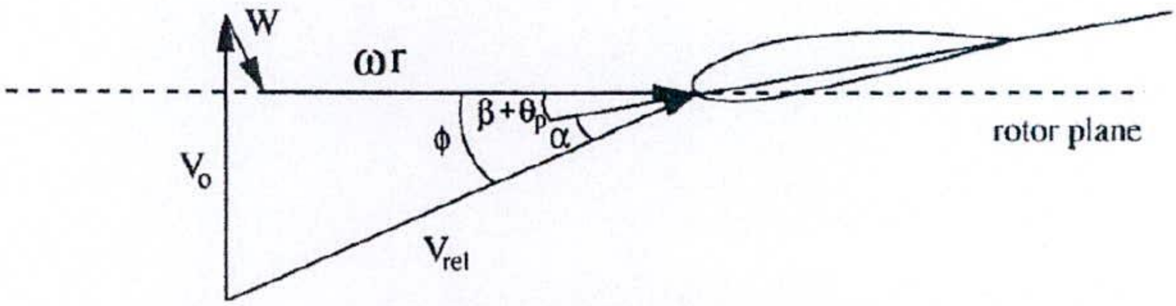


Figure 3.4: Flow around section of a wind turbine blade

The angle of attack for a wind turbine may be determined by the coefficient of lift and drag. The design angle should be the angle where the lift is the biggest, and the drag is the smallest. We determined the angle of attack is 15.5 degrees.

3.2.2.5 Twisting angles

There are some important angles in blade design.

1. The angle of attack α is the angle between the profile's chord line and the direction of the airflow wind.
2. The flow angle ϕ is the angle between the relative velocity and the rotor plane.
3. The pitch angle θ_P is the angle between the tip chord and the rotor plane.
4. The twisting angle β which is the angle measured relative to the tip chord. We can calculate this value using the expression $\phi = \alpha + \beta + \theta_P$.

A rotor blade will stop providing enough lift once the wind hits the blade at a steeper angle of attack. The rotor blades must therefore be twisted to achieve an optimal angle of attack throughout the length of the blade.

Assume that the tip pitch angle θ_P is zero. ϕ will equal $\alpha + \beta$. The angle between the profile's chord line and the rotor plane should be the twisting angle β. Considering W, the induced velocity constant we can easily see from Figure 3.3 that if we grow the rotational speed, ωr it will reduce the flow angle ϕ consequently the blade needs to be twisted to keep the same angle of attack α. This angle α is equal to 15.5 degrees .we calculated the twisting angle is 10.6°.

3.2.2.6 Yaw control

There is another possible control that can be added to a wind turbine. This system will yaw the rotor partly out of the wind so it will also decrease the output power and forces on the system. Yawing the rotor will reduce its swept area. Yaw control is especially suitable for our small turbine, as it subjects the rotor to cyclically varying stress which may ultimately damage the entire structure. This kind of control is called furling. We used rudder for the controlling the yaw.

3.2.2.7 Tip speed ratio

The tip speed ratio is the ratio of the speed of the blade's tip, over the wind speed. After choosing a satisfying profile, we had to design the blade with this profile.For the tip speed ratio, we used the formula:

$$X = V_{TIP} / V_0 = \frac{R\omega}{V_o}$$

We assumed that our blade would be operated at rotational speed of 400 rpm with a nominal wind speed of 10 m/s. If we implement our assumption in this formula, R becomes 0.44 m, and we can get the tip speed ratio

$$X = 5$$

This ratio should not exceed 10, if we take in account noise consideration.

3.2.2.8 Blade Materials

The blade endures many loads during its life. The two main loads are gravity and centrifugal forces. The rotating mass load is a very important factor to take into consideration when designing a blade. The inertia depends on the mass thus we want a light blade. Therefore the choice of material is very important. The blades must be light weight but strong enough to resist the different loads. A rotor blade can be made from different materials. The most commonly used materials are fibre glass and FRP (used to manufacture both, internal and external parts of the blade). Each one of these materials has different characteristics, they have two different chemical compositions and mechanical properties. We selected nylon fiber for our turbine blade.

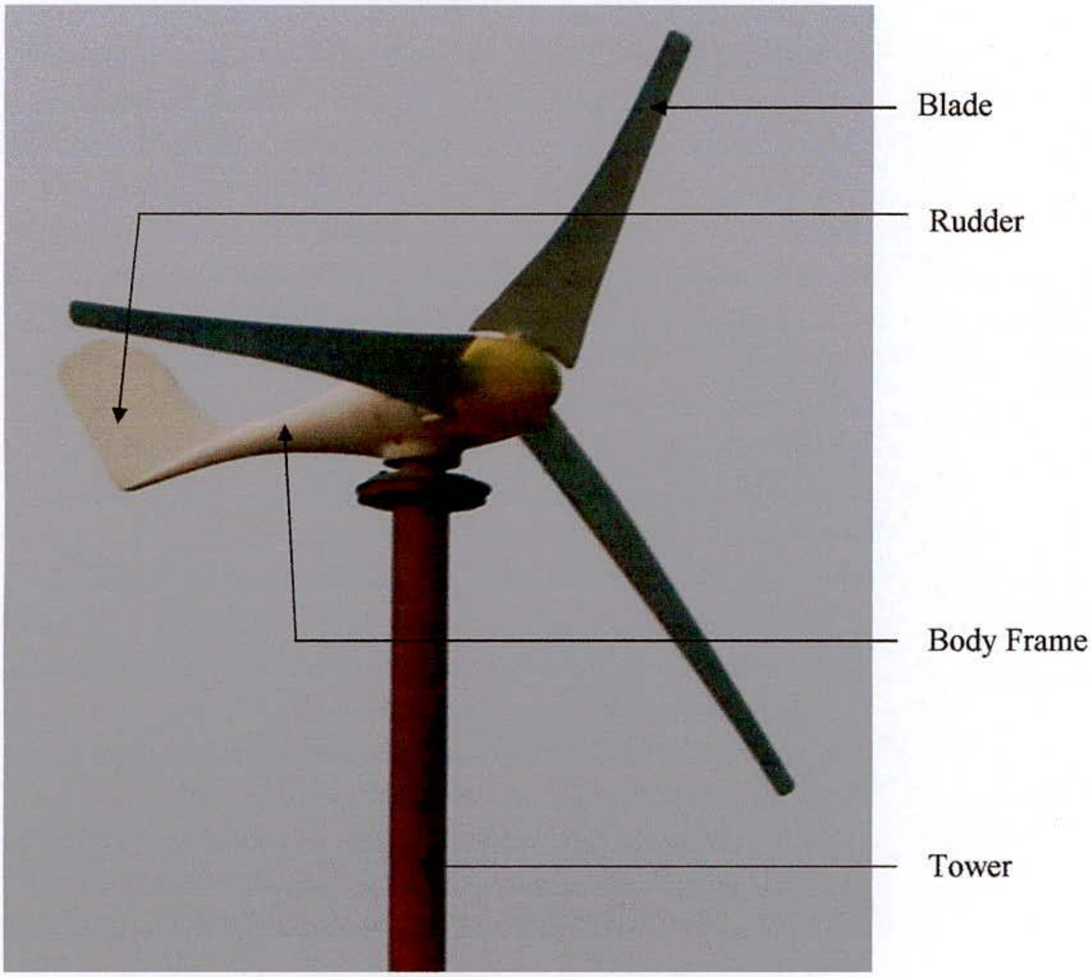


Figure 3.5: Parts of the Wind Turbine.

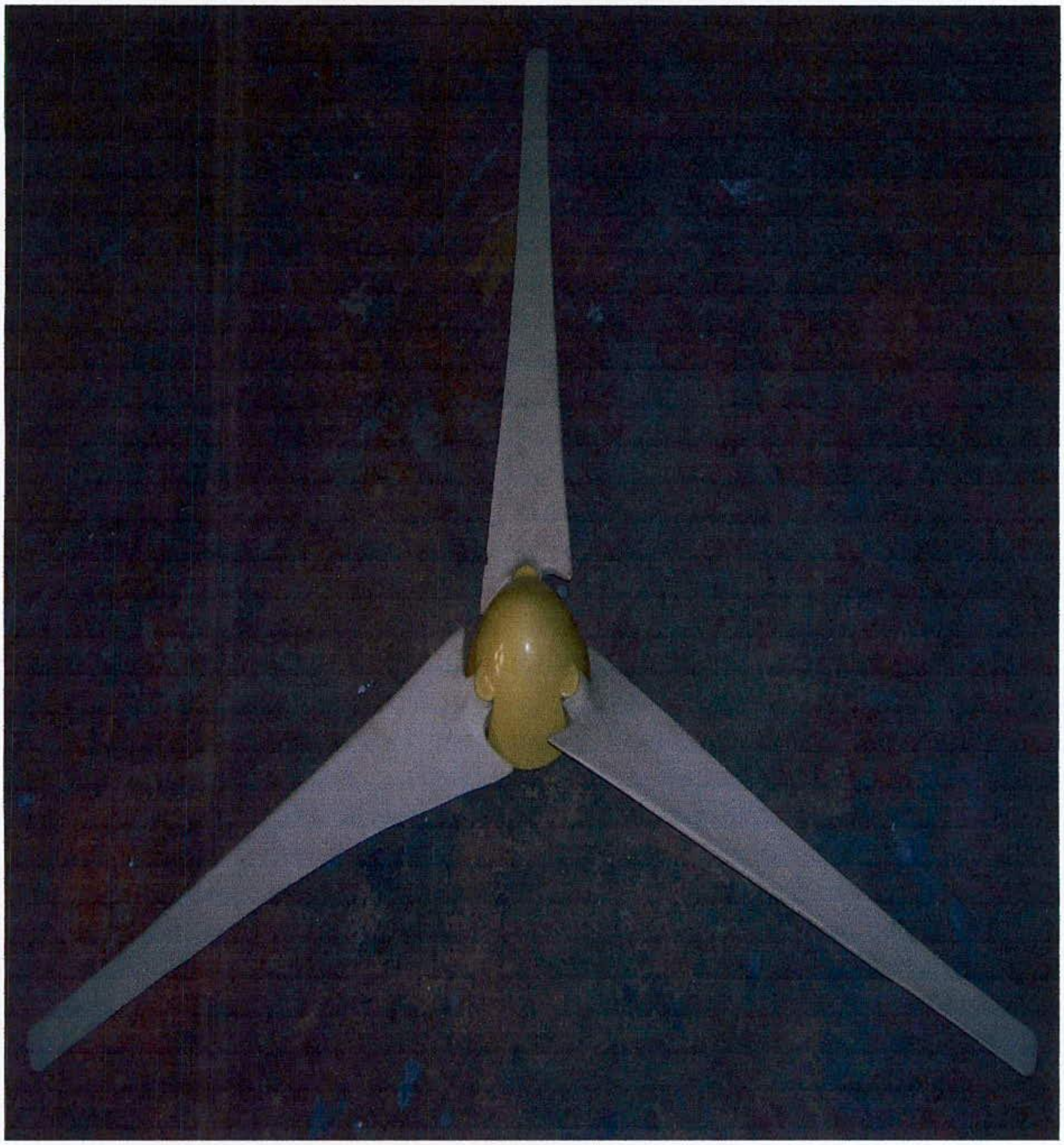


Figure 3.6: Three Blades of our designed Wind Turbine.

3.3 Construction of wind turbine

To design our wind turbine, we assigned some specific parameters. Here some of those are being shown---

Table 3.2 : **Turbine Specification**

Rated Power	100 W
Nominal voltage	12 /v
Start-up wind speed	$\leq 2.5\ ms^{-1}$
Rated wind speed	10 ms^{-1}
Rated rotational speed	400 r/min
Safe speed	55 ms^{-1}
Wind wheel diameter	1.2 m
Blade number	3
Blade material	Nylon fiber
generator	Permanent magnet synchronous generator with three-phase alternating current
Controller system	Electromagnetic / wind turbine hemi lateral
Speed way	Automatic adjustment of wind angle
Working temperature	-40°C ~ 80°C
Tower height	10.3 m

But we didn't fount any company in our own country to make such a turbine. So we had to take abroad help to make this turbine. In spite of this, we could make the turbine tower from our own country in the city of Khulna.

CHAPTER IV

EXPERIMENTAL RESULTS AND DISCUSSION

4.1 Experimental Results:

In the month of February, March & April, we measured our local wind speed, output current & voltage of the wind turbine. Here some of the measured data has been given below---

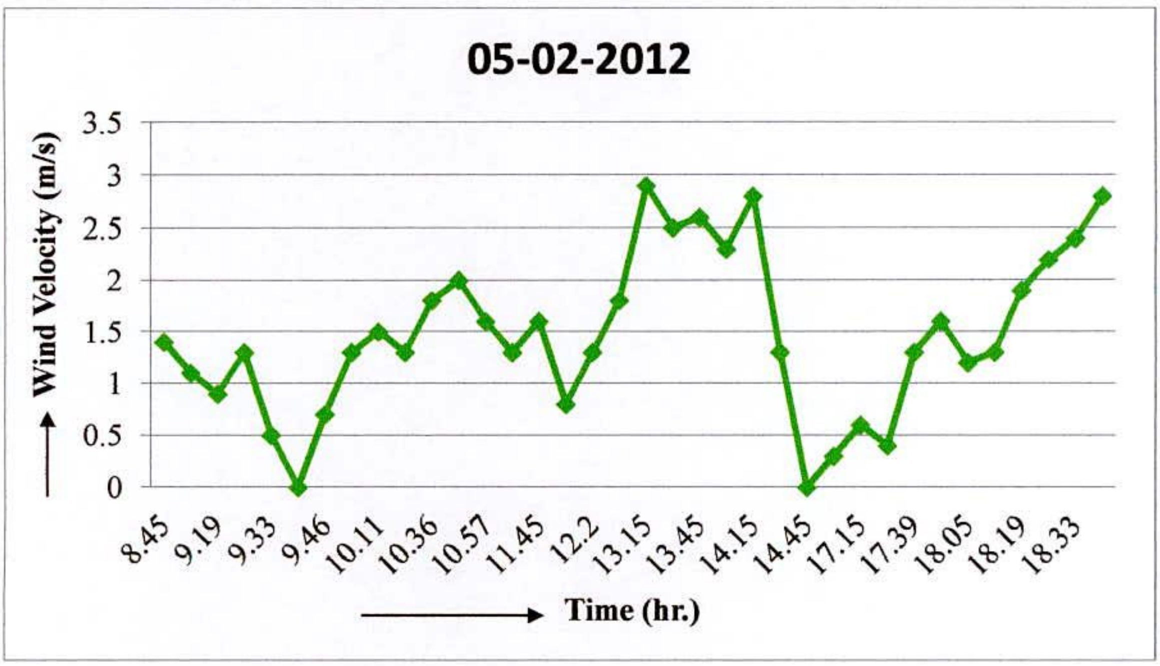


Fig 4.1 (a): Wind velocity at different time on 5th February in KUET.

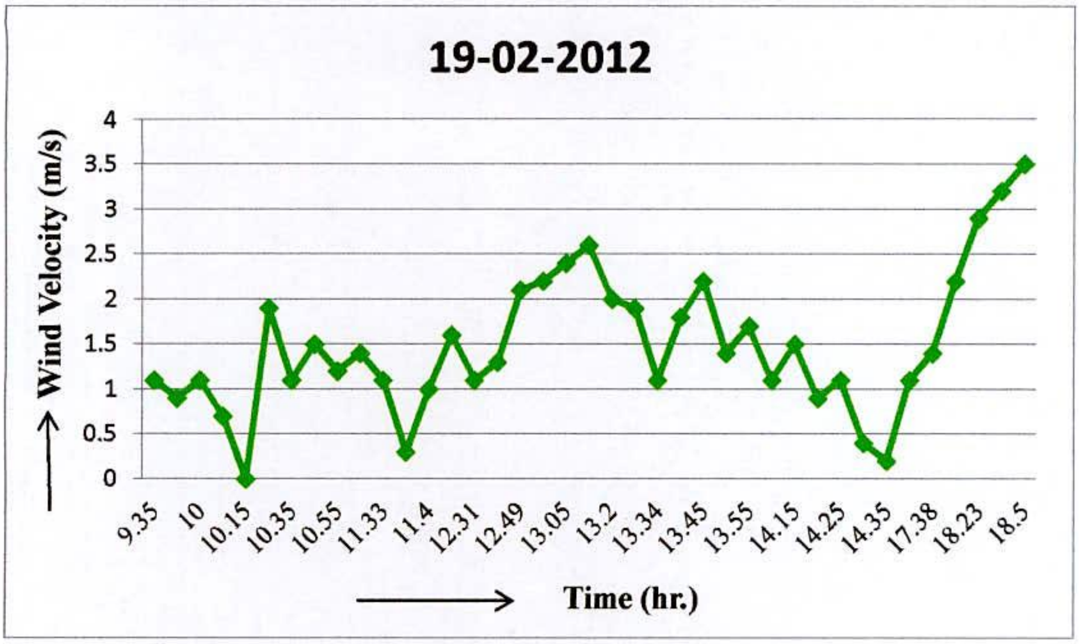


Fig 4.1 (b): Wind velocity at different time on 19th February in KUET.

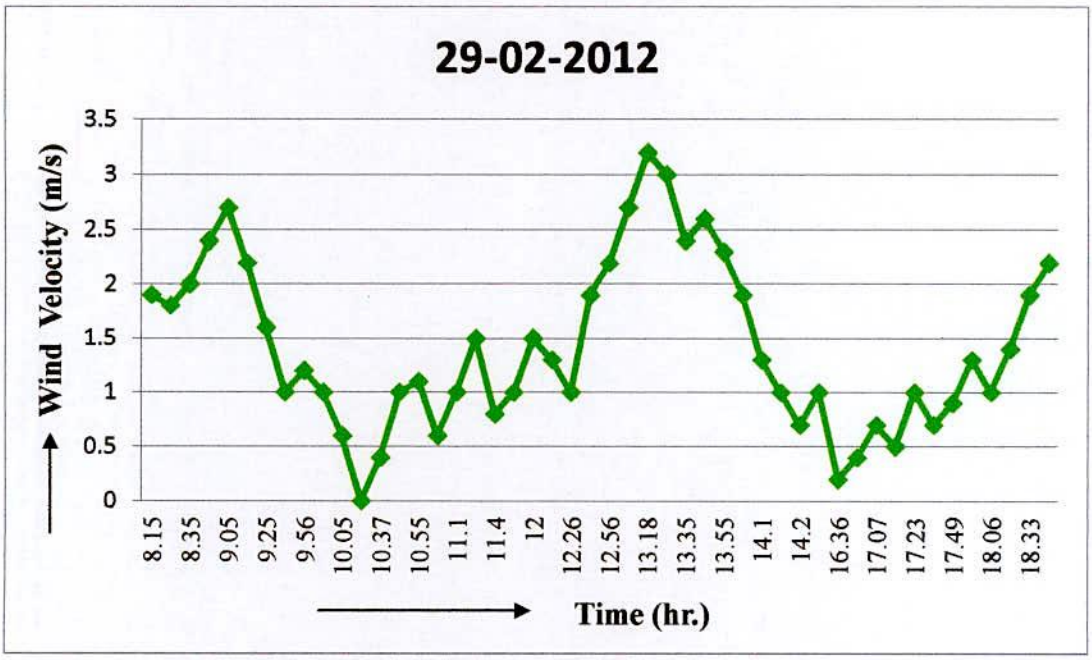


Fig 4.1 (c): Wind velocity at different time on 29th February in KUET.

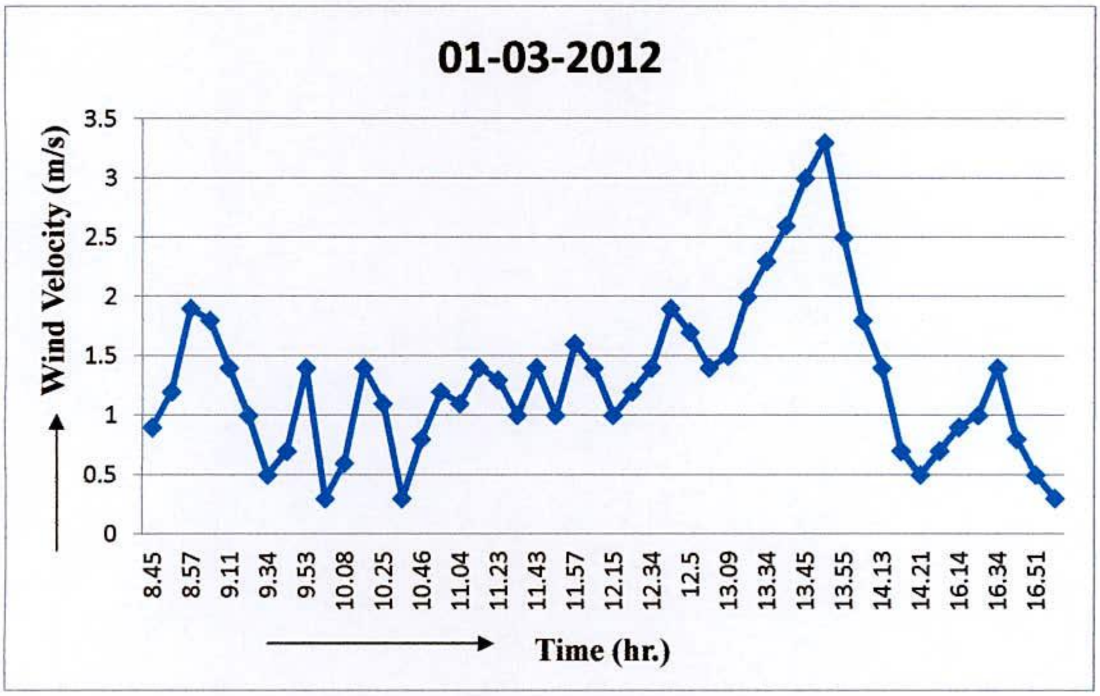


Fig 4.1 (d): Wind velocity at different time on 1st March in KUET.

Fig 4.1 (e): Wind velocity at different time on 15th March in KUET.

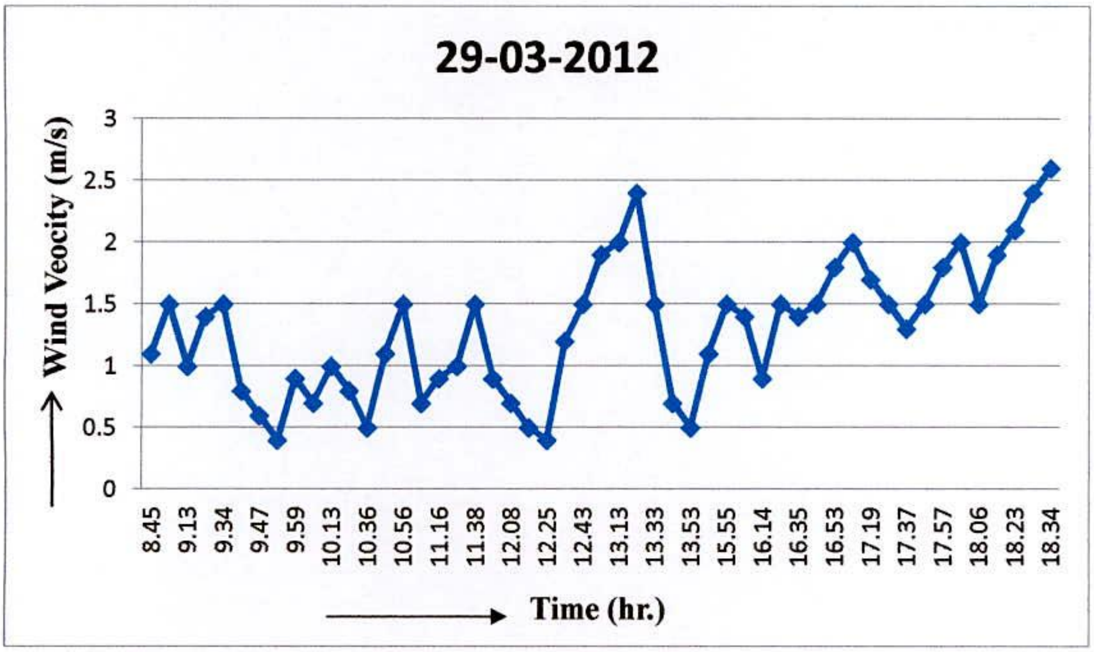


Fig 4.1 (f): Wind velocity at different time on 29th March in KUET.

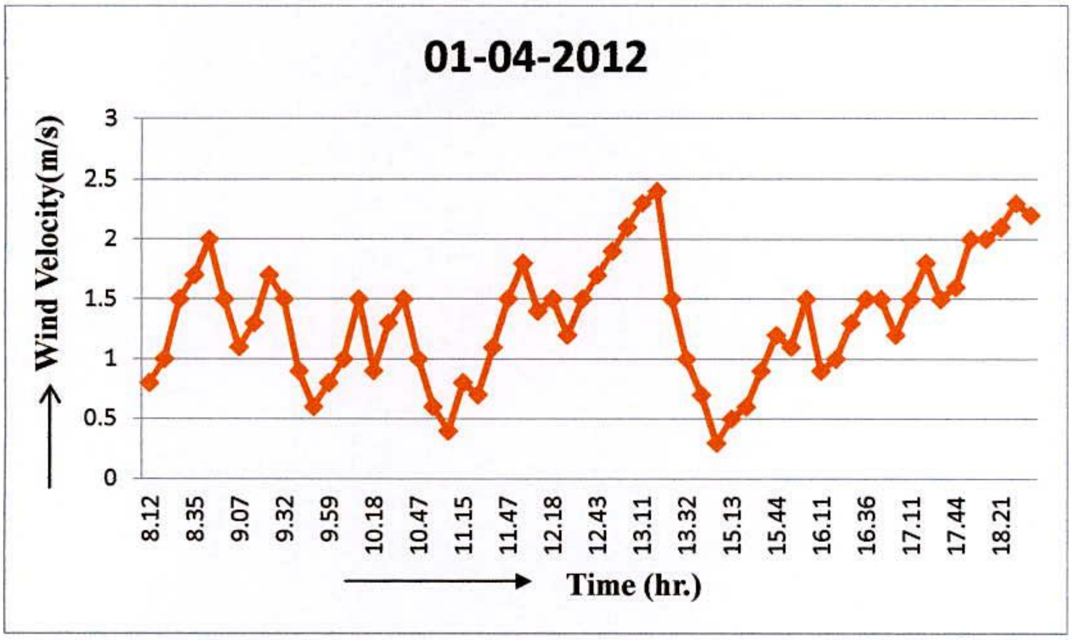


Fig 4.1 (g): Wind velocity at different time on 1st April in KUET.

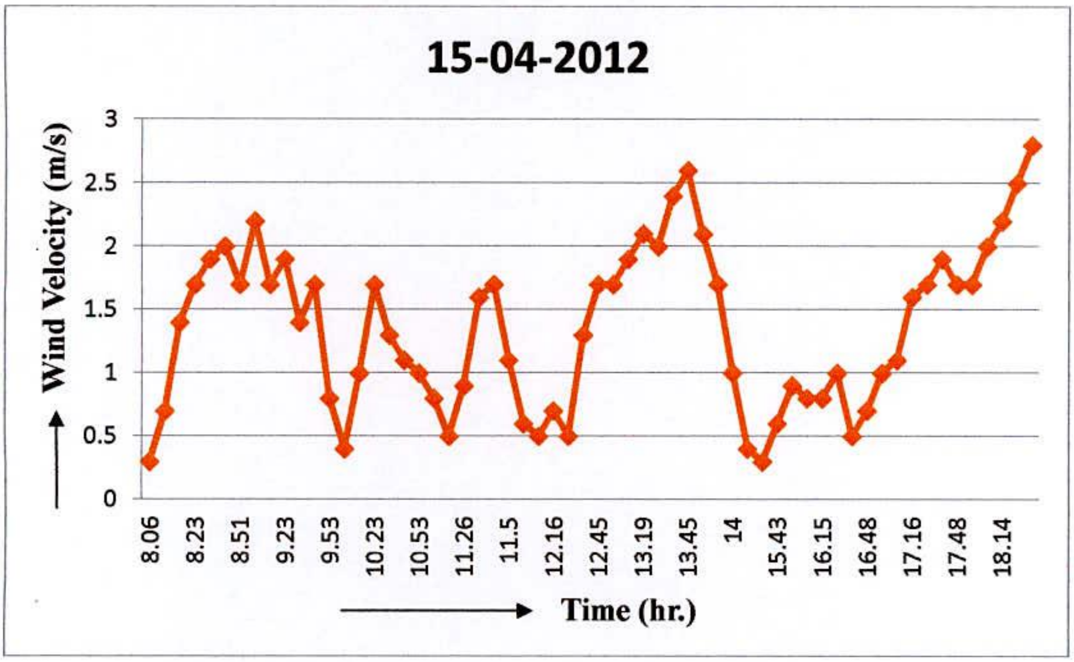


Fig 4.1 (h): Wind velocity at different time on 15th April in KUET.

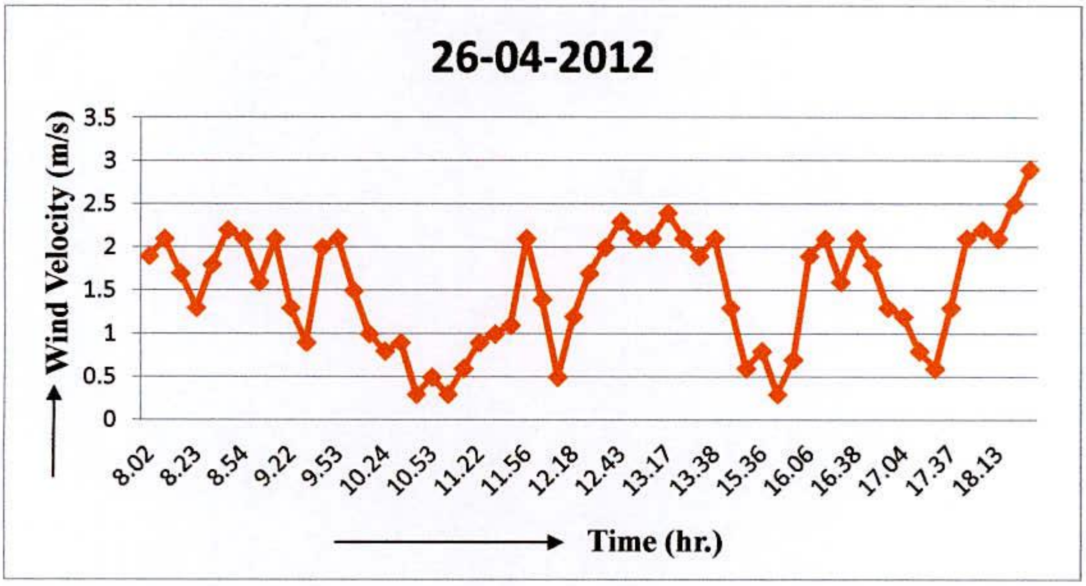


Fig 4.1 (i): Wind velocity at different time on 26th April in KUET.

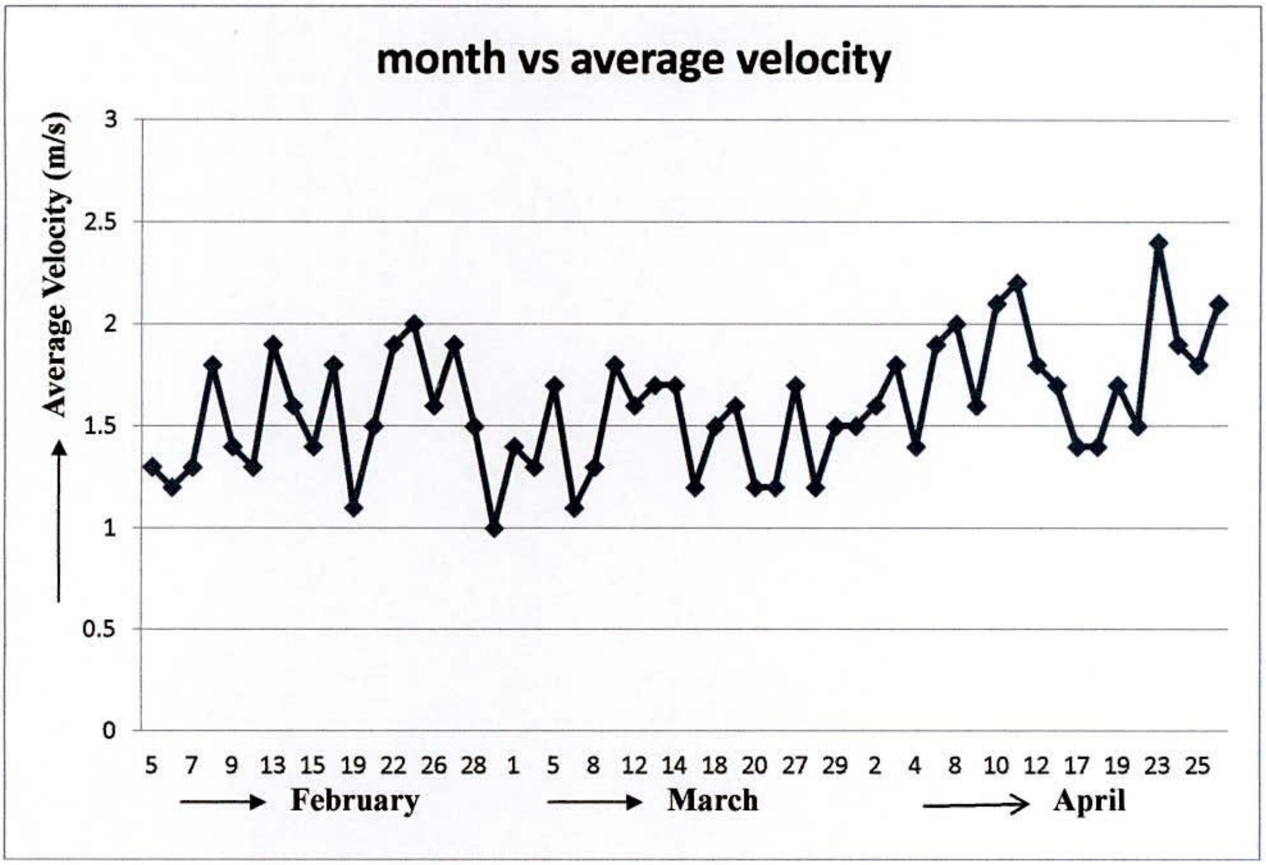


Figure 4.1 (j): Daily average wind speed in different months at KUET in Khulna.

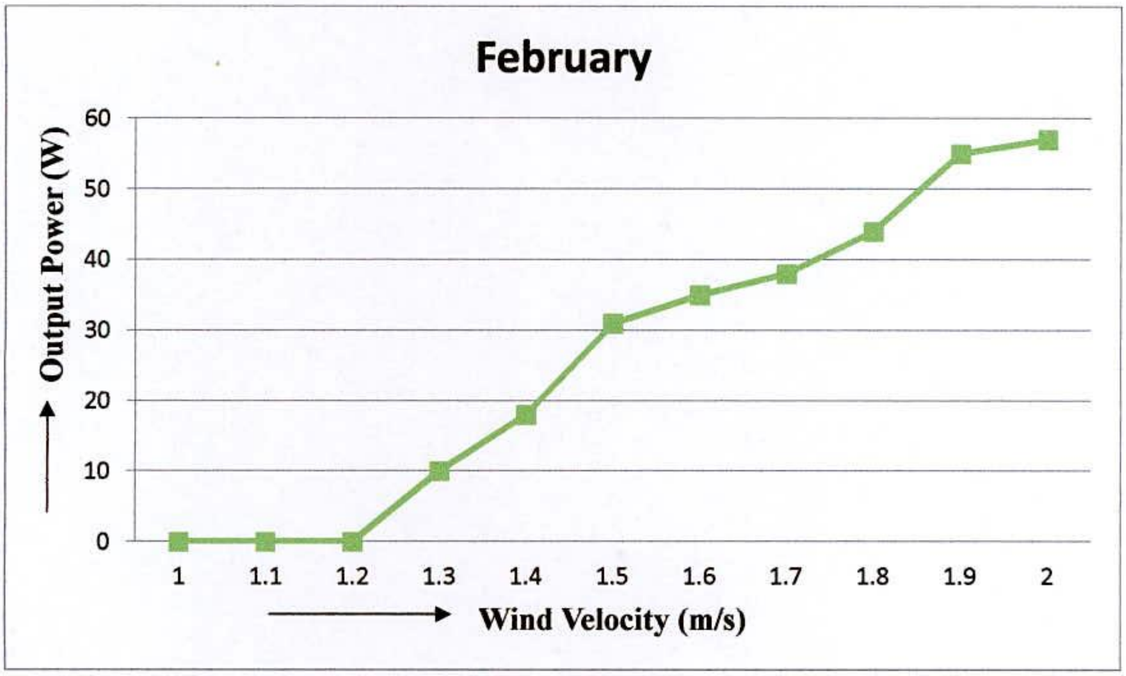


Figure 4.1 (k): Daily Average output power Vs Daily Average wind speed in the month of February at KUET in Khulna.

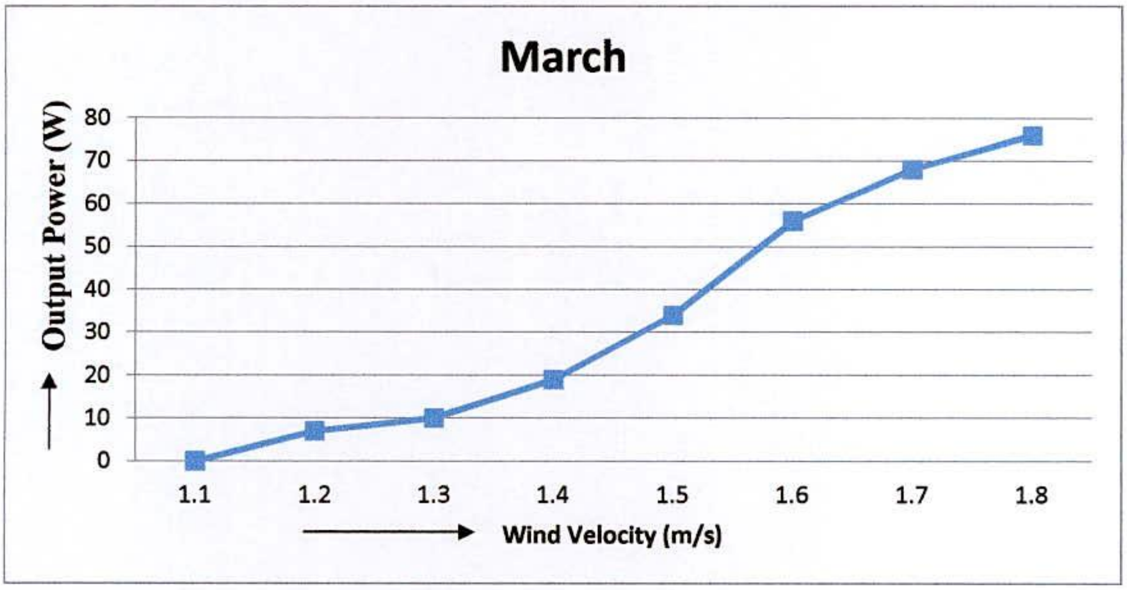


Figure 4.1 (l): Daily Average output power Vs Daily Average wind speed in the month of March at KUET in Khulna.

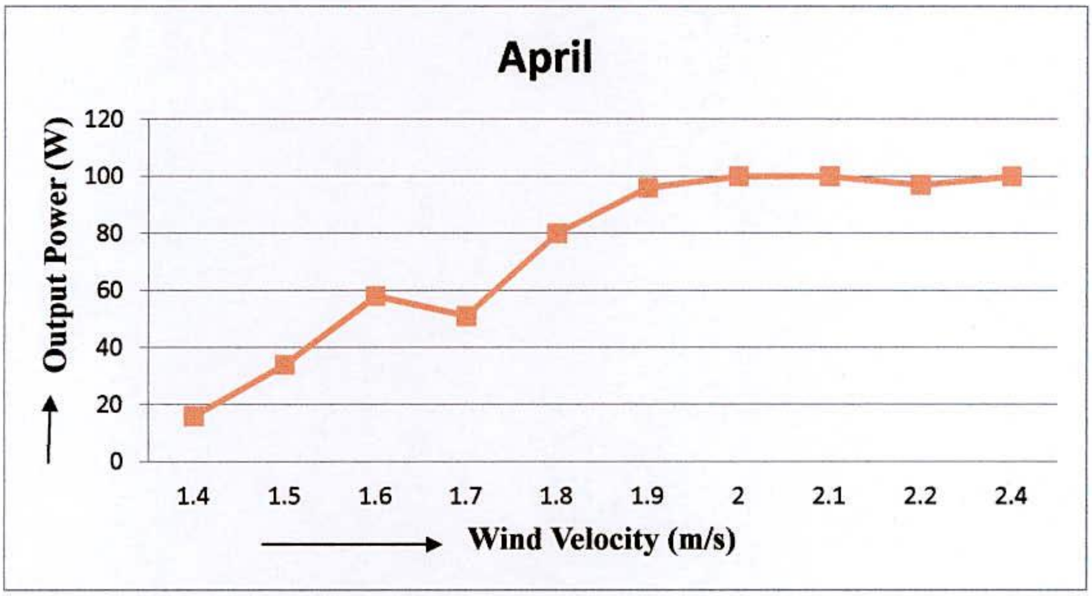


Figure 4.1 (m): Daily Average output power Vs Daily Average wind speed in the month of April at KUET in Khulna.

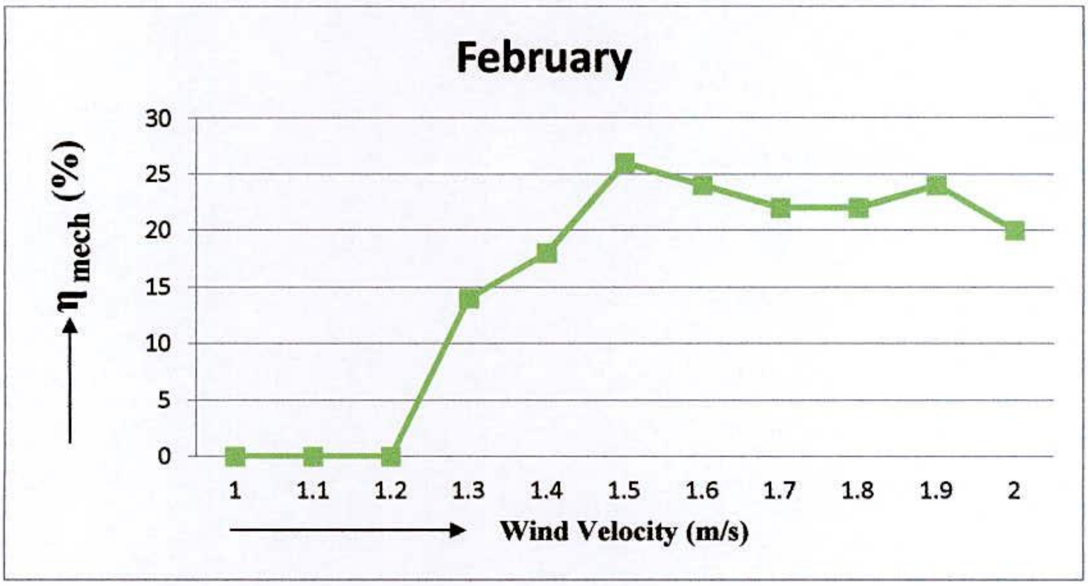


Figure 4.1 (n): Daily Average Mechanical Efficiency in February at KUET.

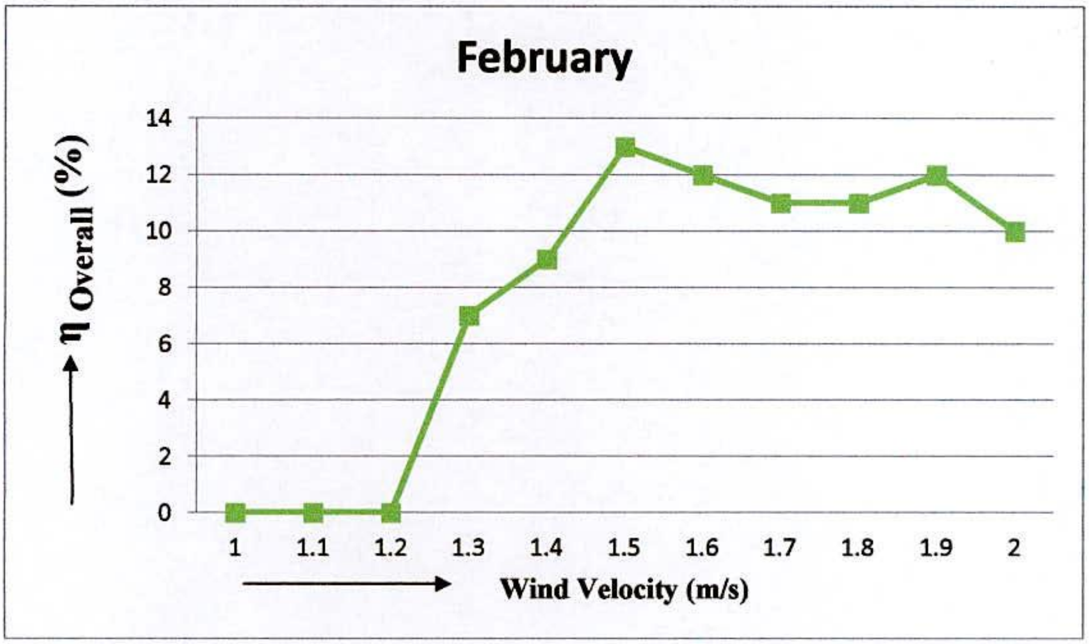


Figure 4.1 (o): Daily Average Overall Efficiency in February at KUET.

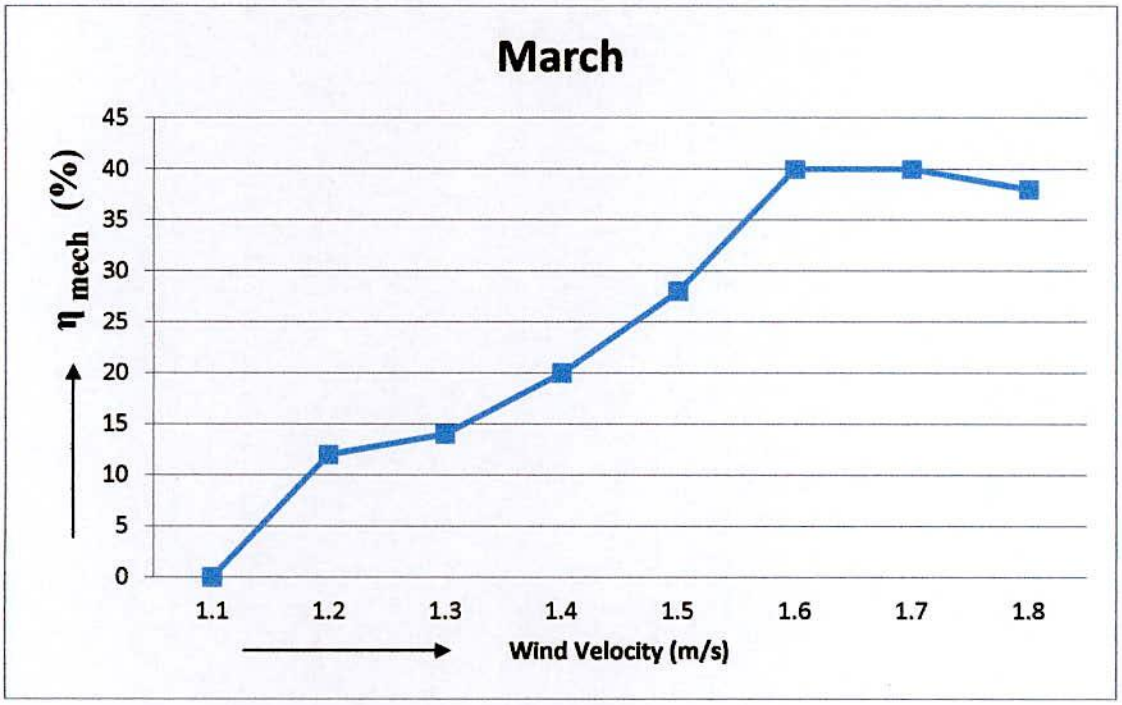


Figure 4.1 (p): Daily Average Mechanical Efficiency in March at KUET.

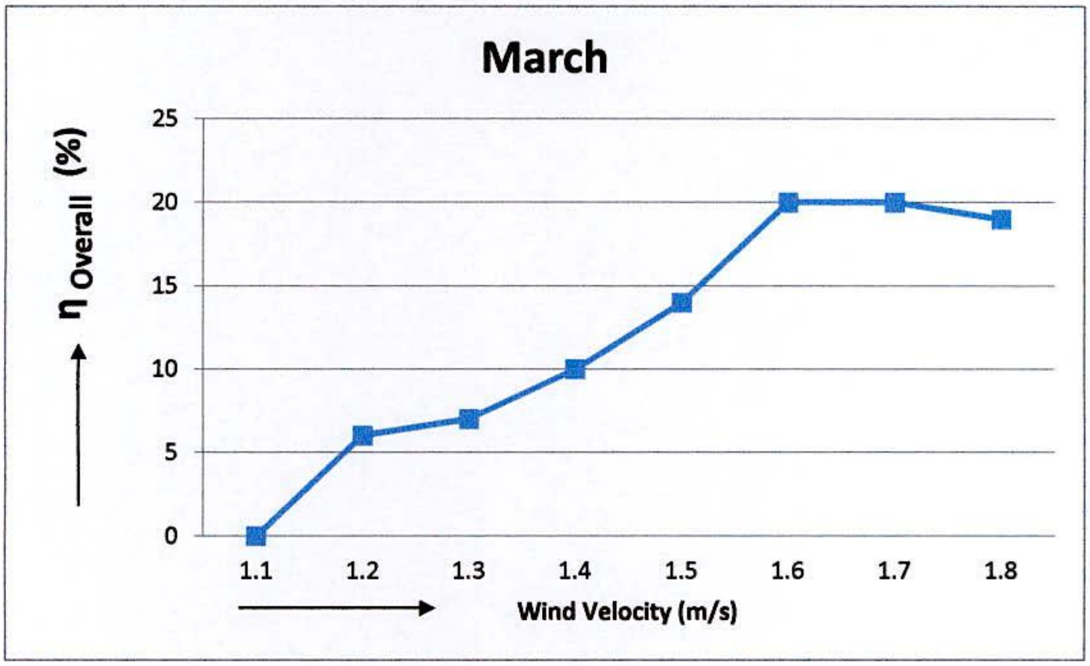


Figure 4.1 (q): Daily Average Overall Efficiency in March at KUET.

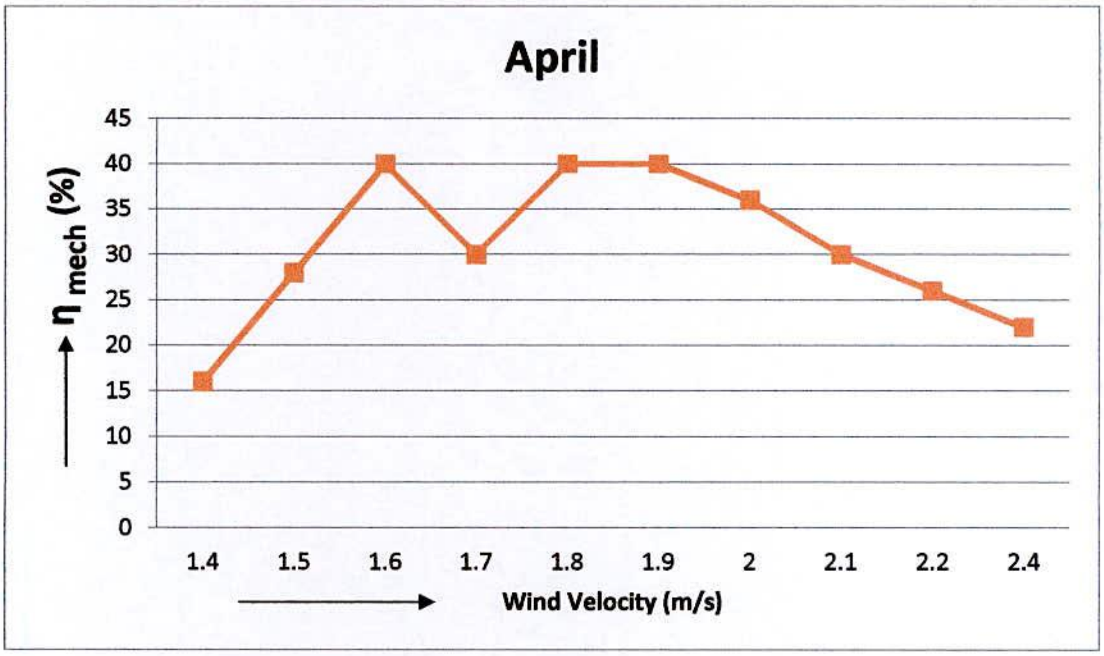


Figure 4.1 (r): Daily Average Mechanical Efficiency in April at KUET.

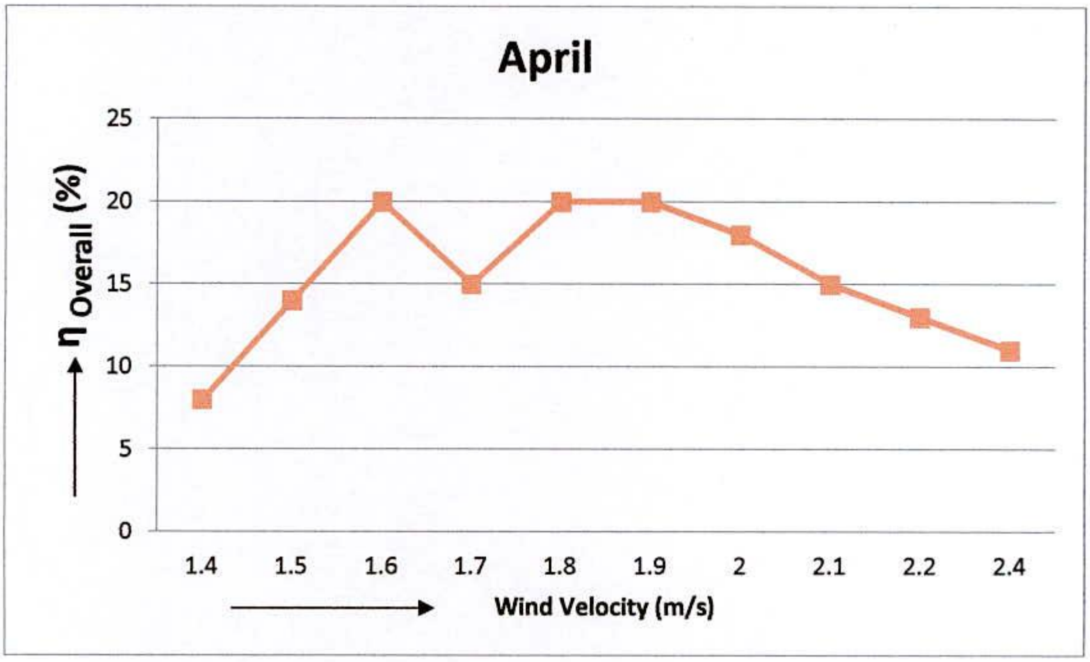


Figure 4.1 (s): Daily Average Overall Efficiency in April at KUET.

From this experiment, it is being seen that in most cases, rate of wind velocity is high in the morning.When time is increased the wind velocity is decreased, on the other hand,wind velocity rate is rapidly climed in the 12.30 p.m. and in the 2 p.m to 5.30 p.m the wind velocity rate is low and it is fluctuated. Moreover, wind velocity is sharply increased in the 5.45 p.m to 7 p.m. On the other side, the output power gradually increasesed as the wind speed increased. We got the highest output power in the month of April which was 100 W.

CHAPTER V

CONCLUSION

5.0 Conclusions

To recapitulate , we developed a low start-up speed wind turbine which rotates in a low wind velocity. We selected sg6043 airfoil which is suitable for our blade design. Furthermore, we considered high lift coefficient and low drag coefficient since chord Length is affected by lift and drag coefficient. We neglected pitch angle and used rudder for controlling Yaw. For this reason, our turbine automatically changes its direction and can rotate below 2.5 ms^{-1}. On the other side, we selected a suitable tip speed ratio for avoiding noise. Besides, we measured the output power and voltage for our turbine in the different times in the month of February, March and April.

We have got the highest power [100W] in the month of April.

Recommendations

The future plan is to enrich our blade design so that we have got high output power. This output power helps our country to produce electricity and decrease pollution of the environment.

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