Design Construction, Simulation and Testing of a 300W Wind Powered Battery Charger

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January 2014

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(Msc/ENG/4904/2009-2010)

A THESIS SUBMITTED FOR THE AWARD OF MASTERS OF SCIENCE IN MECHANICAL ENGINEERING

Mechanical Engineering Department

Ahmadu Bello University

Zaria

April 2013

DECALARATION

I declare that the work in the thesis entitled "Design construction, simulation and testing of a 300W wind powered battery charger" has been performed by me in the Department of Mechanical Engineering under the supervision of Dr. G. Y. Pam and Prof. E. J. Bala.

The information derived from the literature has been acknowledged in the text and a list of references provided. No part of this thesis was previously presented by me for another degree or diploma in an university.

Jesse Mamman	--------------------------	------------------------
(Name of student)	Signature	Date

CERTIFICATION

This thesis entitled "DESIGN CONSTRUCTION, SIMULATION AND TESTING OF A 300W WIND POWERED BATTERY CHARGER" by Mamman, Jesse meets the regulations governing the award of the degree of Master of Science of Ahmadu Bello University, Zaria, and is approved for its contribution to knowledge and literary presentation.

Dr. G. Y Pam Chairman, Supervisory Committee	------------------------- (Signature)	---------------------- Date
Prof. E. J Bala Member, Supervisory Committee	------------------------- (Signature)	---------------------- Date
Dr. Dauda Mohammed Head of Department	------------------------- (Signature)	---------------------- Date
Prof. A. A. Joshua Dean, Postgraduate School	------------------------- (Signature)	---------------------- Date

ACKNOWLEDGEMENTS

Thanks to my incredible wife, Jennifer and my daughter Jochebed for allowing me travel when I should have been with them, and understanding when I sometimes had to lock out on everyone to face this work.

Thanks to my supervisors Dr. G.Y Pam and Prof. E. J Bala , who were really supportive throughout this work. Your interest and insightful guidance proved to give me a direction I would not have found on my own. Thank you Sirs.

The love of my family and siblings propelled me. You provided, you prayed and encouraged. Thank you. Thanks to my guardians, The Tankos, for taking me as a son whenever I was in Zaria. Thanks for allowing me use your car whenever I needed to.

The workshops I worked in; Hombase in Kaduna, ABU Mechnical Engineering workshop, DICON research and development workshop, Femi's carpentry services workshop; thanks to your guys. You helped convert my ideas into a physical product.

Thanks to Shangji for hosting me the times I was in Kaduna. To Feng Darwei for helping deliver my work to Dr. Pam whenever I couldn't travel. Thanks to Ikita for hanging around in the house and helping take care of Jennifer & Jojo selflessly while I was away. Thanks to Parham, Josh, Inans and Nuru for helping with the Installation process. Well done guys!

Thank God for creating the winds, without which any thought of wind energy would not exist.

ABSTRACT

This work reports the design, construction, simulation and testing of a 300W wind battery charger. The design was carried out based on long term available wind data of Jos at 10m height above land. The average wind speed for Jos is 5.24m/s and rated turbine wind speed is 6.29m/s. A computer program for the design was written in JAVA programming language. It was found to match the results from manual calculation and was therefore valid. The designed components of the system were carefully constructed in a well-equipped workshop. The system was coupled and installed on the roof of the Department of Mechanical Engineering, Ahmadu Bello University, Zaria, at a height of 22m. The system was test run and the results recorded for a period of time on two consecutive days. A model was created using a second degree quadratic equation and the system was simulated. The calculated outputs were compared with the actual outputs and a root mean square error of 8.98% was found, showing that the closeness of fit of the calculated outputs to the actual characteristics of the wind-powered turbines is satisfactory. The system efficiency between cut-in and rated wind speed was determined to be 38.16%. A cost evaluation was carried out using current Nigerian market rates and the cost of producing the 300W wind energy battery charger was N74,850.

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ABBREVAITIONS AND SYMBOLS

A = The area swept by the rotor (m^2)

The area of the vane (m^2)

a = Wind shear coefficient

A_W = Fraction by which the standard addendum for the wheel should be multiplied

B = The number of blades

b = Gear face width (mm)

C = Basic dynamic load rating (N)

c = Distance from the flapwise neutral axis (mm)

= Power coefficient

= The maximum theoretically possible rotor power coefficient

C_S = Service factor.

= Thrust coefficient

= Torque coefficient

C_w = Blade Width or Chord (m)

C_0 = Basic static radial load rating (N)

D = Rotor diameter. (m)

d = Diameter of the gear shaft (mm)

D_G = Pitch circle diameter of the gear (mm)

D_P = Pitch circle diameter of the pinion (mm)

E = Modulus of elasticity or Young's modulus for the material (kN/mm^2)

e = Maximum allowable tooth error in action

= Rotor thrust (kg)

= The side force on the vane (kg)

G = Gear ratio or velocity ratio

= Area moment of inertia of blade cross-section at the root (N/mm^2)

k = Shape factor

= Least radius of gyration of the cross-section

L = length of the strongly disturbed air stream upwind and downwind of the rotor (m)

l = Length (mm)

L_r = Rating life

M = Bending moment (Nmm)

m = Mass (kg)

Root flapwise bending moment on a single blade (Nmm)

Bending moment in the edgewise direction at the root of single blade (Nmm)

m = Module

N = rotational Speed (rpm)

= Rotor speed (rpm)

Net present worth of all costs (Naira)

P = The available power in wind (Watts)

= Actual power output values (Watts)

Calculated power outputs (Watts)

= Circular pitch (mm)

Effective mean power output (Watts)

= Generator power output. (Watts)

= Rotor power (Watts)

Q = The mean torque

Re = Reynolds number

Rotor radius (m)

r = Radius at a given station of the blade

Shear force in the root of the blade

= Edgewise shear force

T = Twisting moment

t = Thickness (mm)

T_e = Equivalent torque,

Number of teeth on gear

Number of teeth on pinion

– Weibull random variable

V = Wind velocity. (m/s)

‾ = Mean wind speed (m/s)

v = Pitch line velocity (m/s)

Cut-in speed (m/s)

V_m = Annual mean velocity (m/s)

V_r = Rated speed (m/s)

W = Equivalent dynamic load

w = Width (mm)

W_A = Axial or thrust load (N)

Crippling or buckling load (N)

W_G = Weight of the gear (N)

W_D = The dynamic load (N)

W_N = Normal load (N)

Resultant load acting on pinion (N)

W_{Ra} = Radial load (N)

Static tooth load (N)

W_T = Permissible tangential tooth load (N)

Wear tooth load (N)

x = Overhang *i.e.* the distance between the centre of gear and the centre of bearing. (mm)

X_0 = Radial load factor

y = Half the thickness of the tooth (*t*) at critical section

Y_0 = Axial or thrust load factor.

Z = Height above the earth's surface (m)

= Reference height for which wind speed is known (m)

α = Angle of attack (degrees)

Blade setting angle (degrees)

Percentage error (%)

= rms percentage error (%)

= A factor depending upon the type of bearing.

= Fundamental natural frequency (Hz)

ϕ = Flow angle (degrees)

= Pressure angle or angle of obliquity. (degrees)

Density of air at sea level (15^0C) = 1.225 kg/m^3

The overall turbine efficiency

= Mechanical efficiency

= Gearbox Efficiency

= Electric Efficiency

Generator Efficiency (%)

= Shear stress for the material

Tip speed ratio

Optimal tip speed ratio becomes

= Scale factor

Maximum flapwise stress, (N/m^2)

= Permissible working stress (N/m^2)

= Flexural endurance limit (N/m^2)

Cruching stress (N/m^2)

= Angular speed of blades

Optimal angular spee d

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND OF THE STUDY

Energy is fundamental to all human activities. The existing Millennium Development Goals (MDGs) cannot be achieved without access to adequate and affordable energy. Energy is inevitable for poverty alleviation and the production of goods and services. Globally, more than 1.6 billion people live without access to electricity and 2.4 billion people are without modern energy services for cooking and heating (Community Research and Development Centre, 2007). Majority of the world's poor live in Sub-Saharan Africa. Nigeria is the most populous country in Sub-Saharan Africa, nearly one quarter of the Sub-Saharan Africa's population, and is one of the poorest countries in the world despite the huge resources from crude oil export (Community Research and Development Centre, 2007). An estimated 60-70% of the Nigerian population does not have access to electricity. Energy supply in Nigeria is dominated by fuel wood and women and children are the most affected in the energy crisis (Community Research and Development Centre, 2007).

Renewable energy technology is a promising solution to the energy crisis in Nigeria. Renewable energy, apart from being inexhaustible and hence, sustainable, can be set up in small units and is therefore suitable for community management and ownership. To achieve sustainability in the development of energy, it should be promoted along side with energy efficiency (CREDC, 2007).

1.2 The Nigerian Energy Sector at A Glance

Though Nigeria has a resource of 2.7 billion tonnes of coal, production declined from a peak of 0.91 million tonnes in 1959 to no production in 2001, because of petroleum, which was discovered in commercial quantities in 1956 (Sambo, 2011). There is a wide gap between the renewable energy potential and the amount explored. Table 1.1 and table 1.2 give a summary of the activities in the Nigerian energy sector.

Table 1.1 Fossil Type Energy Resources

Resource Type.	Reserves (Natural Units)
Crude Oil	36.2 billion barrels
Natural Gas	187 trillion Standard Cubic Foot
Coal and lignite	2.7 billion tonnes
Tar Sands	31 billion barrels of oil Equivalent

Source: (Sambo, 2011).

Table 1.2 Renewable Energy Potential

Resource		Capacity
Large Hydropower		11,500 MW
Small Hydropower		3,500 MW
Solar		3.5 kW/m/day – 7.0 kW/m/day
Wind		2-4 m/s @ 10m height Mainland
Biomass	Fuelwood	11 million hectares of forest and woodland
	Animal Waste	245 million assorted in 2001
	Energy Crops and Agric Residue	72 million hectares of Agric.Land

Source: (Sambo, 2011).

1.1.1.1 Renewable Energy Policy, Regulation and Legislation

In 2003, the Federal Government of Nigeria approved a National Energy Policy, which encourages the optimum utilisation of the country's energy resources, including renewables, for sustainable national development with the active participation of the private sector. For example, the following policies are articulated for solar energy, biomass and wind (Sambo, 2011).

Solar Energy:

- The nation shall aggressively pursue the integration of solar energy into the nation's energy mix.

- The nation shall keep abreast with worldwide developments in solar energy technology.

Biomass:

- The nation shall effectively harness non-fuelwood biomass energy resources and integrate them with other energy resources.

- The nation shall promote the use of efficient biomass conversion technologies.

Wind:

- The nation shall commercially develop its wind energy resource and integrate this with other energy resource.

- The nation shall take necessary measures to ensure that at sustainable costs, this form of energy is harnessed and supplied to consumers in the rural areas.

1.1.2 Types of Renewable Energy

Fossil fuels are non-renewable, that is, they draw on finite resources that will eventually dwindle, becoming too expensive or too environmentally damaging to retrieve. In contrast, the many types of renewable energy resources-such as wind and solar energy are constantly replenished and will never run out (http://www.renewableenergyworld.com/rea/tech/home)

Most renewable energy comes either directly or indirectly from the sun. Solar energy, can be used directly for heating and lighting homes and other buildings, for generating electricity, and for hot water heating, solar cooling, and a variety of commercial and industrial uses.

The sun's heat also drives the wind, whose energy is captured with wind turbines. Then, the winds and the sun's heat cause water to evaporate. When this water vapour turns into rain or snow and flows downhill into rivers or streams, its energy can be captured using hydroelectric power plants.

Along with the rain and snow, sunlight causes plants to grow. The organic matter that makes up those plants is known as biomass. Biomass can be used to produce electricity, transportation fuels, or chemicals. The use of biomass for any of these purposes is called bioenergy.

Hydrogen also can be found in many organic compounds, as well as water. It is the most abundant element on earth. But it does not occur naturally as a gas. It is always combined with other elements, such as oxygen to give water. Once separated from another element, hydrogen can be burned as a fuel for conversion into electricity.

Not all renewable energy resources come from the sun. Geothermal energy is tapped from the earth's internal heat for a variety of uses, including electric power production, and the heating and cooling of buildings.

Energy in the ocean's tides comes from the gravitational pull of the moon and the sun upon the earth. In fact, ocean energy comes from a number of sources. In addition to tidal energy, there's the energy of the ocean's waves, which are driven by both the tides and the winds. The sun also warms the surface of the ocean more than the ocean depths, creating a temperature difference that can be used as an energy source. All these forms of ocean energy can be used to produce electricity (http://www.renewableenergyworld.com/rea/tech/home).

1.1.3 Wind Energy Technology

The rotors of wind turbines (WT) transform the kinetic energy of the wind into mechanical energy, and then into electricity. Typical modern wind turbines deployed throughout the world today have features as shown in Figure1.1. The turbine power output is controlled by rotating the blades about their longitudinal axis to change the angle of attack with respect to the relative wind as the blades spin about the rotor hub, which is referred to as “controlling the blade pitch”. The turbine is pointed into the wind by rotating the nacelle about the tower, which is called “yaw control”. Almost all modern turbines operate with the rotor positioned on the windward side of the tower, which is referred to as an “upwind rotor” (Mukund, 1999).Wind sensors on the nacelle tell the yaw controller where to point the turbine, and when combined with sensors on the generator and drive train, tell the blade pitch controller to regulate the power output and rotor speed to prevent overloading structural components. A turbine will generally start producing power once the minimum required wind speed is exceeded. The amount of energy in the wind available for extraction by the turbine increases with the cube of wind speed; thus a 10% increase in wind speed means a 33% increase in available energy. However, a turbine can only capture a portion of this cubic increase in energy because power above the level for which the electrical system has been designed (referred to as the “rated power”) is allowed to pass through the rotor. The height and the size of wind turbines have increased to capture the more energetic winds at higher elevations. For land-based turbines, size is not expected to grow as dramatically in the future as it has in the past. Many turbine designers do not expect land-based turbines to become much larger than about 100 metres in diameter, with corresponding power outputs of about 3 to 5 MW (Mukund, 1999). Larger sizes are physically possible; however, the logistical constraints of transporting the components over the highway and obtaining cranes large enough to lift the components are potential barriers.

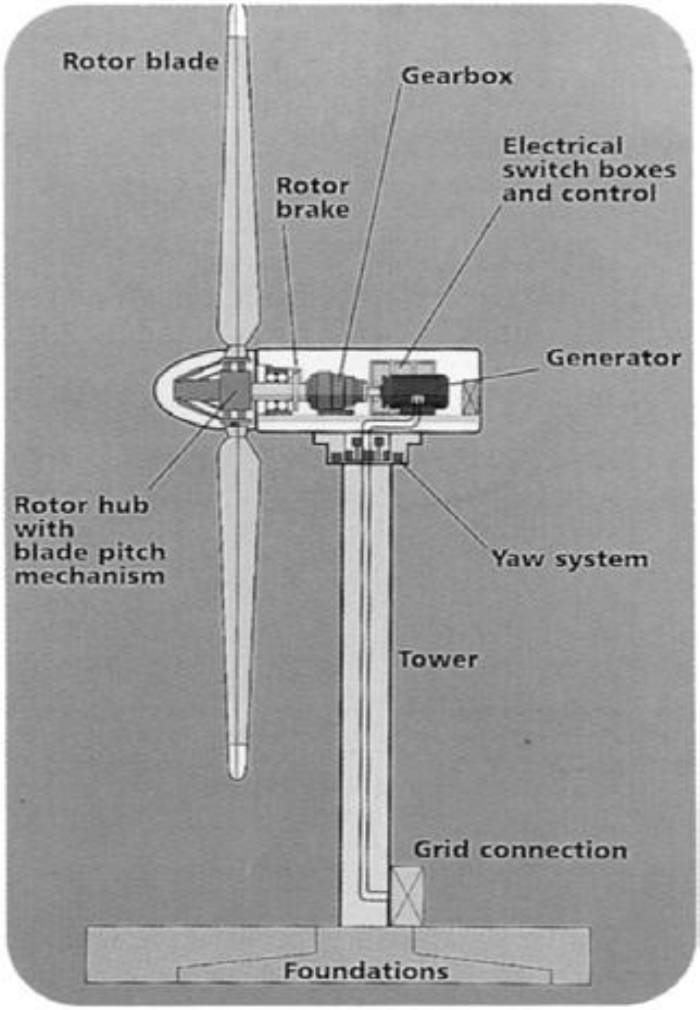


Figure 1.1: Features of a wind turbine (Mukund, 1999)

1.2 STATEMENT OF THE PROBLEM

The electricity grid can provide households and communities with reliable, high quality, predictable and cheap electricity, but this is far from the norm for the majority of the world's population. Whilst being in the forefront of many government-stated development objectives, widespread electrification is still the dream rather than the reality for most. There is practically insufficient power supply in Nigeria, and even the little available is epileptic and inconsistent, yet the exponential growth in its demand is consistent. In areas without the grid, and areas with such undependable power supply, some households use motorcycle, car or lorry batteries to power radios or televisions. Such batteries are often charged in the nearest battery charging workshops. Car-battery charging by road side battery chargers/workshops that depend on such power source is unreliable.

Greenhouse gas emissions causes warming of the earth surface as a result of atmospheric pollution by gases. This is a major problem of fossil fuels. It is now feared that the warming effects are undesirably increasing, causing climate changes and melting polar icebergs. Since the advent of the Industrial Revolution in the 1700s, humans have devised many inventions that burn fossil fuels such as coal, oil, and natural gas. Burning these fossil fuels, as well as other activities such as clearing land for agriculture or urban settlements, releases some of the same gases that trap heat in the atmosphere, including carbon dioxide, methane, and nitrous oxide. These atmospheric gases have risen to levels higher than at any time in at least the last 650,000 years. As these gases build up in the atmosphere, they trap more heat near the earth’s surface, causing earth’s climate to become warmer than it would naturally.

1.3 THE PRESENT WORK

This work focused on designing, constructing, simulating and testing a 300W wind battery charger. Mechanics, car owners and home users can use such systems for battery charging. A computer programme written in the JAVA programming language was developed for carrying out design calculations with ease. Nevertheless, the design calculations were carried out manually and compared with the JAVA programme output for authenticating the programme. The design will be for operation in Jos, the Plateau state capital. Jos is located on latitude 80°24'N and between longitude 80°32'E and 100°38'E. It is in the middle belt of Nigeria. The altitude of Jos is about 1250 m (4100 ft) above sea level on the Delimi River, with average monthly temperatures ranging between 21° and 25° C **(**Microsoft ® Encarta ®, 2009).

1.4 AIM AND OBJECTIVES

The aim of this work is to design, model and simulate, construct and test a 300W battery charging system to operate in Jos, the Plateau state capital.

The specific objectives are:

i. To select the most suitable materials for each component of the system,

ii. To determine the rotor size, and design the blades and select an appropriate alternator for the system,

iii. To develop a programme in JAVA programming language for detailed design calculations,

iv. To model and simulate the power output from the system,

v. To construct the system and determine by experiment the power output from it, and

vi. To estimate the cost of the system.

1.5 JUSTIFICATION OF THE WORK

The research work will enable the development of a wind battery charging system. This would provide alternative for battery charging when the wind is blowing despite fluctuating conventional power supply. It will also demonstrate the potential for the availability of wind battery charging systems and workshops in remote areas that are not connected to the electricity grid.

With growing awareness and demand for the preference of renewable energy by international environmental organisations, the application of wind energy for battery charging will contribute to the cause. Every renewable energy system installed means reduction in a potential increase of greenhouse effect.

Jos has one of the best wind energy potential in Nigeria (Pam, 2008). At present, there is only one known electricity generation wind turbine in Jos, and even that system was not designed for the location. It was simply bought and installed, and would therefore not perform optimally. This work presents this potential in realistic terms, and will encourage the practice of wind energy generation to a reasonable extent in Jos and in Nigeria in general. Designing and manufacturing a model of a wind powered battery charger locally has the following advantages:

i. Firstly, locally produced machines are likely to be cheaper to buy, especially where foreign exchange is scarce and the local market is not large enough to negotiate discounts.

ii. Secondly, they will be easier to maintain, because local technicians will understand them. Many small wind generators have failed prematurely due to poor understanding of the technology.

– Thirdly, the machines could be more suited to local conditions (wind data, regimes, types and size of loads, etc.).

- Lastly, local manufacturing enterprises are used, which helping in creating more jobs.

CHAPTER TWO

LITERATURE REVIEW

2.1 HISTORY OF WIND ENERGY APPLICATIONS

The use of wind energy can be traced back thousands of years to many ancient civilisations. The ancient human histories have revealed that wind energy was discovered and used independently at several sites of the earth (Tong, 2010).

2.1.1 Sailing

As early as about 4000 B.C., the ancient Chinese were the first to attach sails to their primitive rafts . From the oracle bone inscription, the ancient Chinese scripted on turtle shells in the Shang Dynasty (1600 B.C.–1046 B.C.) an ancient Chinese character that represented sail - in ancient Chinese- often appeared. In the Han Dynasty (220 B.C.–200 A.D.), Chinese junks were developed and used as ocean-going vessels (Tong, 2010). As recorded in a book written in the third century, there were multi-mast, multi-sail junks sailing in the South Sea, capable of carrying 700 people with 260 tonnes of cargo (Tong, 2010). Two ancient Chinese junks are shown in figure 2.1. Figure 2.1(a) is a two-mast Chinese junk ship for shipping grain, quoted from the famous encyclopedic science and technology book *Exploitation of the works of nature* (Song, 1637). Figure 2.1(b) illustrates a wheel boat (Yu, 1842) in the Song Dynasty (960–1279). This type of wheel boats was used during the war between Song and Jin Dynasty (1115–1234) (Wells, 1921). Approximately at 3400 BC, the ancient Egyptians launched their first sailing vessels initially to sail on the Nile river, and later along the coasts of the Mediterranean (Tong 2010). Around 1250 BC, Egyptians built fairly sophisticated ships to sail on the Red Sea (Wells, 1921). The wind-powered ships had dominated water transport for a long time until the invention of steam engines in the 19th century.

(a) two-mast junk ship (b) wheel boat

Figure 2.1: Ancient Chinese junks (ships) (Tong, 2010).

2.1.2 Wind in Metal Smelting Processes

About 300 BC, ancient Sinhalese had taken advantage of the strong monsoon winds to provide furnaces with sufficient air for raising the temperatures inside furnaces in excess of 1100°C in iron smelting processes. This technique was capable of producing high-carbon steel (Juleff, 1996). The double acting piston bellows was invented in China and was widely used in metallurgy in the fourth century BC (Temple, 1986). It was the capacity of this type of bellows to deliver continuous blasts of air into furnaces to raise high enough temperatures for smelting iron. In such a way, ancient Chinese could once cast several tonnes of iron.

2.1.3 Windmills

China has a long history of using windmills. The unearthed mural paintings from the tombs of the late Eastern Han Dynasty (25–220 AD) at Sandaohao, Liaoyang City, have shown the exquisite images of windmills, evidencing the use of windmills in China for at least approximately 1800 years (Tong, 2010). The practical vertical axis windmills were built in Sistan (eastern Persia) for grain grinding and water pumping, as recorded by a Persian geographer in the ninth century (Hassanm and Hill, 1986). The horizontal axis windmills were invented in northwestern Europe in 1180s (Drachmann, 1961). The earlier windmills typically featured four blades and mounted on central posts – known as Post mill. Later, several types of windmills, e.g. Smock mill, Dutch mill, and Fan mill, were developed in the Netherlands and Denmark, based on the improvements on Post mill. The horizontal axis windmills have become dominant in Europe and North America for many centuries due to their higher operation efficiency and technical advantages over vertical axis windmills.

2.1.4 Wind Turbines

Unlike windmills which are used directly to do work such as water pumping or grain grinding, wind turbines are used to convert wind energy to electricity. The first automatically operated wind turbine in the world was designed and built by Charles Brush in 1888 (Tong, 2010). This wind turbine was equipped with 144 cedar blades having a rotating diameter of 17 m. It generated a peak power of 12 kW to charge batteries that supply DC current to lamps and electric motors (Tong, 2010). As a pioneering design for modern wind turbines, the Gedser wind turbine was built in Denmark in the mid 1950s (Krohn, 2002). Today, modern wind turbines in wind farms have typically three blades, operating at relatively high wind speeds of power outputs of up to several megawatts.

2.1.5 Kites

Kites were invented in China as early as the fifth or fourth centuries BC (Temple, 1986) A famous Chinese ancient legalist Han Fei-Zi (280–232 BC) mentioned in his book that an ancient philosopher, Mo Ze (479–381 BC) spent three years to make a kite with wood but failed after a day's flight (Tong, 2010).

2.2 WIND ENERGY CHARACTERISTICS

Wind energy is a special form of kinetic energy in the air as it flows. Wind energy can be either converted into electrical energy by energy converting machines or directly used for pumping water, sailing ships, or grinding grain.

2.2.1 Wind Power

2.2.1.1 Available Wind Power

The available power in wind, *P*, can be expressed as (Manwell *et al*, 2009).

(2.1)

The wind power per unit area, P/A or wind power density is:

(2.2)

Where;

density of air. At sea level (15^0C) = 1.225 kg/m^3

A = the area swept by the rotor

V = wind velocity.

2.2.1.2 The Betz Limit

Wind turbine rotor performance is usually characterised by its power coefficient, , given by (Manwell *et al*, 2009).

(2.3)

Where = rotor power

The non-dimensional power coefficient represents the fraction of the power in the wind that is extracted by the rotor. The maximum theoretically possible rotor power coefficient, (Betz, 1920). In practice, three effects lead to a decrease in the maximum achievable power coefficient, which include:

i. . Rotation of the wake behind the rotor;

ii. . Finite number of blades and associated tip losses and

iii. . Non-zero aerodynamic drag,

The overall turbine efficiency, , is a function of both the rotor power coefficient and the mechanical (including electrical) efficiency, , of the wind turbine (Manwell *et al*, 2009).

(2.4)

Thus:

= (2.5)

Where = generator power output.

2.2.1.3 Blade Swept Area

As shown in figure 2.2, the blade swept area can be calculated from the formula:

(2.6)

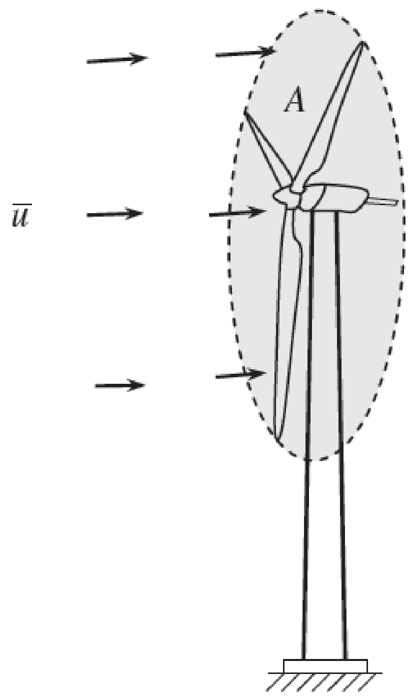


Figure 2.2: Swept area of wind turbine blades

where *l* is the length of wind turbine blades and *r* is the radius of the hub. Thus, by doubling the length of wind turbine blades, the swept area can be increased by a factor of up to 4. When $l >> 2r$, $A \approx$.

2.2.1.4 Wind Speed Variation

The wind power output is proportional to the cubic power of the mean wind speed, therefore a small variation in wind speed can result in a large change in wind power. Doubling the wind speed increases the wind power by a factor of eight (Manwell *et al,* 2009).

2.2.2 Wind Characteristics

Wind varies with the geographical locations, time of day, season, and height above the earth's surface, weather, and local landforms. The understanding of the wind characteristics will help in optimising wind turbine design, developing wind measuring techniques, and selecting wind farm sites.

2.2.2.1 Wind Speed

Wind speed is one of the most critical characteristics in wind power generation. In fact, wind speed varies in both time and space, determined by many factors such as geographic and weather conditions. Wind speed is a random parameter. For this reason, measured wind speed data are usually dealt with using statistical methods.

The diurnal variations of average wind speeds are often described by sine waves. As an example, the diurnal variations of hourly wind speed values, which are the average values calculated based on the data between 1970 and 1984, at Dhahran, Saudi Arabia have shown the wavy pattern (Siddiqi *et al.,* 2005). The wind speeds are higher in daytime and the maximum speed occurs at about 3 p.m., indicating that the daytime wind speed is proportional to the strength of sunlight. Wind speed at Lubbock, TX is near constant during dark hours, and follows a curvilinear pattern during daylight hours (George *et al.,* 1994). Diurnal wind patterns at five locations in the Great Plains follow a pattern similar to that observed by George *et al* (1996). Based on the wind speed data for the period 1970–2003 from up to 66 onshore sites around the United Kingdom (UK), monthly average wind speed is inversely propositional to the monthly average temperature, i.e. it is higher in the winter and lower in the summer (Sinden, 2007). The maximum wind speed occurs in January and the minimum in August. The month-to-month variation of mean wind speed values over the period of 1970–1984 at Dhahran, Saudi Arabia has shown a wavy pattern (Hassanm and Hill, 1986). However, because the variation in temperature at Dhahran is small over the whole year, there is no clear correlation between wind speed and temperatures. The year-to-year variation of yearly mean wind speeds depends highly on selected locations and thus there is no common correlation to predict it. For instance, except for several years, the annual mean wind speeds decrease all the way from 1970 to 1983 at Dhahran, Saudi Arabia (Siddiqi, 2005). In the UK, this variation was displayed in a more fluctuated manner for the period 1970–2003 (Sinden, 2007). Similarly, a significant variation in the annual mean wind speed over a 20-year period (1978–1998) with maximum and minimum values ranging from less than 7.8 to nearly 9.2 m/s was observed. The long-term wind data (1978–2007) obtained from automated synoptic observation system of meteorological observatories in Jeju Island were analysed and reported (Ko *et al* 2009). The results showed that fluctuation in the yearly average wind speed occurred at the observed sites.

2.2.2.2 Weibull Distribution

The variation in wind speed at a particular site can be best described using the Weibull distribution function, which illustrates the probability of different mean wind speeds occurring at the site during a period of time. The probability density function of a Weibull random variable is (Tong, 2010).

(2.7)

where is the scale factor, which is closely related to the mean, and *k* is the shape factor, which is a measurement of the width of the distribution. These two parameters can be determined from the statistical analysis of measured wind speed data at the site (Ulgen and Hepbasli, 2002). It has been reported that Weibull distribution can give good fits to observed wind speed data

(Yilmaz and Celik, 2008). As an example, the Weibull distributions for various mean wind speeds are displayed in figure 2.3.

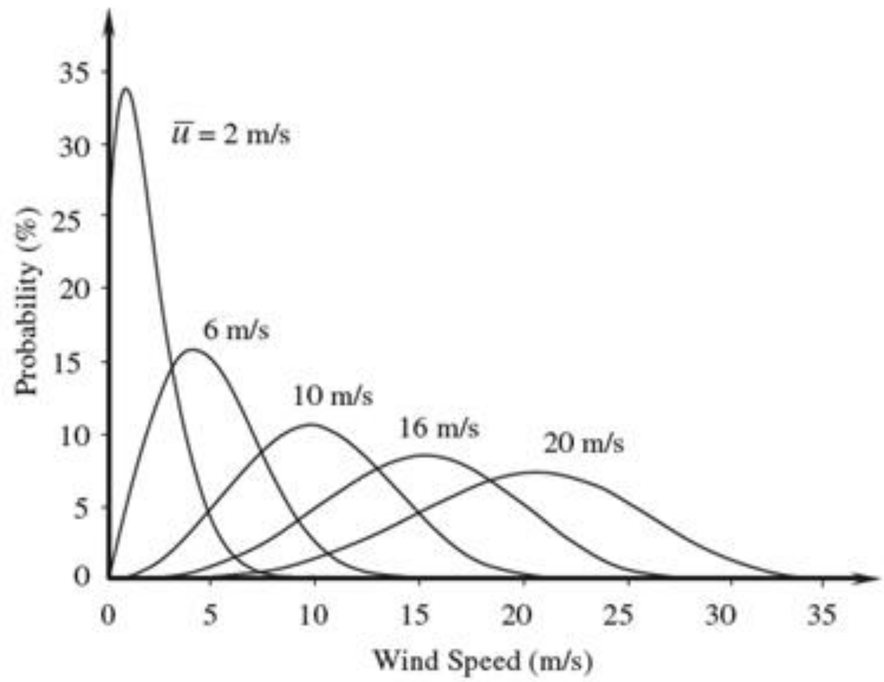


Figure 2.3: Weibull distributions for various mean wind speeds (Yilmaz and Celik, 2008).

2.2.2.3 Wind Shear

Wind shear is a meteorological phenomenon in which wind increases with the height above the ground. The effect of height on the wind speed is mainly due to roughness on the earth's surface and can be estimated using the Hellmann power equation that relates wind speeds at two different heights. The Hellman power equation is given by (Vanek and Albright, 2008),

(2.8)

where, *Z* is the height above the earth's surface, is the reference height for which wind speed ( ) is known, and *a* is the wind shear coefficient. In practice, *a* depends on a number of factors, including the roughness of the surrounding landscape, height, time of day, season, and locations. The wind shear coefficient is generally lower in daytime and higher at night. Empirical results indicated that wind shear often follows the “1/7 power law” (i.e. a = 1/7) (Gipe, 2004). The values of wind shear coefficient for different surface roughness are provided. Because the power output of wind turbines strongly depend on the wind speed at the hub height, modern wind turbines are built at the heights greater than 80 m, for capturing more wind energy and lowering cost per unit power output (Gipe, 2004).

2.3 MODERN WIND TURBINES

A modern wind turbine is an energy-converting machine, which converts the kinetic energy of wind into mechanical energy and in turn into electrical energy. In the recent three decades, remarkable advances in wind turbine design have been achieved along with modern technological developments. It has been estimated that advances in aerodynamics, structural dynamics, and micrometeorology may contribute to a 5% annual increase in the energy yield of wind turbines (Shikha *et al,* 2003). Various wind turbine concepts have been developed and actualized for maximising the wind energy output, minimising the turbine cost, and increasing the turbine efficiency and reliability.

2.3.1 Wind Turbine Classification

Wind turbines can be classified according to the turbine generator configuration, airflow path relative to the turbine rotor, turbine capacity, the generator-driving pattern, the power supply mode, and the location of turbine installation.

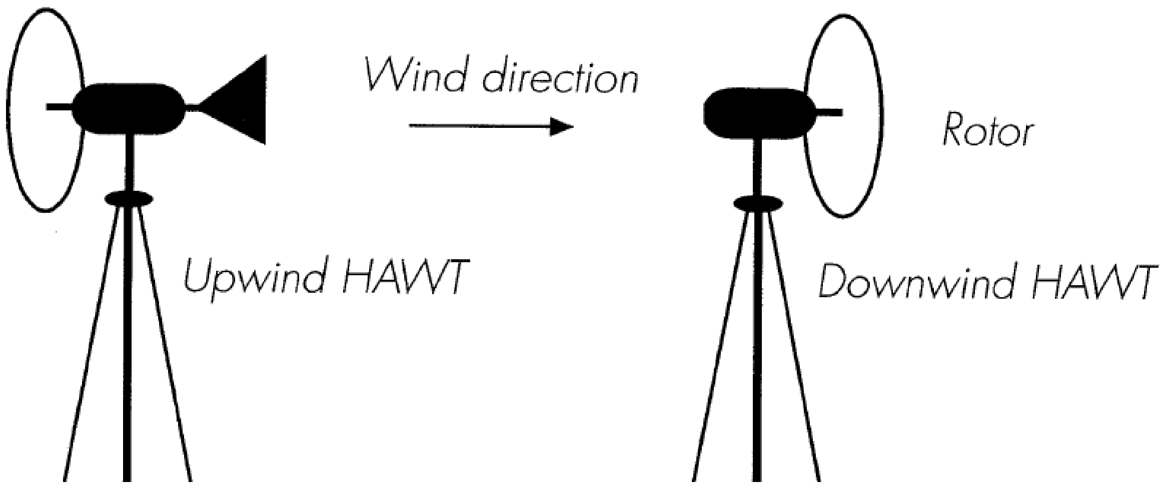


Figure 2.4 Horizontal axis wind turbines (Piggot, 2003)

2.3.1.1 Horizontal-axis And Vertical-axis Wind Turbines

When considering the configuration of the rotating axis of rotor blades, modern wind turbines can be classified into the horizontal-axis and vertical-axis turbines. Most commercial wind turbines today belong to the horizontal-axis type, in which the rotating axis of blades is parallel to the wind stream (see Fig. 2.4). The advantages of this type of wind turbines include the high turbine efficiency, high power density, low cut-in wind speeds, and low cost per unit power output. Several typical vertical-axis wind turbines are shown in figure 2.5. The blades of the vertical-axis wind turbines rotate with respect to their vertical axes that are perpendicular to the ground. A significant advantage of vertical-axis wind turbine is that the turbine can accept wind from any direction and thus no yaw control is needed.

Since the wind generator, gearbox, and other main turbine components can be set up on the ground, it greatly simplifies the wind tower design and construction, and consequently reduces the turbine cost. However, the vertical axis wind turbines must use an external energy source to rotate the blades during initialisation. The axis of this type of wind turbine is supported only at one end at the ground, its maximum practical height is thus limited. Due to the lower wind power efficiency, vertical-axis wind turbines today make up only a small percentage of wind turbines.

2.3.1.2 Upwind and Downwind Wind Turbines

Based on the configuration of the wind rotor with respect to the wind flowing direction, the horizontal-axis wind turbines can be further classified as upwind and downwind wind turbines. The majority of horizontal-axis wind turbines being used today are upwind turbines, in which the wind rotors face the wind. The main advantage of the upwind designs is to avoid the distortion of the flow field as the wind passes through the wind tower and nacelle.

For a downwind turbine, wind blows first through the nacelle and tower and then the rotor blades. This configuration enables the rotor blades to be made more flexible without considering tower strike. However, because of the influence of the distorted unstable wakes behind the tower and nacelle, the wind power output generated from a downwind turbine fluctuates greatly. In addition, the unstable flow field may result in more aerodynamic losses and introduce more fatigue loads on the turbine. Furthermore, the blades in a downwind wind turbine may produce higher impulsive or thumping noise.

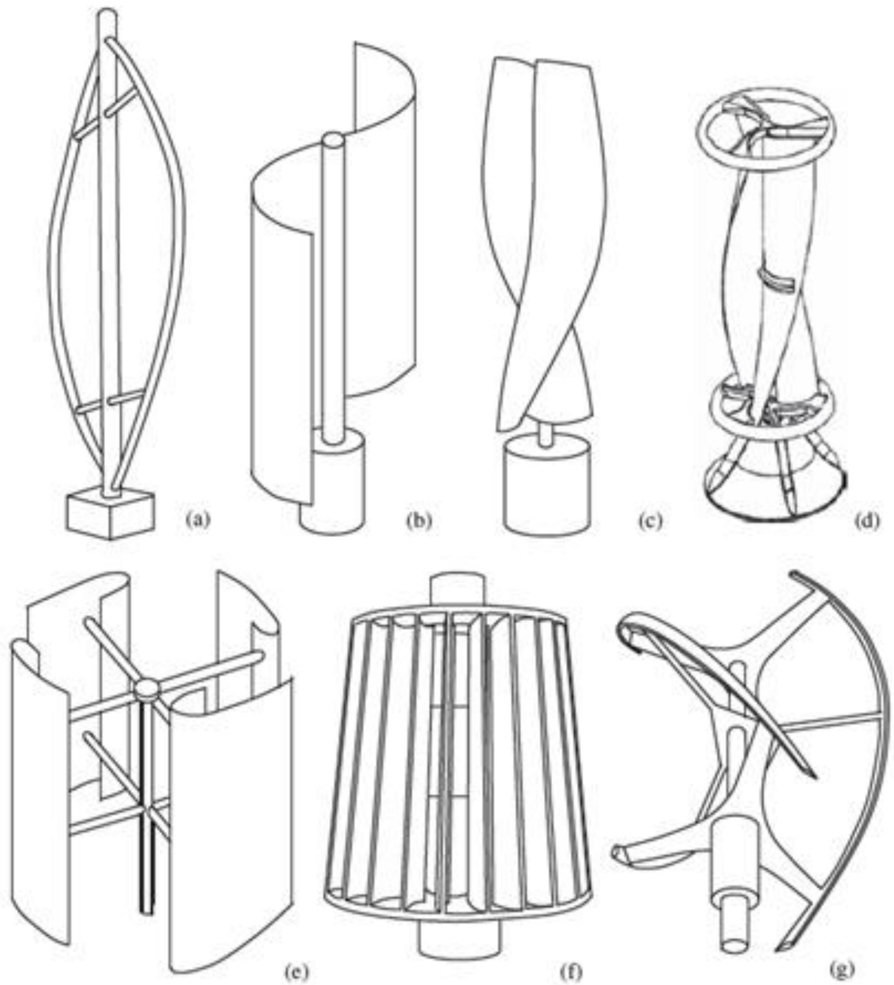


Figure 2.5: Several typical types of vertical-axis wind turbines: (a) Darrius; (b) Savonius; (c) Solarwind™ (d) Helical (e) Noguchi (f) Maglev (g) Cochrane. (Tong, 2010).

2.3.1.3 Wind Turbine Capacity

Wind turbines can be divided into a number of broad categories in view of their rated capacities: micro, small, medium, large, and ultra-large wind turbines. Though a restricted definition of micro wind turbines is not available, it is accepted that a turbine with a rated power less than several kilowatts can be categorised as a micro wind turbine (European Wind Energy Association, 2009). Micro wind turbines are especially suitable in locations where the electrical grid is unavailable. They can be used on a per-structure basis, such as street lighting, water pumping, and residents at remote areas, particularly in developing countries. Because micro wind turbines need relatively low cut-in speeds at start-up and operate in moderate wind speeds, they can be extensively installed in most areas around the world for fully utilising wind resources and greatly enhancing wind power generation availability. Small wind turbines usually refer to the turbines with the output power less than 100 kW (Tong, 2010). Small wind turbines have been extensively used at residential houses, farms, and other individual remote applications such as water pumping stations, telecom sites, etc., in rural regions. Distributed small wind turbines can increase electricity supply in the regions while delaying or avoiding the need to increase the capacity of transmission lines. The most common wind turbines are of the medium size types with power ratings ranging from 100 kW to 1 MW. This type of wind turbines can be used either on-grid or off-grid systems for village power, hybrid systems, distributed power, wind power plants, etc. Megawatt wind turbines up to 10 MW may be classified as large wind turbines. In recent years, multi-megawatt wind turbines have become the mainstream of the international wind power market. Most wind farms presently use megawatt wind turbines, especially in offshore wind farms. Ultra-large wind turbines are referred to wind turbines with the capacity more than 10 MW. This type of wind turbine is still in the early stages of research and development.

2.3.1.4 Direct Drive and Geared Drive Wind Turbines

According to the drive train condition in a wind generator system, wind turbines can be classified as either direct drive or geared drive groups. To increase the generator rotor rotating speed to gain a higher power output, a regular geared drive wind turbine typically uses a multi-stage gearbox to take the rotational speed from the low-speed shaft of the blade rotor and transform it into a fast rotation on the high-speed shaft of the generator rotor. The advantages of geared generator systems include lower cost and smaller size and weight. However, utilisation of a gearbox can significantly lower wind turbine reliability and increase turbine noise level and mechanical losses. By eliminating the multi-stage gearbox from a generator system, the generator shaft is directly connected to the blade rotor. Therefore, the direct-drive concept is more superior in terms of energy efficiency, reliability, and design simplicity.

2.3.1.5 On-grid and Off-grid Wind Turbines

Wind turbines can be used for either on-grid or off-grid applications. Most medium-size and almost all large-sized wind turbines are used in grid tied applications. One of the obvious advantages for on-grid wind turbine systems is that there is no energy storage problem.

As the contrast, most of small wind turbines are off-grid for residential homes, farms, telecommunications, and other applications. However, as an intermittent power source, wind power produced from off-grid wind turbines may change dramatically over a short period of time with little warning. Consequently, off-grid wind turbines are usually used in connection with batteries, diesel generators, and photovoltaic systems for improving the stability of wind power supply.

2.3.1.6 Onshore and Offshore Wind Turbines

Onshore wind turbines have a long history on their development. There are a number of advantages of onshore turbines, including lower cost of foundations, easier integration with the electrical-grid network, lower cost in tower building and turbine installation, and more convenient access for operation and maintenance. Offshore wind turbines have developed faster than onshore since the 1990s due to the excellent offshore wind resource, in terms of wind power

€ €

intensity and continuity. A wind turbine installed offshore can make higher power output and operate more hours each year compared with the same turbine installed onshore. In addition, environmental restrictions are more lax at offshore sites than at onshore sites. For instance, turbine noise is no longer an issue for offshore wind turbines.

2.3.2 Wind Power Parameters

2.3.2.1 Power Coefficient

The conversion of wind energy to electrical energy involves primarily two stages: in the first stage, kinetic energy in wind is converted into mechanical energy to drive the shaft of a wind generator. The critical converting devices in this stage are wind blades. For maximising the capture of wind energy, wind blades need to be carefully designed.

The power coefficient, , discussed in section *2.2.1.2* deals with the conversion efficiency in the first stage, defined as the ratio of the actually captured mechanical power by the blades to the available power in wind (Manwell *et al*, 2009).

Due to the presence of various aerodynamic losses in wind turbine systems, for instance, blade-tip, blade-root, profile, and wake rotation losses, etc., the real power coefficient is much lower than its theoretical limit, 0.593, usually ranging from 30 to 45% (Manwell *et al*, 2009).

2.3.2.2 Total Power Conversion Coefficient and Effective Power Output

In the second stage, mechanical energy captured by wind blades is further converted into electrical energy via electrical generators. In this stage, the converting efficiency is determined by several parameters which include:

i. Gearbox Efficiency, : The power losses in a gearbox can be classified as load-dependent and no-load power losses. The load-dependent losses consist of gear tooth friction and bearing losses and no-load losses consist of oil churning, windage, and shaft seal losses. The planetary gearboxes, which are widely used in wind turbines, have higher power transmission efficiencies over traditional gearboxes.

ii. Generator Efficiency, : It is related to all electrical and mechanical losses in a wind generator, such as copper, iron, load, windage, friction, and other miscellaneous losses.

iii. Electric Efficiency, : It encompasses all combined electric power losses in the converter, switches, controls, and cables.

Therefore, the total power conversion efficiency from wind to electricity, , is the product of these parameters, (Manwell *et al*, 2009).

(2.9)

The effective mean power output, , from a wind turbine to feed into a grid becomes

(2.10)

where,

and

2.3.2.4 Power Curve

As can be seen from eqn (2.10) the effective mean electrical power output from a wind turbine, , is directly proportional to the available mean wind power, , and the total effective wind turbine efficiency, . The power curve of a wind turbine displays the power output (either the real electrical power output or the percentage of the rated power) of the turbine as a function of the wind speed. Power curves are usually determined from field measurements. As shown in figure 2.6, the wind turbine starts to produce usable power at a low wind speed, defined as the cut-in wind speed. The power output increases continuously with the increase of the wind speed until reaching a saturated point at which

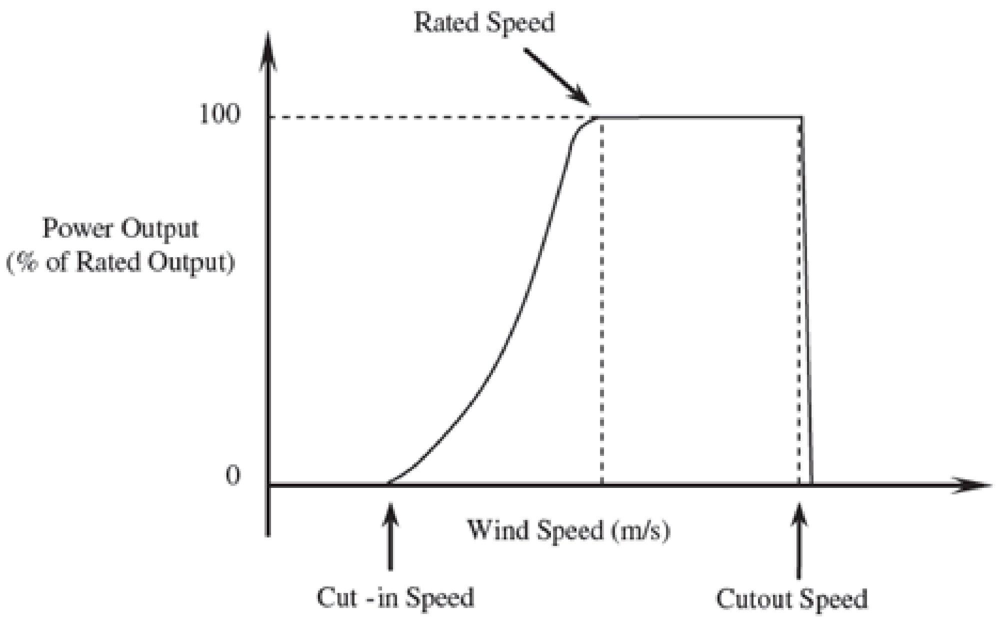


Figure 2.6: Typical wind turbine power curve (Tong, 2010)

the power output reaches its maximum value, defined as the rated power output. Correspondingly, the speed at this point is defined as the rated wind speed. From the rated wind speed, further increase in the wind speed will not increase the power output due to the activation of the power control. When the wind speed becomes too large to potentially damage the wind turbine, the wind turbine needs to shut down immediately to avoid damaging the wind turbine. This wind speed is defined as the cut-out wind speed. Thus, the cut-in and cut-out wind speeds define the operating limits of a wind turbine. There are a number of methods available for forecasting the wind turbine power performance curves. Based on statistical tools, a comparison of five different methods has been performed (Cabezon *et al*, 2004). The best results were obtained when the fuzzy logic tool and tuning over the transfer functions were applied for wind turbines. More recently, based on a stochastic model for the power conversion process, Gottschall and Peinke (2008) proposed a dynamic method for estimating the power performance curves and the dynamic approach has been verified to be more accurate than the common IEC standard 61400-12-1 (IEC, 2005). A novel method, based on the stochastic differential equations of diffusive Markov processes, was developed to characterise wind turbine power performance directly from high-frequency fluctuating measurements (Anahua *et al*, 2007).

2.3.2.5 Tip Speed Ratio

The tip speed ratio is an extremely important factor in wind turbine design, which is defined as the ratio of the tangential speed at the blade tip to the actual wind speed, (Tong, 2010)

(2.11)

where *l* is the length of the blade, *r* is the radius of the hub, is the angular speed of blades and is the mean wind speed.

If the blade angular speed is too small, most of the wind may pass undisturbed though the blade swept area making little useful work on the blades. On the contrary, if is too large, the fast rotating blades may block the wind flow reducing the power extraction. Therefore, there exists an optimal angular speed at which the maximum power extraction is achieved. For a wind turbine with *n* blades, the optimal angular speed can be approximately determined by (Ragheb, 2009).

(2.12)

where L is the length of the strongly disturbed air stream upwind and downwind of the rotor, and — is the mean wind speed.

Substituting equation (2.12) into equation (2.11), the optimal tip speed ratio becomes

$$— \quad — \qquad (2.13)$$

Empirically, the ratio ($l + r$)/ L is equal to about 2 (Ragheb, 2009). Thus, for three-blade wind turbines (i.e. $n = 3$), ≈ /3. If the aerofoil blade is designed with care, the optimal tip speed ratio may be about 25–30% higher than the calculated optimal values above. Therefore, a wind turbine with three blades would have an optimal tip speed ratio of .

2.3.2.6 Wind Turbine Capacity Factor

Due to the intermittent nature of the wind, wind turbines do not generate power all the time. Thus, a capacity factor of a wind turbine is used to provide a measure of the wind turbine's actual power output in a given period (e.g. a year) divided by its power output if the turbine has operated at rated speed the entire time. A reasonable capacity factor would be 0.25 - 0.30 and a very good capacity factor would be around 0.40 (Tong, 2010). In fact, wind turbine capacity factor is very sensitive to the average wind speed.

2.3.3 Wind Turbine Controls

Wind turbine control systems continue to play an important role for ensuring a wind turbine reliable and safe operation and to optimise wind energy capture. The main control systems in a modern wind turbine include pitch control, stall control (passive and active), yaw control, and others. Under high wind speed conditions, the power output from a wind turbine may exceed its rated value. Thus, power control is required to control the power output within allowable fluctuations for avoiding turbine damage and stabilising the power output. There are two primary control strategies in the power control: pitch control and stall control.

2.3.3.1 Pitch Control

The pitch control system is a vital part of the modern wind turbine. This is because the pitch control system not only continually regulates the wind turbine's blade pitch angle to enhance the efficiency of wind energy conversion and power generation stability, but also serves as the security system in case of high wind speeds or emergency situations. It requires that even in the event of grid power failure, the rotor blades can be still driven into their feathered positions by using either the power of backup batteries or capacitors or mechanical energy storage devices (Tong, 2010). Early techniques of active blade pitch control applied hydraulic actuators to control all blades together. However, these collective pitch control techniques could not completely satisfy all requirements of blade pitch angle regulation, especially for megawatts wind turbines with the increase in blade length and hub height. This is because the wind is highly turbulent and the wind speed is proportional to the height from the ground. Therefore, each blade experiences different loads at different rotation positions. As a result, more superior individual blade pitch control techniques have been developed and implemented, allowing control of asymmetric aerodynamic loads on the blades, as well as structural loads in the non-rotating frame such as tower side-side bending. In such a control system, each blade is equipped with its own pitch actuator, sensors and controller. In today’s wind power industry, there are primarily two types of blade pitch control systems: hydraulic controlled and electric controlled systems. The hydraulic pitch control system uses a hydraulic actuator to drive the blade rotating with respect to its axial centre line. The most significant advantages of hydraulic pitch control system include its large driving power, lack of a gearbox, and robust backup power. Due to these advantages, hydraulic pitch control systems historically dominate wind turbine control in Europe and North America for many years (Tong, 2010).

Electric pitch control systems have been developed alternatively with the hydraulic systems. This type of control system has a higher efficiency than that of hydraulic controlled systems (which is usually less than 55%) and avoids the risk of environmental pollution due to hydraulic fluid being spilled or leaked. In an electric pitch control system, the motor connects to a gearbox to lower the motor speed to a desired control speed. A drive pinion gear engages with an internal ring gear, which is rigidly attached to the roof of the rotor blade. Alternatively, some wind turbine manufacturers use the belt-drive structure adjusting the pitch angle. The use of electric motors can raise the responsiveness rate and sensitivity of blade pitch control. To enhance operation reliability, the use of redundant pitch control systems was proposed to be equipped in large wind turbines (Weitkamp *et al*, 2004).

2.3.3.2 Stall Control

Besides pitch control, stall control is another approach for controlling and protecting wind turbines. The concept of stall control is that the power is regulated through stalling the blades after rated speed is achieved. Stall control can be further divided into passive and active control approaches. Passive stall control is basically used in wind turbines in which the blades are bolted to the hub at a fixed installing angle. In a passive stall-regulated wind turbine, the power regulation relies on the aerodynamic features of the blades. In low and moderate wind speeds, the turbine operates near maximum efficiency. At high wind speeds, the turbine is automatically controlled by means of stalled blades to limit the rotational speed and power output, protecting the turbine from excessive wind speeds.

Compared with pitch control, a passive stall control system has a simple structure and avoids using a complex control system, leading to high reliability of the control system. In addition, the power fluctuations are lower for stall-regulated turbines. However, this control method has some disadvantages, such as lower efficiency, the requirement of external equipment at the turbine start, larger dynamic loads acting on the blades, nacelle, and tower, dependence on reliable brakes for the operation safety. Therefore, this control technique has been primarily used for small and medium wind turbines. Since the capacity of wind turbines has entered the multi-megawatt power range in recent years, pitch control has become dominant in the wind power market. The active stall control technique has been developed for large wind turbines. An active stall wind turbine has stalling blades together with a blade pitch system. Since the blades at high wind speeds are turned towards stall, in the opposite direction as with pitch-control systems, this control method is also referred to as negative pitch control. Compared with passive stall control, active control provides more accurate control on the power output and maintains the rated power at high wind speeds. However, with the addition of the pitch-control mechanism, the active stall control mode increases the turbine cost and decreases operation reliability. With megawatt wind turbines becoming the mainstream in the wind power industry from the late 1990s, pitch control is more favourable than stall control. It has been reported that the number of pitch-regulated turbines is four times higher than that of stall-regulated turbines and the trend is going to continue in coming decades (European Wind Energy Association, 2009).

2.3.3.3 Yaw Control

In order to maximise the wind power output and minimise the asymmetric loads acting on the rotor blades and the tower, a horizontal-axis wind turbine must be oriented with rotor against the wind by using an active yaw control system. Like wind pitch systems, yaw systems can be driven either electrically or hydraulically. Generally, hydraulic yaw systems were used in the earlier time of the wind turbine development (Hildingsson and Westin, 1999). In modern wind turbines, yaw control is done by electric motors. The yaw control system usually consists of an electrical motor with a speed reducing gearbox, a bull gear which is fixed to the tower, a wind vane to gain the information about wind direction, a yaw deck, and a brake to lock the turbine securely in yaw when the required position is reached. For a large wind turbine with high driving loads, the yaw control system may use two or more yaw motors to work together for driving a heavy nacelle. In practice, the yaw error signals obtained from the wind vane are used to calculate the average yaw angle in a short interval. When this average yaw angle exceeds the preset threshold, the yaw motor is activated to align the turbine with the wind direction. Thus, with heavily filtered wind direction measurements, the actions of yaw control are rather limited and slow.

2.3.3.4 Other Control Approaches

In the early time of wind turbine design, ailerons were once used to control the power output. This method involves placing moveable flaps on the trailing edge of rotor blades (Kaz´miekowski *et al*, 2002). The ailerons change the lift and drag characteristics of the blades and eventually change the rotor torque, which enables the regulation of rotor speed and rotor power output. However, this method was less successful and was subsequently abandoned. Another possibility is to yaw the rotor partly out of the wind to decrease power. This technique of yaw control is in practice used only for tiny wind turbines (>1 kW) (Tong, 2010).

2.4 WIND ENERGY RESEARCH AND DEVELOPMENT IN NIGERIA

Adaramola and Oyewola (2011) reviewed the wind speed distribution and characteristics in Nigeria and discussed the potential of using this resource for generation of wind power in the country. Since power output from a wind turbine is strongly dependent on the wind speed and accurate information about the wind data in a targeted location for wind turbine is essential. They reported that wind speeds in Nigeria range from about 2 to 9.5 m/s based on recent reported data and the trend shows that wind speeds are low in the south and gradually increase to relatively high speeds in the north. The areas that are suitable for exploitation of wind energy for electricity generation as well as for water pumping and small scale applications were identified. Also some of the challenges facing the development of wind energy and suggested solutions were presented.

The Community Research and Development Centre (CREDC, 2007) with financial support from the Global Greengrants Fund and the Environmental Rights Action/Friends of the Earth Nigeria convened a one-day Conference on Promoting Renewable Energy and Energy Efficiency in Nigeria. They reported that access to energy is fundamental for socio-economic development and for poverty alleviation. A huge development challenge in Nigeria is reaching out to the 60-70% of the Nigerian population that does not have access to electricity and modern energy services. Renewable energy technology is a promising solution to the energy crisis in Nigeria. Renewable energy, apart from being sustainable and inexhaustible, can be set up in small units and is therefore suitable for community management and ownership. That renewable energy cannot be spoken of without energy efficiency. To achieve sustainability in the development of renewable energy, it should be promoted alongside energy efficiency.

Ogbonnaya *et al*. (2006) researched the prospects of wind energy in Nigeria. They used metrological data collected from some selected weather stations in Nigeria and analysed such data to show that wind power prospects in Nigeria is high. From the analysis also, it was clearly seen that coastal and hilly areas are excellent sites for wind power development. Therefore, using wind energy charging systems for electric power generation and supply in Nigeria, such as Jos and Sokoto, will be cost effective.

Argungu et al (2005) used measurement on wind information data at ten carefully selected stations onshore across the country for a period of one year. The measurement was made at 10m and 30m height for eight of the ten sites while for the other two at 10m and 40m height. The result indicated that Sokoto, Jos, Pankshin/Gemu and Kano recorded wind speed of 5.4, 5.2, 5.0 and 4.9 m/s respectively, followed by Maiduguri, Lagos, and Enugu which also indicated relatively strong wind speed capable enough for electricity generation. Moreover, Gumel and Ibi (2005) showed fairly good wind potentials of 4.1 and 3.6m/s, which could be used for other applications. These resources if effectively harnessed could be integrated into the national energy mix to complement the hydropower in electricity generation.

Pam (2008) determined the potential of wind energy utilisation in northern Nigeria. Two methods, “available wind power” and “extractable wind power”, were used for the assessment. The available wind power also known as the wind power potential was assessed at height of 10, 30, 50 and 100m above sea level. Two wind machines; the 5m Poldaw wind pump for water pumping and 20kW Jacobs wind turbine were used to estimate the wind water pumping potential and wind electricity potential respectively. Also, wind speeds for 19 locations in northern Nigeria were modelled using the Weibull distribution model.

Oluseyi (2008) made an assessment of utilisation of wind energy resources in Nigeria**.** The study critically reviewed the prospects and challenges of utilising wind energy resources for power generation in Nigeria. The various initiatives by governments and researchers were surveyed and the nation is found to sit in the midst of enormous potential for wind harvest for power generation. The far northern states, the mountainous regions and different places of the central and south-eastern states were identified as good areas for wind harvest together with the offshore areas spanning from Lagos through Ondo, Ogun, Cross-Rivers to Rivers states along the Atlantic Ocean in the south–south. Despite this great potential and huge prospect, the country is found to still suffer from serious energy crises due to her over dependence on hydropower, which also is susceptible to seasonal variation in the amount of water levels at dams. There is yet to be a committed wind energy project for power generation on-going in the country. Several challenges bedevilling the development and utilisation of wind energy resources were identified and suggestions highlighted to help pull the nation out of this lingering energy crisis.

Isyaku (2010) designed, constructed and tested a 700W horizontal axis wind turbine for household use in Sabon Gida village, Kano. The machine was designed based on a 5 year wind data to operate at 10 metres height at a wind speed of 6.225 m/s in Kano. The machine developed was tested on the roof of the Department of Mechanical Engineering, Ahmadu Bello University, Zaria, at a height of 22 metres and average wind speed of 6.15 m/s. The machine achieved an overall efficiency of 11.1%

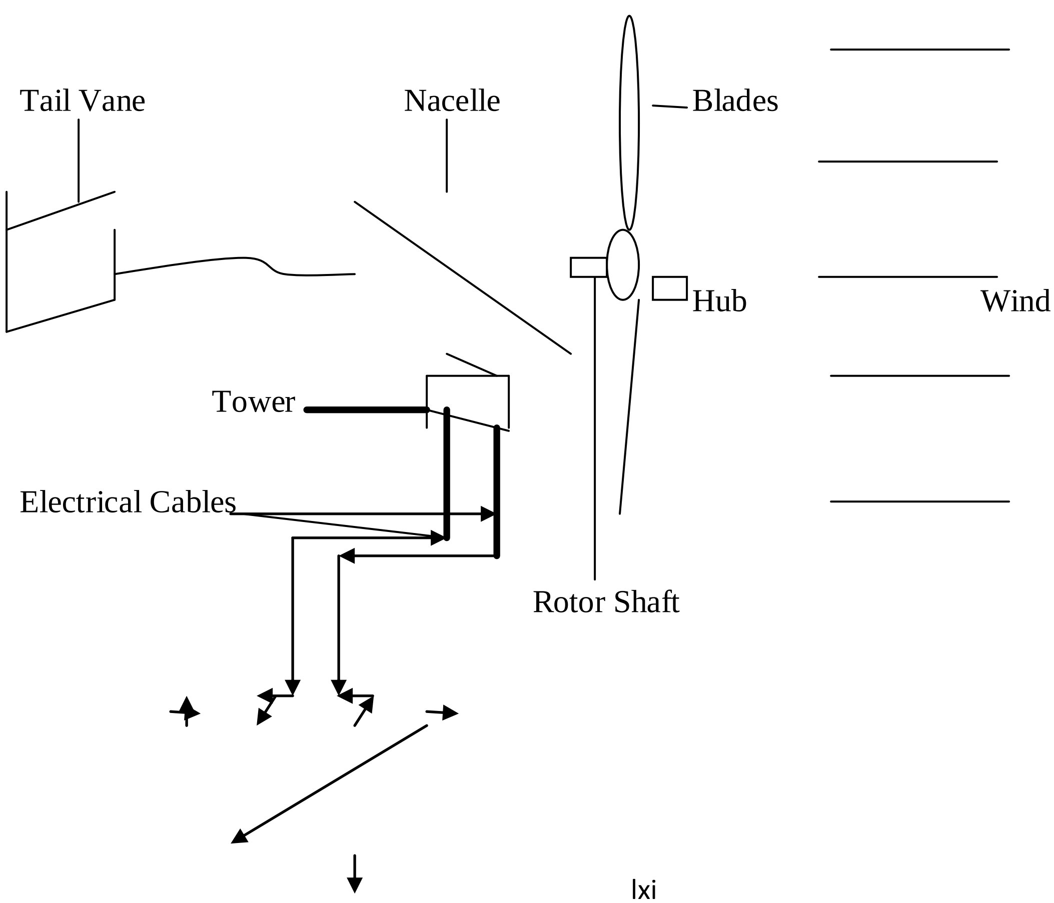
Sarki (1987) designed a vertical axis windmill with a rated power of 45 Watts at the prevailing wind speed in Zaria. He designed the windmill such that the components are easy to fabricate, transport and assemble by even unskilled labourers in remote areas. Low cost and ready availability of materials were also considered in the design. A study of the prospects of wind energy in ten northern states was also carried out.

CHAPTER THREE

MATERIALS AND METHODS

3.1 DESCRIPTION OF THE WIND TURBINE GENERATOR

The wind turbine generator transforms the kinetic energy of the wind into mechanical energy, and then into electricity. The system is made up of three rotor blades, connected to a shaft via a hub. The blades, hub and shaft rotate as a unit. The shafts are passed through bearings. The generator is a car alternator. The shaft going into the alternator and that coming from the rotor are joined with a gearing system to step up the rotational speed in the alternator. These features are shown in Figure 3.1. The turbine is pointed into the wind by rotating the nacelle about the tower, which is called “yaw control”. This is achieved with the help of the tail vane. The turbine operates with the rotor positioned on the windward side of the tower, which is referred to as an “upwind rotor”. The turbine will generally start producing power once the minimum required wind speed is exceeded. The amount of energy in the wind available for extraction by the turbine increases with the cube of wind speed; thus a 10% increase in wind speed means a 33% increase in available energy. However, a turbine can only capture a portion of this cubic increase in energy because power above the level for which the electrical system has been designed (referred to as the “rated power”) is allowed to pass through the rotor. The power produced by this generator is used to directly charge a battery.



Battery

Figure 3.1 Schematic diagram of the wind battery charging system.

3.2 MATERIALS

3.2.1 Materials for Various Components of Wind Turbines

It is generally easier to build small wind turbine rotors than those for large wind turbines. The rotor weight plays a less significant role in the design, and there is more focus on using minimum cost manufacturing techniques (such as injection molding for the smallest machines). While glass reinforced plastic is the most common material (as in large machines), it is also easily possible to use wood or recyclable thermoplastics for rotor blades manufacturing. A summary of commonly used wind turbine manufacturing materials is shown in Table 3.1.

Table 3.1 Materials used in wind turbines (Manwell *et al*, 2009).

Subsystems or components	Material category	Material subcategory
Blades	Composites	Glass fibers, carbon fibers, wood laminates, polyester resins, epoxies
Hub	Steel	
Gearbox	Steel	Various alloys, lubricants
Generator	Steel, copper	Rare earth based permanent magnets
Mechanical equipment	Steel	
Nacelle cover	Composites	Fiberglass
Tower	Steel	
Foundation	Steel, concrete	
Electrical and control system	Copper, silicon	

3.2.2 Wind Data

The main data for the research is long-term (≥5 years) observed wind speed data from surface anemometers. This observed wind speed data is available on request from the Nigerian Meteorological Agency (NMA), Oshodi, Lagos. Existing five year meteorological wind speed data of various locations of the Northern Nigeria (Jos inclusive) that were available in Knots were collected by Pam (2008). He used FORTRAN programming language to read data files in knots, converting it to m/s, projecting the data from 10m height to any height of interest, arranging the data into frequency tables, computing the mean wind speeds and standard deviations, the mean velocity cubed for each location, and presenting the summarised data in a data file.

This design is for Jos. Therefore, the long term wind data for Jos is necessary to carry on. Table 3.2 shows processed five years wind data for Jos at 10m height obtained from Pam (2008).

Table 3.2 Summary of observed wind data for Jos

Month	**Mean Velocity (m/s)**	**Mean velocity cube $(m/s)^3$**	**Standard Deviation**
January	5.72809315	272.302155	2.15917301
February	5.47525883	237.104996	2.03520584
March	5.49014044	229.0625	1.89364374
April	5.58810043	207.421387	1.40317738
May	5.54655933	202.44397	1.3851037
June	5.04935217	156.550568	1.34935135
July	5.10948467	177.689102	1.67917204
August	5.12773752	169.245636	1.46873915
September	4.26437521	98.8915482	1.29276574

October	4.51344633	123.579185	1.4970926
November	5.27568626	183.119568	1.5153234
December	5.75198793	255.17807	1.95098472
Annual	**5.23967171**	**192.267883**	**1.71270287**

3.3 DESIGN THEORIES

The principal component groups in a wind turbine are the rotor, the drive train, the main frame, the yaw system, and the tower. The rotor includes the blades, hub, and aerodynamic control surfaces. The drive train includes the gearbox (if any), the generator, mechanical brake, and shafts and couplings connecting them. The yaw system components depend on whether the turbine uses free yaw or driven yaw. The type of yaw system is usually determined by the orientation of the rotor (upwind or downwind of the tower).Yaw system components include at least a yaw bearing and may include a yaw drive (gear motor and yaw bull gear), yaw brake, and yaw damper. The main frame provides support for mounting the other components and a means for protecting them with a nacelle cover. The tower group includes the tower itself, its foundation, and may include the means for self-erection of the machine (Manwell *et al*, 2009).

3.3.1 Rotor Design

3.3.1.1 Rotor Swept Area

The rotor swept area can be determined from equation (2.5)

(3.1)

where, *D* is the rotor diameter.

3.3.1.2 Tip Speed Ratio

Tip speed ratio is the magic number which most concisely describes the rotor of a windmill. It indicates how many times faster than the wind speed the blade tip is designed to run. The rotor will do best at a particular tip speed ratio, but it will inevitably have to work over a range of speeds. The power coefficient will vary depending on tip speed ratio, for any particular rotor design. It will do best at the 'design' or 'rated' tip speed ratio, but acceptable over a range of speeds. The tip speed ratio is given by (Manwell *et al*, 2009)

— – (3.2)

where, is rotor speed in rpm, is the tip speed ratio, and R is the rotor radius. Typical choices for tip speed ratio and blade number for generator and pumps are shown in table 3.3 (Piggot, 2003).

Table 3.3 Tip speed ratio for various wind turbines

Tip Speed Ratio	**No. Of Blades**	**Functions**
1	6-20	Slow pumps
2	4-12	Faster pumps
3	3-6	Dutch 4-bladed
4	2-4	Slow generators
5-8	2-3	Generator
8-15	1-2	Fastest possible

3.3.1.3 Number of Blades

The number of blades used is largely dictated by the tip speed ratio. The choice can be made from Table 3.3. The number of blades, *B*, can also be selected and rounded up from the equation (Piggot, 2003)

(3.3)

For generators, two blades rattle more than three. This is partly because there is a difference in wind speed between the top and bottom halves of the windmill’s swept area known as *wind shear.* Another kind of wobble occurs when the wind turbine ‘yaws’. Two bladed rotors undergo a judder in yaw (Piggot, 2003). However, careful design considerations can yield optimum performance for even two bladed wind turbines.

3.3.1.4 Blade Profile

To achieve a good power coefficient, a blade profile that creates the optimum lift is needed, while minimising drag. In other words, the drag/lift ratio (drag divided by the lift) has to be minimised (Piggot, 2003). It helps to use a more aerodynamic shape, like thats of the wing sections shown in figure 3.2 (Manwell *et al*, 2009).

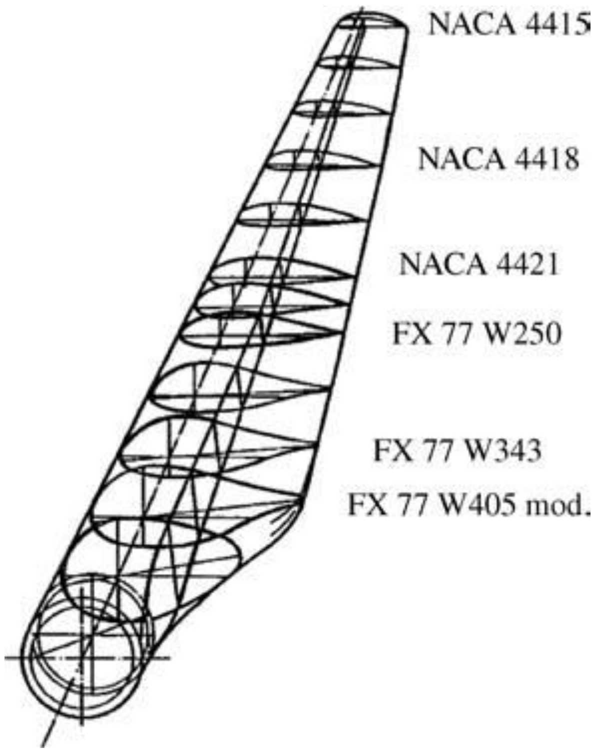


Figure 3.2: Airfoil cross-sections with radius. Source (Tong, 2010)

The angle of attack is the angle between the chord line and direction of the approaching wind, as seen by the wing section. There are graphs in data books which show how lift varies for common wing sections, at different angles of attack. Figure 3.3 shows the graph for NACA 4412 (Piggot, 2003).

The lift coefficient increases as the angle of attack increases until a point is reached, known as stall, where the airflow over the back of the section separates off, and a zone of turbulence appears as seen in figure 3.3. A stalled wing has low lift and very high drag (Piggot, 2003).

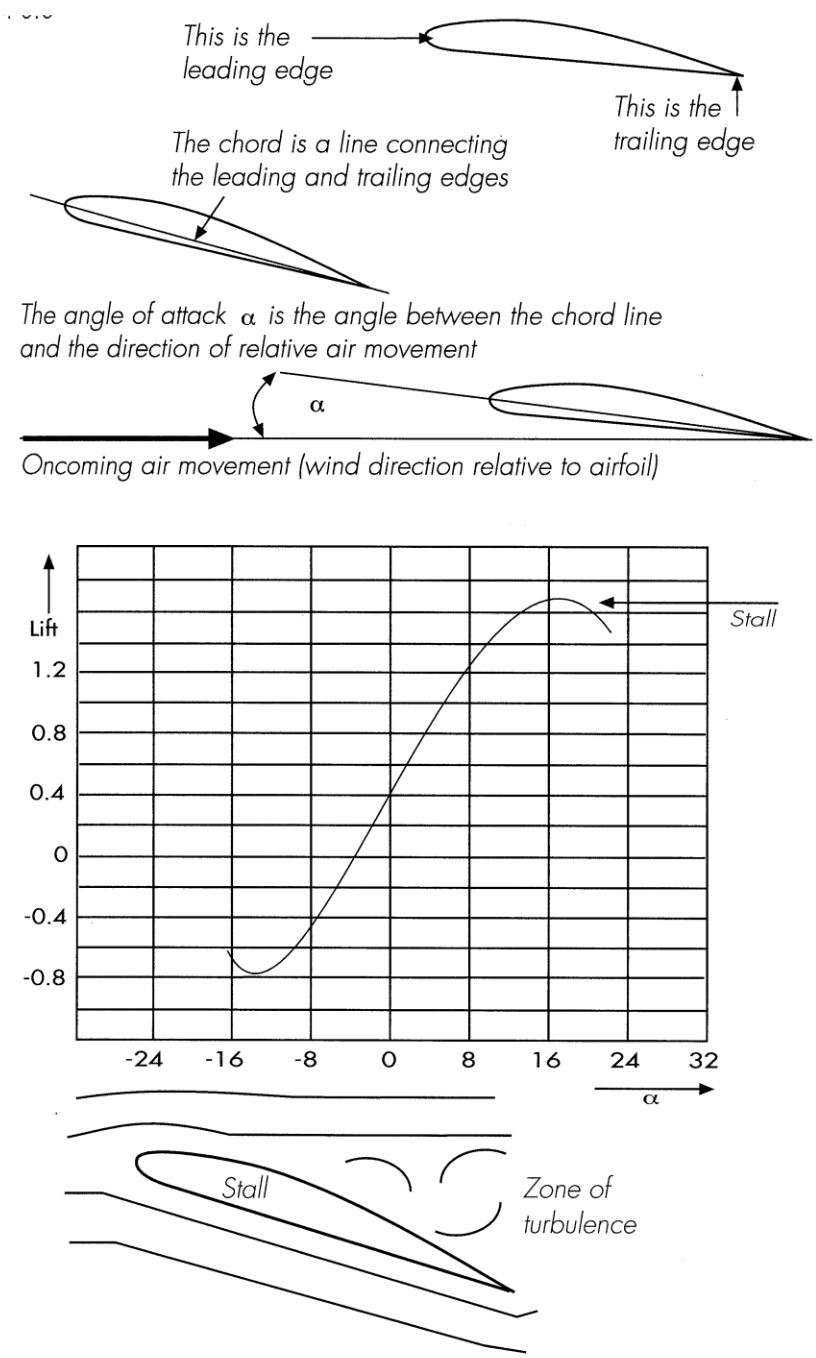


Figure 3.3: Lift versus angle of attack for the NACA 4412 (Re =10^7) (Piggot, 2003)

Wind tunnel studies show that the drag to lift ratio is not a constant factor. It varies with tilt of the section. The best ratio is usually at an angle of attack of around 4^0 (Piggot, 2003).

The data in table 3.4 shows that there is no huge variation in lift coefficient between the shapes, but there is in drag/lift ratio. Streamlined shapes like the NACA sections have much less drag than crude shapes.

Table 3.4: Data for some simple sections (Piggot, 2003)

Section	Drag/ Lift Ratio	Angle α	Lift Coefficient C/L
Flat plate	0.1	5^{o}	0.8
Curved plate (10% curvature)	0.02	3^{o}	1.25
Curved plate with tube concave side	0.03	4^{o}	1.1
Curved plate with tube convex side	0.2	14^{o}	1.25
Airfoil NACA 4412	0.01	4^{o}	0.8

A list of sections that could be used, with their best drag/lift ratios.

3.3.1.4 Blade Setting Angle (β)

Sometimes referred to as the 'pitch', the blade setting angle (β) is the angle between the chord line and the plane of rotation of the wind turbine rotor. The following steps should be followed to find the optimum angle (Piggot, 2003):

i. Decide what angle of attack (α) to operate at (usually 4^0) for minimum value of drag to lift ratio.

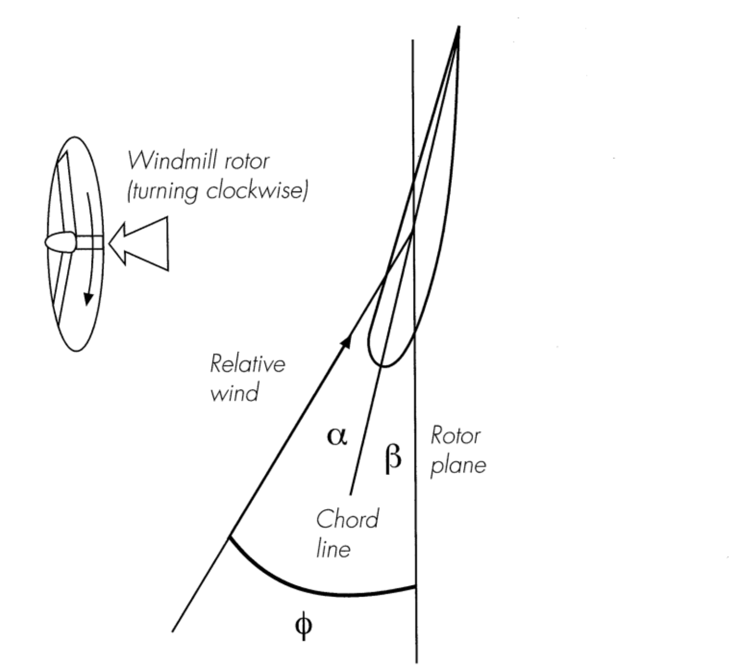
ii. Find the direction of the relative wind striking the leading edge of the blade at each section (Figure 3.4) . This will be the sum of two velocities: the wind velocity through the rotor and the 'headwind' velocity caused by the rotation of the rotor itself. This can be called the flow angle, ϕ

iii. The blade setting angle is the difference between the flow angle and the angle of attack. i.e

(3.4)

When = rotor radius, r = radius at given station, is given by (Piggot, 2003)

(3.5)



The setting angle, β, equals the flow angle, ϕ, minus the angle of attack, α.

Fig. 3.4The setting angle is adjusted for the best angle of attack

%

3.3.1.5 Blade Width or Chord (C_w)

The blade design process involves specifying the chord width of the blade at each station along the span. To calculate the chord in theory, the aerodynamic thrust (from lift calculations) is equated with the force for the Betz change of momentum (Newton's Law) and eventually arrived at the following workable formula (Piggot, 2003):

$$\frac{-}{\quad} \qquad (3.6)$$

Where B = number of blades

Chord width could also be chosen as a percentage of the rotor diameter. Table 3.5 gives the blade widths for a selection of tip speed ratios and number of blades. Station 1 is nearest the hub, station 5 nearest the tip, so the chord gets thinner nearer the tip.

Table 3.5: Chord width as a of diameter (Piggot, 2003).

Tip Speed Ratio:	4	6	8	10
Number of blades:	3	3	2	2
Station 1	21.4	12.3	11.6	7.8
2	15.4	7.5	6.5	4.2
3	11.2	5.2	4.4	2.9
4	8.7	4.0	3.4	2.2
5	7.1	3.2	2.7	1.7

3.3.1.6 Blade Thickness

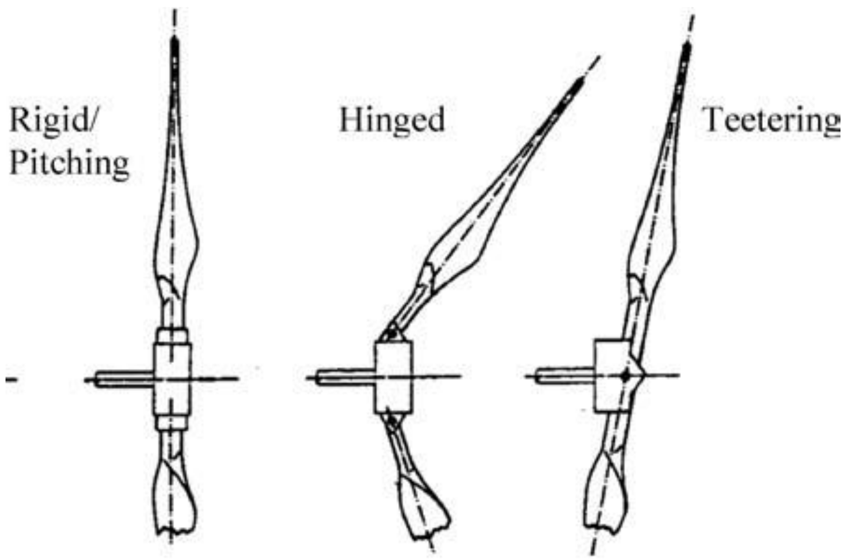
Thin sections have better drag to lift ratio, so they should be used where possible, for best performance. Near the root, where the speed ratio is low, the drag to lift ratio is not so important, but the strength of the blade is the most important factor. So, a thick section at the root is more appropriate.

3.3.1.7 Rotor Hub

The hub of the wind turbine is the component that connects the blades to the main shaft and ultimately to the rest of the drive train. The hub transmits and must withstand all the loads generated by the blades. Hubs are generally made of steel, either welded or cast. Details of hubs differ considerably depending on the overall design philosophy of the turbine (Manwell *et al* 2009).

There are three basic types of hub design that have been applied in modern horizontal axis wind turbines: (1) rigid hubs, (2) teetering hubs, and (3) hubs for hinged blades.

a) Rigid hubs as the name implies, have all major parts fixed relative to the main shaft. They are the most common design, and are nearly universal for machines with three (or more) blades.
b) Teetering hubs allow relative motion between the part that connects to the blades and that which connects to the main shaft. Like a child's teeter-totter (seesaw), when one blade moves one way, the other blade moves the other way. Teetering hubs are commonly used for two- and one bladed wind turbines.
c) Hubs for hinged blades allow independent flapping motion relative to the plane of rotation. Such hubs are not presently used on any commercial wind turbines but they have been employed on some historically important turbines (Smith–Putnam) and are presently receiving renewed attention. Some of the common types of hubs are illustrated in figure 3.5



(a) Rigid **(b) Hinged** **(c) Teetering**

Fig 3.5: Hub options

Source: Gasch, 1996 (Manwell *et al*, 2009).

3.3.2 Wind Turbine Rotor Dynamics

Imposed loads and dynamic interactions produce forces and motions in wind turbines which need to be understood during the design process. The effects of all of the various types of loads (static, steady, cyclic, transient, impulsive, and stochastic) need to be determined. The most important rotor loads on a wind turbine are those associated with thrust on the blades and torque to drive the rotor.

3.2.2.1 Thrust

The thrust, *T*, may be found from the following equation (Manwell *et al.*, 2009).

(3.7)

where is the thrust coefficient. For the ideal case (Manwell *et al.,* 2009).. In terms of this simple model, then, total thrust on a given rotor varies only with the square of the wind speed.

3.3.2.2 Bending Moments and Stresses

Blade bending moments are usually designated as either flapwise or edgewise. Flapwise bending moments cause the blades to bend upwind or downwind. Edgewise bending moments are parallel to the rotor axis and give rise to the power-producing torque. They are sometimes referred to as 'lead–lag' (Manwell *et al.,* 2009).

i. *Axial Forces and Moments*

The flapwise bending moment at the root of an ideal blade of a turbine with multiple blades is given by the product of the thrust force per blade and 2/3 of the radius. The root flapwise bending moment on a single blade, , for a turbine with *B* blades is (Manwell *et al* 2009).

– – (3.8)

The maximum flapwise stress, , due to bending at the root is given by (Manwell *et al.,* 2009).

—— (3.9)

where c is the distance from the flapwise neutral axis and is the area moment of inertia of blade cross-section at the root. For a wind turbine blade in bending, the neutral axis would be nearly the same as the chord line and would be approximately half the airfoil thickness.

The shear force,   , in the root of the blade is simply the thrust divided by the number of blades:

(3.10)

In summary, for a given ideal rotor, bending forces and stresses vary with the square of the wind speed and are independent of blade angular position (azimuth). Furthermore, blades on rotors designed for higher tip speed ratio operation have smaller chords and cross-sectional area moment of inertia, so they experience higher flapwise stresses.

ii. *Edgewise Forces and Moments*

As mentioned above, the edgewise moments give rise to the power-producing torque. In terms of blade strength, aerodynamic edgewise moments are generally of less significance than their flapwise counterparts. (It should be noted, however, that edgewise moments due to blade self-weight can be quite significant in larger turbines). The mean torque *Q* is the power divided by the rotational speed. For the ideal rotor, as shown in eqn 3.11, torque is given by:

– — — (3.11)

In the more general case, torque can then be expressed in terms of a torque coefficient, (the power coefficient divided by the tip speed ratio), where (Manwell *et al.*, 2009):

– (3.12)

For an ideal rotor, the rotational speed varies with the wind speed, so torque varies as the square of the wind speed. Furthermore, rotors designed for higher tip speed ratio operation have lower torque coefficients, so they experience lower torques (but not necessarily lower stresses). Again, according to this simple model there is no variation in torque with blade azimuth.

iii. Edgewise (Lead–Lag) Moment

The bending moment in the edgewise direction (designated by z) at the root of single blade, is simply the torque divided by the number of blades:

(3.13)

There is no correspondingly simple relation for edgewise shear force, , but it can be found from integrating the tangential force;

(3.14)

3.3.3 Drive Train Design

3.2.3.1 Gear Design

Gears are elements used in transferring power from one shaft to another. Most wind turbine drive trains include a gearbox to increase the speed of the input shaft to the generator. An increase in speed is needed because wind turbine rotors, and hence, main shafts, turn at a much lower speed than is required by most electrical generators. Small wind turbine rotors turn at speeds on the order of a few hundred rpm. Larger wind turbines turn more slowly. Most conventional generators require between 1500 rpm (60 Hz) to 1800 rpm (50 Hz) (Manwell *et al.,* 2009).

Design Procedure for Spur Gears: The most basic, and most common gear is the spur gear. In order to design spur gears, the following procedure may be followed

iv. First of all, the design tangential tooth load is obtained from the power transmitted and the pitch line velocity by using the following relation (Khurmi and Gupta, 2005):

$$- \qquad (3.15)$$

Where,

W_T = Permissible tangential tooth load in newtons,

P = Power transmitted in watts,

v = Pitch line velocity in m /s ——

D = Pitch circle diameter in metres

N = Speed in r.p.m., and

C_S = Service factor.

v. Apply the Lewis equation as follows (Khurmi and Gupta, 2005):

$$(3.16)$$

Where = permissible working stress

b = gear face width

= circular pitch = $-$ (T – number of teeth)

y = Half the thickness of the tooth (*t*) at critical section.

m = module = D/T (The recommended series of modules in Indian Standard are 1, 1.25, 1.5, 2, 2.5, 3, 4, 5, 6, 8, 10, 12, 16, 20, 25, 32, 40 and 50. The modules 1.125, 1.375, 1.75, 2.25, 2.75, 3.5, 4.5,5.5, 7, 9, 11, 14, 18, 22, 28, 36 and 45 are of second choice) (Khurmi and Gupta, 2005).

Notes : (*i*) The Lewis equation is applied only to the weaker of the two wheels (*i.e.* pinion or gear).

(*ii*) When both the pinion and the gear are made of the same material, then pinion is the weaker.

(*iii*) The product ($\sigma_w \times y$) is called ***strength factor*** of the gear.

(iv) The face width (b) may be taken as 3 P_c to 4 P_c (or 9.5 m to 12.5 m) for cut teeth and 2 P_c to 3 P_c (or 6.5 m to 9.5 m) for cast teeth.

The number of teeth on pinion, , in order to avoid interference may be obtained from (Khurmi and Gupta, 2005) as:

(3.17a)

A_W = Fraction by which the standard addendum for the wheel should be multiplied,

G_r = Gear ratio or velocity ratio =

$T_G / T_P = D_G / D_P = N_P/N_G$ (3.17b)

= Pressure angle or angle of obliquity.

vi. Calculate the dynamic load (W_D) on the tooth by using Buckingham equation given by (Khurmi and Gupta, 2005)

$W_D = W_T + W_I = W_T +$ (3.18)

In calculating the dynamic load (W_D), the value of tangential load (W_T) may be calculated by neglecting the service factor (C_S) *i.e.* $W_T = P / v$, where P is in watts and v in m / s.

vii. Find the static tooth load (*i.e.* beam strength or the endurance strength of the tooth) by using the relation (Khurmi and Gupta, 2005),

(3.19)

Where = flexural endurance limit = 1.75 × B.H.N. (in MPa) for steel

B.H.N = Brinel Hardness Number

For safety against breakage, W_S should be greater than W_D.

viii. Finally, find the wear tooth load by using the following relation (Khurmi and Gupta, 2005),

. (3.20)

Where D_P = Pitch circle diameter of the pinion in mm. The wear load should not be less than the dynamic load (W_D) (Khurmi and Gupta, 2005).

Systems of Gearing Tooth:

ix. The **14 $^1/_2$°** ***composite system*** is used for general purpose gears. It is stronger but has no interchangeability. The tooth profile of this system has cycloidal curves at the top and bottom and involute curve at the middle portion. The teeth are produced by formed milling cutters or hobs.

x. The tooth profile of the **14 $^1/_2$°** ***full depth involute system*** was developed for use with gear hobs for spur and helical gears.

xi. The tooth profile of the **20°** ***full depth involute system*** may be cut by hobs. The increase of the pressure angle from **14 $^1/_2$°** to 20° results in a stronger tooth, because the tooth acting as a beam is wider at the base.

xii. The **20°** ***stub involute system*** has a strong tooth to take heavy loads.

3.3.3.2 Shaft Design

Shafts are cylindrical elements designed to rotate. Their primary function is normally to transmit power, and so they carry or are attached to gears, pulleys, or couplings. In wind turbine generators, shafts are typically found in gearboxes and generators, and in linkages (Khurmi and Gupta, 2005)

Design of Shaft for Spur Gears:

The shaft experiences bending loads due to the weight of the rotor and due to the normal gear tooth load, and the torsional moments due to power transmission. In order to find the diameter of shaft for spur gears, the following procedure may be followed.

- First of all, find the normal load (*W_N*), acting between the tooth surfaces. It is given by (Khurmi and Gupta, 2005)

  $$W_N = \text{——} \qquad (3.21)$$

  A thrust parallel and equal to W_N will act at the gear centre

- The weight of the gear is given by the following (Khurmi and Gupta, 2005)

  $$W_G = 0.00118\ T.b.m^2 \qquad (3.22)$$

- Resultant load acting on pinion is (Khurmi and Gupta, 2005),

  $$\overline{\qquad\qquad\qquad\qquad} \qquad (3.23)$$

- If the gear is overhung on the shaft, then bending moment on the shaft due to the resultant load is

  $$M = \quad \times x \qquad (3.24)$$

  Where x = Overhang *i.e.* the distance between the centre of gear and the centre of bearing.

- Since the shaft is under the combined effect of torsion and bending, therefore we shall determine the equivalent torque. We know that equivalent torque is given by

  $$T_e = \overline{\qquad\qquad} \qquad (3.25)$$

where T = twisting moment = $W_T \times D/2$

- Now the diameter of the gear shaft (d) is determined by using the following relation (Khurmi and Gupta, 2005):

$$T_e = — \quad (3.26)$$

Where, = Shear stress for the material of the gear shaft

3.3.3.3 Bearing Selection

Ball bearings are widely used in wind turbine components. They are used in the main shaft mountings, gearboxes, generators, yaw systems, blade pitch systems, and teetering mechanisms to name just a few. The bearings are designated by a number. In general, the number consists of at least three digits. Additional digits or letters are used to indicate special features *e.g.* deep groove, filling notch, etc. The last three digits give the series and the bore of the bearing. The last two digits from 04 onwards, when multiplied by 5, give the bore diameter in millimeters. The third from the last digit designates the series of the bearing. The most common ball bearings are available in four series as follows (Khurmi and Gupta, 2005):

1. Extra light (100), **2.** Light (200) **3.** Medium (300) **4.** Heavy (400)

Notes : 1. If a bearing is designated by the number 305, it means that the bearing is of medium series whose bore is 05 × 5, *i.e.*, 25 mm

Selection of the most appropriate bearing would be on the basis of the following:

i. *Basic Static Load Rating:* For radial ball bearings, the basic static radial load rating (C_0) is given by the following generation (Khurmi and Gupta, 2005)

(3.27)

where,

i = Number of rows of balls in any one bearing,

Z = Number of ball per row,

D = Diameter of balls, in mm,

= Nominal angle of contact *i.e.* the nominal angle between the line of action of the ball load and a plane perpendicular to the axis of bearing, and

= A factor depending upon the type of bearing.

The value of the factor ( ) for bearings made of hardened steel are taken as follows :

= 3.33, for self-aligning ball bearings. = 12.3, for radial contact and angular contact groove ball bearings (Khurmi and Gupta, 2005).

ii. *Static Equivalent Load:* The static equivalent radial load (W_{0R}) for radial or roller bearings under combined radial and axial or thrust loads is given by the greater magnitude of those obtained by the following two equations, *i.e* (Khurmi and Gupta, 2005)

$$W_{0R} = X_0.W_{Ra} + Y_0.W_A;\text{ and } W_{0R} = W_{Ra} \qquad (3.28)$$

where,

W_{Ra} = Radial load,

W_A = Axial or thrust load,

X_0 = Radial load factor, and

Y_0 = Axial or thrust load factor.

iii. *Dynamic Equivalent Load:* The dynamic equivalent radial load (W) for radial and angular contact bearings, except the filling slot types, under combined constant radial load (W_R) and constant axial or thrust load (W_A) is given by (Khurmi and Gupta, 2005)

$$W = X.V.W_R + Y.W_A \qquad (3.29)$$

where,

V = rotation factor,

= 1, for all types of bearings when the inner race is rotating,

= 1, for self-aligning bearings when inner race is stationary,

= 1.2, for all types of bearings except self-aligning, when inner race is stationary.

The values of radial load factor (X) and axial or thrust load factor (Y) for the dynamically loaded bearings may be read from Tables (Khurmi and Gupta, 2005).

iv. *Dynamic Load Rating for Rolling Contact Bearings under Variable Loads:* The approximate rating (or service) life of ball or roller bearings is based on the fundamental equation expressed as follows (Khurmi and Gupta, 2005)

$$- \quad \text{or} \quad — \qquad (3.30)$$

where ,

L_r = Rating life, C = Basic dynamic load rating, W = Equivalent dynamic load and k = 3, for ball bearings, k = 10/3, for roller bearings. The relationship between the life in revolutions ( ) and the life in working hours (L_H) is given by

$$= 60\ N.L_H \qquad (3.31)$$

where N is the speed in r.p.m.

v. Reliability of a Bearing: According to Weibull, the relation between the bearing life and the reliability is given as (Khurmi and Gupta, 2005)

$$- \quad - \quad \text{or} \; - \quad - \qquad (3.32)$$

Where,

L is the life of the bearing corresponding to the desired reliability R and a and b are constants whose values are a = 6.84, and b = 1.17

3.3.3.4 Key Design

A key is a piece of mild steel inserted between the shaft and hub to connect these two together in order to prevent relative motion between them. Keys are used as temporary fastenings and are subjected to considerable crushing and shearing stresses. A keyway is a slot or recess in a shaft and hub of the pulley to accommodate a key (Khurmi and Gupta, 2005).

i. *Square sunk key*: For the width (w) and thickness (t) of the key (Khurmi and Gupta, 2005),

$$w = t = d / 4 \qquad (3.33)$$

$$l = 1.571\, d \qquad (3.34)$$

where d = Diameter of the shaft or diameter of the hole in the hub l = length of key

ii. If T = Torque transmitted by the shaft

and = Shear and crushing stresses for the material of key. Considering shearing of the key (Khurmi and Gupta, 2005),

– (3.34)

Considering crushing of the key,

– – (3.35)

The key is equally strong in shearing and crushing, if

– – (3.36)

The permissible crushing stress for the usual key material is at least twice the permissible shearing stress. Thus, a square key is equally strong in shearing and crushing.

[illegible]
τ

3.3.3.5 Coupling and Key Design

Sleeve or Muff-coupling is the simplest type of rigid coupling, made of cast iron. It consists of a hollow cylinder whose inner diameter is the same as that of the shaft. It is fitted over the ends of the two shafts by means of a gib head key. The power is transmitted from one shaft to the other shaft by means of a key and a sleeve. It is therefore, necessary that all the elements must be strong enough to transmit the torque. The usual proportions of a cast iron sleeve coupling are as follows (Khurmi and Gupta, 2005):

Outer diameter of the sleeve, $D = 2d + 13$ mm (3.37)

and length of the sleeve, $L = 3.5\ d$ *(3.38)*

where d is the diameter of the shaft.

iii. Sleeve or Muff-coupling design

The safe value of shear stress for cast iron may be taken as 14 MPa (Khurmi and Gupta, 2005).

The torque transmitted by a hollow section is given by (Khurmi and Gupta, 2005)

— —— — (3.39)

Where

k = d/D

T = Torque to be transmitted by the coupling, and

= Permissible shear stress for the material of the sleeve which is cast iron.

From this expression, the induced shear stress in the sleeve may be checked.

3.3.3.6 Design for Bolts

Bolts are subjected to shear stress due to the torque transmitted. The number of bolts (n) at a particular coupling or joint depends upon the diameter of shaft and the pitch circle diameter of bolts is taken as 3 d (Khurmi and Gupta, 2005).

where,

d = Diameter of shaft

σ_{cb} = Allowable crushing stress for bolt material

The load on each bolt is given by the following relation (Khurmi and Gupta, 2005):

–

Therefore total loads on the bolts = –

The torque may be determined as follows:

Torque, – — (3.41)

d_1 = Nominal or outside diameter of bolt,

D_1 = Diameter of bolt circle,

n = Number of bolts,

t_f = Thickness of flange,

= Allowable shear stress for bolt material

From equation (3.41) the diameter of bolt (d_1) may be obtained. Now the diameter of bolt may be checked in crushing. The area resisting crushing of all the bolts is given as :

$$\sigma_{cb} = n \times d_1 \times t_f$$

and crushing strength of all the bolts given by :

$$= (n \times d1 \times t_f)\ \sigma_{cb}$$

Therefore, Torque, $T = (n \times d_1 \times t_f \times \sigma_{cb})$ — (3.42)

From equation (3.42) the induced crushing stress in the bolts may be checked.

3.3.4 Mechanical Control

In addition to its main task of converting wind power to electricity, the wind turbine generator must adapt to circumstances. It must face itself into the wind. It also needs to protect itself from the violence of the wind greater than the rated wind speed (Piggot, 2003).

3.3.4.1 Facing into the Wind (Tail vane Design)

The vane catches the wind, pulls on the boom, and swivels the machine about its yaw axis to face the wind. The amount of turning moment which the tail vane needs to produce will depend on such things as (Piggot, 2003):

i. Friction in the yaw bearing
ii. Aerodynamic forces on the rotor (thrust, self orienting forces, etc), and
iii. The tendency of the center of gravity to swing downhill, if the tower is not quite vertical.

The yaw moment produced by the tail vane is simply the side force on the vane multiplied by the length of the boom. A longer boom will compensate for a smaller vane. The side force (   ) on the vane will depend on the area of the vane (   ) and the wind speed squared (   ) (Piggot, 2003).

(3.43)

(3.44)

Where is the rotor thrust. As a rule of thumb, the actual boom should be about equal to the length of one blade, i.e half of the rotor diameter, with a vane centred at its end. The vanes are rarely smaller than 3% (1/30th) of the swept area of the rotor. This is approximately equivalent to;

(3.44)

The tail vane can be cut from any sheet material. Plywood makes a very durable vane.

3.3.4.2 Avoiding Overload

One approach is to use centrifugally operated 'air brakes', but this is rather like monitoring with one foot on the brake and the other on the throttle. Keep a low profile and ride out the storm. There are two common types of 'governing systems' which aerodynamically limit the power captured by the rotor (Piggot, 2003):

i. One which yaws or tilts the whole machine, so that the rotor becomes skew to the wind. In the side-facing position it literally presents a 'low profile'. Wind speed through the rotor is reduced and so the power captured.
ii. One which adjusts the pitch of individual blades. Twisting the blades changes the angle of attack, reducing the lift.

3.3.5 Nacelle Housing

The nacelle housing provides weather protection for the wind turbine components which are located in the nacelle. These include, in particular, electrical and mechanical components that could be affected by sunlight, rain, ice, or snow. Nacelle housings are normally made from a lightweight material, such as fiberglass, metal sheets etc. On larger machines, the nacelle housing is of sufficient size that it can be entered by personnel for inspecting or maintaining the internal components (Manwell, 2009). On small and medium-size turbines, a separate nacelle housing is normally attached to the main frame in such a way that it can be readily opened for access to items inside. A component which some turbines have, and which is closely related to the nacelle cover, is the spinner or nose cone.

3.3.6 Tower Design

A tower is normally at least as high as the diameter of the rotor. For smaller turbines the tower may be much higher than that. There are three types of towers in common use for horizontal axis wind turbines (Manwell, 2009):

i. Free-standing lattice (truss);
ii. Cantilevered pipe (tubular tower); and
iii. Guyed lattice or pole.

Wind turbine towers are usually made of steel, although sometimes reinforced concrete is used.

3.2.6.1 Loads:

The tower can experience two major types of load: (1) steady and (2) dynamic (Khurmi and Gupta, 2005). Steady tower loads arise primarily from aerodynamically produced thrust and torque. The weight of the machine itself is also a significant load. The effects of loading must be considered especially on bending and buckling. The crippling or buckling load, , under various end conditions is represented by a general equation (Khurmi and Gupta, 2005):

(3.46)

where,

E = Modulus of elasticity or Young's modulus for the material of the column,

A = Area of cross-section,

= Least radius of gyration of the cross-section, *L* = Length of the column, and

C = Constant, representing the end conditions of the column or end fixity coefficient.

Dynamic effects can be a significant source of loads, especially on soft or soft–soft towers. A stiff tower is one whose fundamental natural frequency is above the blade-passing frequency, a soft tower is one whose natural frequency is between the blade-passing frequency and the rotor frequency, and a soft–soft tower is one whose natural frequency is below both the rotor frequency and the blade-passing frequency. For either a soft or soft–soft tower, the tower can be excited during start-up or shutdown of the turbine. For the simple case, when the turbine/tower can be approximated by a uniform cantilever with a point mass on the top, the following equation may be used (Manwell, 2009).

(3.47)

where is the fundamental natural frequency (Hz), *I* is the moment of inertia of the tower cross-section, is the mass of the tower, is the mass of the turbine, and *L* is the height of the tower.

3.3.7 Generator Selection

The generator converts the mechanical power from the rotor into electrical power. The generator is the heart of the wind turbine, and the hardest part to get right. A reliable low speed generator with good efficiency especially in light winds is the best choice. Permanent magnet alternators qualify on all these counts, and they are by far the most popular choice in successful small wind turbines. In these generators, permanent magnets provide the magnetic field, so there is no need for field windings or supply of current to the field. In one example, the magnets are integrated directly into a cylindrical cast aluminum rotor. The power is taken from a stationary armature, so there is no need for commutator, slip rings, or brushes. Because the construction of the machine is so simple, the permanent magnet generator is quite rugged. The operating principles of permanent magnet generators are similar to those of synchronous machines. In fact, they are frequently referred to as permanent magnet synchronous generators, with the acronym PMSG. The main difference is that the field is provided by permanent magnets instead of electromagnets. In addition, these machines are usually run asynchronously. That is, they are not generally connected directly to the AC network. The power produced by the generator is initially variable voltage and frequency AC. This AC is often rectified immediately to DC. The DC power is then either directed to DC loads or battery storage, or else it is inverted to AC with a fixed frequency and voltage. In the latter case, they are an option for variable-speed wind turbines (Manwell, 2009). In an event where permanent magnet alternators cannot be found, car alternators can serve the purpose.

3.3.8 Battery Energy Storage

Battery energy storage is very common with small hybrid power systems and is occasionally used in large electrical networks as well. Batteries have proven to be a popular energy storage medium, based primarily on their convenience and cost. Battery storage systems are modular, and multiple batteries can store large amounts of energy. Lead acid batteries are most prevalent, although nickel–cadmium batteries are occasionally used (Manwell, 2009). Batteries are inherently DC devices. Thus, a battery energy storage in AC systems requires a power converter. An important aspect of batteries is their terminal voltage, which varies according to current and state of the charge. Typical battery voltage during a discharge–charge cycle is illustrated in Figure 3.6. It can be seen that the terminal voltage drops as the battery is discharged. When charging is initiated, the terminal voltage jumps to a value above the nominal cell voltage. As the cell becomes fully charged, the terminal voltage increases even more before gasing occurs (the production of hydrogen gas in the cells) and the terminal voltage levels off.

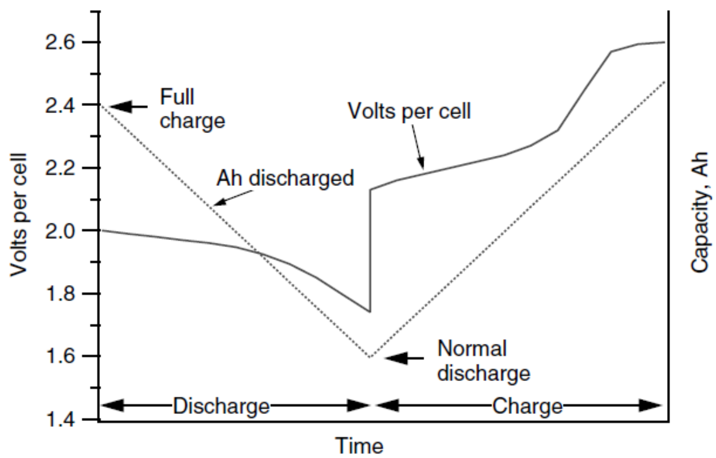


Fig 3.6: Typical battery voltage and capacity curve

Source: Fink and Beaty, 1978 (Manwell, 2009).

A number of aspects of battery behaviour affect their use in power systems. These are summarised as follows (Manwell, 2009):

i. Battery capacity: Effective battery capacity is a function of current. Thus, the amount of available storage is a function of the rate at which the storage is used.

ii. Terminal voltage: Terminal voltage is a function of state of charge and current level. This affects the operation of the power transfer circuit between the battery storage and the rest of the system.

iii. Efficiency: Batteries are not 100% efficient. Battery losses can be minimized by intelligent controller operation, but most of the losses are due to differences in voltage during discharging and charging and are inherent to battery operation.

iv. Battery life: Batteries have a limited useful life. Battery life is a function of the number and depth of charge–discharge cycles, and is also related to the battery design.

v. Temperature effects: Battery capacity and life are functions of temperature. Usable battery capacity decreases as the temperature decreases. Typically, battery capacity at 0^0C is only half that at room temperature. Above room temperature, battery capacity increases slightly, but battery life decreases dramatically.

3.4 DESIGN CONSIDERATIONS

The following parameters were considered for the design of the wind battery charger

a) The mean annual wind velocity from Table 3.2 of 5.24m/s

b) The generator rating of 300W was used.

c) Based on the studies carried out, the specific output of horizontal axis wind turbine is particularly dependent on the ratio of the rated speed V_r to the annual mean velocity V_m and independent of the wind velocity distribution over the earth. The important range of V_r / V_m = 1 to 2 is most favourable (Edwin, 1982).

λ

d) A power coefficient of 0.40 was used. This is because the theoretical maximum of 0.593 (Manwell, 2009) cannot be attained in practice due to power losses in the drive train and other turbine components.

e) A tip speed ratio, , of six (6) was adopted.This falls within the suitable tip speed ratio range from generators as shown in Table 3.3

f) Three (3) tapered blades were used. This is also from table 3.3 is a suitable number for wind generators, and the choice of three provides more rotor balance than two (Piggot, 2003).

g) The blade profile of NACA 4412 was selected for making the blades.

h) An angle of attack of 4^0 for minimum drag/lift coefficient of about 0.8 (Piggot, 2003) considered in the diagram.

i) The 20° *full depth involute system* was be used for the gearing. The increase of the pressure angle from 14 $^1/_2$° to 20° results in a stronger tooth, because the tooth acting as a beam is wider at the base.

j) A service factor of two (2) was used for the gear design for heavy shock and 24 hour day operation.

- Minimum allowable static stress of cast iron and mild steel are $60N/mm^2$ and $105N/mm^2$ respectively (Khurmi and Gupta, 2005).
- Modulus of Elasticity of cast iron and mild steel are $100kN/mm^2$ and $200kN/mm^2$ respectively (Khurmi and Gupta, 2005).
- The flexural endurance limit for grey cast iron is 84 N/mm^2 (Khurmi and Gupta, 2005).
- The surface endurance limit for grey cast iron is 630 N/mm^2 (Khurmi and Gupta, 2005).

- Tooth error based on pitch line velocity is read from Table 3.6 (Khurmi and Gupta, 2005):

Table 3.6: Values of maximum allowable tooth error in action (*e*) as a function of pitch line velocity, for well cut commercial gears.

Pitch line velocity (*v*) m/s	**Tooth error in action (*e*) mm**	**Pitch line velocity (*v*) m/s**	**Tooth error in action (*e*) mm**	**Pitch line velocity (*v*) m/s**	**Tooth error in action (*e*) mm**
1.25	0.0925	8.75	0.0425	16.25	0.0200
2.5	0.0800	10	0.0375	17.5	0.0175
3.75	0.0700	11.25	0.0325	20	0.0150
5	0.0600	12.5	0.0300	22.5	0.0150
6.25	0.0525	13.75	0.0250	25 and over	0.0125
7.5	0.0475	15	0.0225		

3.5 DESIGN CALCULATIONS

INITIAL DATA	**CALCULATION AND SKETCES**	**RESULTS**
From the wind data for Jos, the annual mean velocity V_m at a height of 10m is	**<u>Rated wind speed for the machine (V_r)</u>** To optimise between the specific output and the wind turbine system size, the choice of 1.2 as a ratio of the rated wind speed to the mean velocity in this design can give a very good approximation. Thus, $V_r = 1.2\ V_m = 1.2 \text{ X } 5.24 \text{ m/s} = 6.29 \text{ m/s}$	$V_r = 6.29$m/s

5.24m/s		
P = 300Watts = 0.4 V = V_r = 6.29/s. = 1.2kg/m^3 (at sea level)	**Rotor swept diameter (D)** The actual extractable power from the wind by the rotor is given by Equation (2.3) A = = 4.93 = D = = = 2.5	D ≈ 2.5m.
α = 4 6 B = 3	**Blade profile** The airfoil section selected is the NACA 4412 i. The blade chord or blade width at various sections along the span of the rotor blades is given by Equation (3.6) Taking reference from tip of the blade, At station 5, r = R = 1.25 = 0.06m At station 4, r = R = 1.0 = 0.08m	= 0.06m = 0.08m

	At station 3, r = R = 0.75 = 0.11m At station 2, r = R = 0.5 = 0.16m At station 1, r = R = 0.25 = 0.26m ii. The blade setting angle is given by that at station 4 because this is the best choice for a non twisted blade (Piggot, 2003) $\beta = \phi - \alpha$ From equations (3.4) & (3.5) At station 4, r=R=1.0 $\beta = \quad - 4 = 7.91 - 4 = 3.91^0$ iii. Rotor speed (N) From equation (3.2) N = = 288.3 r.p.m	= 0.11m = 0.16m = 0.26m $\beta = 3.91^0$ N = 288.3

	Therefore at rated speed and tip speed ratio of 6, the rotor rotates at 288.3 r.p.m	r.p.m
	<u>Surface area of the tail vane</u> The design surface area of the tail vane should be greater than the rotor diameter square divided by 40, (see equation (3.44)) $A_t > D^2/40$ $A_t > 2.5^2/40$ $A_t > 0.16m^2$ Say $A_t = 0.16 \times 1.5 = 0.24m^2$ The side force is given by equation (3.43) Side force, $F_{side} = A_t \times V_r^2/16$ $F_{side} = 0.24\times 6.29^2/16 = 0.59kg$ The rotor thrust is given by equation (3.44) Rotor Thrust = $D^2 V_r^2/24$ Rotor Thrust = $2.5^2\times6.29^2/24 = 10.3kg$	$A_t = 0.24m^2$ $F_{side} = 0.58kg$ Rotor Thrust = 10.3kg
$C_S = 2$ P =300W (full depth in-volute system) taking	**<u>Gear Design</u>** i. Gear ratio: Speed of gear (driver), N_G = 288.3 rpm Expected speed of pinion (driven), N_P = 1200 rpm (1200 rpm is rated speed of alternator) Gear ratio = N_P/ N_G (Equation 3.17b)	Gear Ratio = 5

= 40 *A*W = 1 (Fraction by which the standard addendum for the wheel should be Multiplied)	= 1200/288.3 = 4.16 ii. Tangential Tooth Load: − (Equation 3.15) ——— = —————— = 2.51 m/s ——— = 239.04N iii. Face width of the pinion The velocity factor C_V is given as ——— = ——— = 0.642 The number of teeth on pinion in order to avoid interference may be obtained from equation (3.17a) = 17.10 Lewi's form factor, *Y*, or tooth form factor for full depth involute system is calculated as follows ——— = 0.103 The Module (m) = D_P/T_P = 40/18 = 2.22mm	2.52 m/s Y = 0.103 m = 2.5mm

K = 0.111, for 20° full depth (Khurmi and Gupta, 2005). involute system		The nearest standard value for the module is 2.5mm The number of teeth on the gear wheel is $T_G = 5 \quad 18 = 90$ In actual practice, face width b, is taken as 9.5m to 12.5m. We choose 10m b = 10m = 10×2.5 = 25mm	$T_G = 90$
$E_P = E_G$ = 100kN/m^2 (Young modulus of cast iron) (Khurmi and Gupta, 2005). e = 0.0800 at pitch line velocity of 2.51m/s (Khurmi and Gupta, 2005).	iv.	Dynamic load (W_D) on the tooth: From equation (3.18) $W_D = W_T + W_I = W_T +$ (Khurmi and Gupta, 2005) W_T = P/v = 300/2.51 = 119.52 W_D = 119.52+ = 226.78N	b = 25mm
	v.	Static tooth load (W_S): Using Equation (3.19) W_S = The design is safe against tooth breakage since the	W_D = 226.78N W_S =

		static tooth load (W_S) is greater than the dynamic load (W_D).	
for cast iron (Khurmi and Gupta, 2005).	vi.	Wear tooth load (W_W):	
		$W_W = D_P.b.K_f.Q$ (Khurmi and Gupta, 2005).	
		Q = ——= —— = 1.67	
630N/mm^2 for cast iron.		K_f = ——— — — ———— —— ——	
		=1939.25 N/mm^2	
		The design is safe since the wear tooth load is not less than the dynamic tooth load	
		Standard proportions of the system for a 20^o full depth involute system with module, m= 2.5mm are as follows (Khurmi and Gupta, 2005).:	
		Addendum = 1m = 2.5 mm	
		Dedendum = 1.25m = 3.125mm	
		Working depth = 2m = 5mm	
		Minimum total depth = 2.25m = 5.625mm	
		Total Thickness = 1.5708m = 3.925mm	
		Minimum clearance = 0.25m = 0.625mm	
		Fillet radius at root = 0.4m = 1mm	

= 45N/mm^2 for mild steel.	**Design of rotor shaft** The shaft experiences bending loads due to weight of the rotor and due to the normal gear tooth load, and the torsional moments due to power transmission. i. Pinion Shaft The normal load is calculated using eqn (3.21) W_N = ——= / = 254.38N The weight of the pinion is determined from Equation (3.22) as: $W_P = 0.00118\ T_P . b.m^2 = 0.00118 \times 18 \times 25 \times 2.5^2$ = 3.32N Resultant load acting on pinion is found as follows: = 257.44N Pinion is overhang on the shaft at 100mm, therefore bending moment of the shaft due to resultant load is calculated as follows: M = × 100 = 257.44 × 100 = 25744N-mm And twisting moment of the shaft	W_N = 254.38N W_P =3.32N M = 25744N-mm T = 5087.6Nmm

(Khurmi and Gupta, 2005).	$T = W_T \times D_P/2 = 254.38 \times 40/2 = 5087.6$N-mm	
	Equivalent twisting moment is found as follows	$T_e =$ 26241.9 Nmm
	$T_e =$	
	=	
	= 26241.9 N-mm	
	Let d_P = diameter of pinion. From equation (3.26)	
	$T_e =$ — = — = 26241.9	
	= 2969.98	
	,	
	Thus, the minimum shaft diameter for the pinion is 14.37mm	
	ii. Gear Shaft	
	We have calculated above the normal load	
	$W_N = 254.38$N	
	Weight of the gear	
	$W_G = 0.00118\ T_G . b.m^2 = 0.00118 \times 90 \times 25 \times 2.5^2$	$W_G = 16.59$N
	= 16.59N	
	Resultant load acting on the gear	
		W_R=270.05N

		= 270.05N	
		The gear is overhung on the shaft at 100mm, therefore bending moment of the shaft due to resultant load is	M =
		M = × 100 = 270.05× 100 = 27005Nmm	27005Nmm
		And twisting moment of the shaft	T =
		$T = W_T \times D_G/2$ = 254.38 × 200/2 =25438Nmm	25438Nmm
		Equivalent twisting moment	
		$T_e =$ =	
		= 37099.35 Nmm	T_e =
		Let d_G = diameter of gear shaft. From	37099.4 Nmm
		T_e = — = — = 37099.35	
		= 4723.64	
		Thus the minimum shaft diameter of gear is 16.13mm.	

CHAPTER FOUR

CONSTRUCTION, TESTING, RESULTS AND DISCUSIONS

4.8 THE DESIGNED WIND TURBINE SYSTEM

4.8.1 Design Calculations With JAVA Programming Language

Detailed design calculations for the wind turbine are shown in section 3.5. These calculations were very cumbersome. Therefore a computer programme was developed with the Java programming language. All the major aspects of the wind turbine design and analysis were captured in the programme. The programme was tested for the same system designed in section 3.5. The flow chart and programming codes in JAVA are shown in appendix A. The results from running the programme are shown in appendix B. These results agree with calculations done manually in section 3.5, and therefore validate the computer programme developed. The programme will run on any computer with a java compiler and runtime environment. This should reduce the problem of manual calculation for future research in this particular field.

4.8.2 Design Drawings

Detailed drawings for the assembly and component designs are shown in appendix C. The drawings show the assembled system and also the various designed components. These drawings were done with Auto CAD.

4.9 CONSTRUCTION OF THE SYSTEM COMPONENTS

4.9.1 Rotor Blades

Wood is probably the best choice for one-off construction of windmill blades. Properties of wood to be considered when making wooden blades include lightness, strength, workability and good resistance to fatigue (Piggot, 2003). White capara wood properties are close to the aforementioned properties and was therefore, used for the blade construction. Three pieces of wood each with dimensions150mm by 30mm, and 1200mm long were used. The same steps were carefully followed for carving each blade into the same shape for highest symmetry possible. With the use of an automated saw, a wood chisel, plane, calipers, compasses, tape measure, ruler and pencil, a step-by-step description of the process for blade carving (Piggot, 2003) was followed to produce three NACA 412 profiled blades. The flat surface with a setting angle of four degrees will face the wind with the curved surface behind. Holes were drilled on the root of the blades for bolting on the hub. Plates 1 – 6 in appendix D show some of the production processes of the blades.

4.9.2 Rotor Hub

The rotor hub was manufactured by cutting two metal sheets of thickness 2mm into the shape of the root of the rotor when the roots of the three blades are shaped to be 120 degrees apart. This also ensures that the leading edge of one blade is 120 degrees ahead of the subsequent one. Holes were drilled on both metal sheets on equivalent points as the blade roots. This allows the bolts to pass through the metal sheet in front, the blade root and the metal sheet behind, together forming the hub. A hole is drilled through the middle for mounting the hub onto the shaft. Plates 7 – 9, in appendix D show the production processes of the hub.

4.9.3 Shaft

The shafts were made by cutting, turning, milling and polishing solid mild steel rods to the required diameter at each point. Different portions of the shaft had different diameters. Key holes were also made to lock the gear assemblies and bearings onto the shaft. The rotor shaft has a thread at the head for bolting the rotor hub firmly on the shaft. This will enable the assembly to rotate securely as a unit. Plates 10 - 11 in appendix D show the production processes.

4.2.4 Gears

The gear of diameter 160mm and the pinion of diameter 40mm were manufactured from tephlon using gear cutters and drill bits. The gear hubs were constructed to fit into the shaft diameter and locked with keys. The gear ratio is 4:1. Plates 12 - 14 in appendix D show the production processes.

4.2.5 Nacelle

The nacelle is made up of a supporting table constructed by cutting metal sheet 300mm by 2.5mm, by 500mm long and a house enclosing fabricated from sheet metals by shaping to form a three-dimensional box curved at the top. The casing support was provided by appropriately welding angle iron and steel bars. Ventilation holes were made at the sides to allow air to circulate and cool the alternator and gears. A window was inserted for maintenance access whenever the need arises. Plates 15 - 17 in appendix D, show the production processes.

4.2.6 Tail Vane

The tail vane was manufactured by shaping plywood into a trapezoidal sheet with surface area of $0.24m^2$**.** This sheet was mounted on a boom made of a rectangular hollow pipe of dimensions 1200mm x 50mm x 30mm. The other end of the boom was attached to the boom by a weld joint. Plate 18 in appendix D shows the constructed vane.

4.2.7 Tower

A hollow steel pipe of 150mm outer diameter, 145 inner diameter and length of 2000mm was used for the tower. The base was welded on a very thick metal sheet that would be placed on the foundation. Four holes were drilled close to the four corners of the metal sheet, so that it can be bolted onto the foundation. A cast of cement (33kg), gravel (99kg), sand (50kg) and water (17kg) was made on the roof of the Mechanical Engineering building of the Ahmadu Bello University Zaria, and left for twenty one days to dry. Bolts were welded on a metal frame and built into the cast. A set of ball bearing was built into the bottom of the nacelle to fill into the top of the tower and a stopper/locker was constructed to firmly hold the turbine on the tower and allow it to rotate along the axis of the bearing, thereby allowing yaw. Plates 19 - 22 in appendix D, show the stages of making the tower and its foundation.

4.2.8 Standard Parts

Some parts of the system are standard components. Some of such parts include the shaft and yaw bearings, the bolts and nuts. They were purchased from reliable dealers of spare parts.

4.2.9 Coupling & Finishing

The system components were manufactured such that they can be coupled into a single unit on installation. The nacelle, tail vane, tower and hub were painted with light green oil paint. The blades were first of all treated before painted with the same oil paint as the other components.

4.3 INSTALLING AND TESTING THE SYSTEM

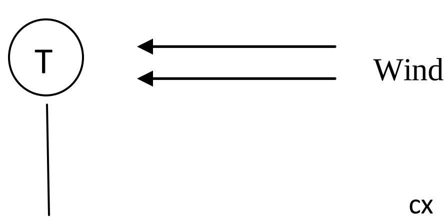
The various components were coupled together to form the 300 Watts wind turbine battery charging system as shown in plates 24 and 25 in appendix D. Plate 23 shows the anemometer for observing instantaneous wind speed. The installation was done on the top of the third floor (roof) of the Mechanical Engineering Department, Ahmadu Bello University Zaria, at a height of approximately 22m. The tower was mounted on the cast concrete base and tightly held by using the four bolts cast together with the base.

4.3.1 Testing Set Up

The line diagram for the set-up is shown in figure 4.1. The set up comprises of 0 - 45 range ammeter (A), 0 – 20V range voltmeter, 12V/45AH storage battery, 3W electric load (R), and system generator (G).

4.3.2 Testing Procedure

The installed system operates as described in section 3.1. The wind speed, generator output current (A) and voltage were read on an anemometer, ammeter and a voltmeter, respectively. The corresponding power output at a given wind speed, voltage and current were calculated and recorded. This was carried out at an interval of two minutes for thirty minutes on two consecutive days (Tuesday, January 29, 2012 from 6:12pm to 6:48pm, and on Wednesday, January 30, 2013 from 12:10pm to 12:42pm).



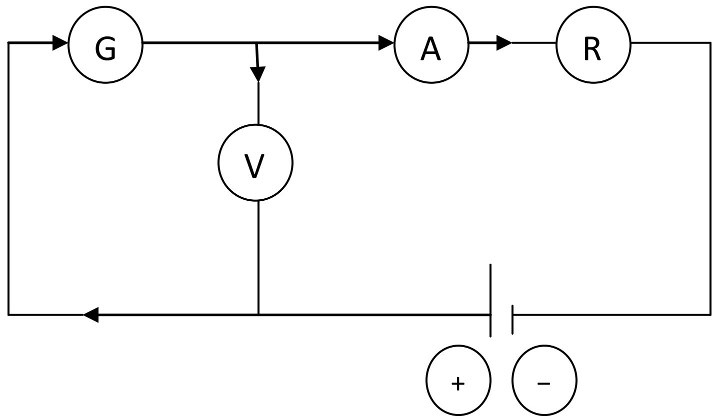


Figure 4.1 Electrical power measuring set up

4.3.3 Test Results and Discussions

The results from the test carried out as described in section 4.3.2 were recorded as shown in Table 4.1 and Table 4.2. At low speeds (0.4 – 3.7 m/s), the alternator was not excited, therefore no outputs were obtained. On both days, it was observed that until the wind speed was about 3.8 m/s, the blades did not rotate fast enough to excite the alternator.

In Table 4.3, only readings with power outputs from the two days were selected, combined, and arranged from the lowest (cut in wind speed) to the highest (rated wind speed). The power outputs at various wind speed were calculated and recorded in watts by multiplying the voltage by the corresponding current.

It can be seen from the results (see Table 4.1 and 4.2) table that the power output fluctuated. This is due to the variability of the wind velocity with time.

Table 4.1 Instantaneous and power output measured on Tuesday, January 29 2012 from 6:12 PM to 6:48PM

Time (hours)	Instantaneous Wind Speed (m/s)	Power(Watts)
6:12	4.3	69.88
6:15	5.4	178.99
6:17	3.2	-
6:19	2.6	-
6:21	2.2	-
6:23	3.2	-
6:25	3.0	-
6:28	5.7	212.26
6:32	3.1	-
6:34	2.2	-
6:36	3.6	-
6:38	2.4	-
6:40	0.4	-
6:42	2.3	-
6:44	1.0	-
6:46	2.1	-
6:48	1.4	-

Table 4.2 Instantaneous and power output measured on Wednesday, January 30 2013 from 12:10PM to 12:42PM

Time (hours)	Instantaneous Wind Speed (m/s)	Power(Watts)

12:10	3.7	-
12:12	3.0	-
12:14	3.6	-
12:15	5.9	235.52
12:17	3.7	-
12:19	6.1	260.88
12:23	5.0	142.61
12:25	3.2	-
12:27	2.0	-
12:29	2.3	-
12:31	2.4	-
12:34	1.3	-
12:36	3.8	21.49
12:40	3.1	-
12:42	3.0	-

Table 4.3 Combined outputs from Table 4.1 and Table 4.2

Instantaneous Wind	**Power(Watts)**

Speed (m/s)	
3.8	21.49
4.3	69.88
5.0	142.61
5.4	178.99
5.7	212.26
5.9	235.52
6.1	260.88

4.4 SIMULATION OF THE WIND TURBINE POWER CURVE

To estimate the power output from a wind-powered turbine from equation 4.1, knowledge of the power output function, P(V), is required.

4.4.1 Method of Analysis

The power output function, *P(V)*, of the wind-powered turbine generator in terms of the cut-in speed, and rated speed is as follows (Pam, 2008):

(4.1)

This is assuming a quadratic variation of the power output with wind speed between cut-in and rated wind speeds. Where the wind speed is evaluated at the wind turbine hub height and *A, B and C* are coefficients that can be determined by the following conditions:

Where

By employing Cramer's rule (Stroud, 1995), A, B and C can be shown to be

— **(4.2)**

— **(4.3)**

— **(4.4)**

Where

(4.5)

An error analysis could be carried out to test the "goodness-of-fit" of the stated assumptions made on the power output function between cut-in and rated wind speeds. If *n* actual power output values, , from the wind-turbine output curve are available in the range and the analysis yields calculated power outputs, , within the same velocity range, then the percentage error, , between the actual and calculated power outputs at each of the *n* points is given by:

(4.6)

For the n values, the root mean square percentage error, is given by

(4.7)

The rms percentage error, , can be used as an index for the closeness of fit to the actual characteristics of the wind-powered turbines.

4.4.2 Simulation Data Analysis

The power curve for the turbine was obtained. The turbine has a cut-in wind speed , rated speed , and rated power

Thus, the mean velocity, , can be calculated as follows:

For a second degree power variation, inserting the values for into equations (4.1) to (4.7), we obtain A = -317.87, B =77.63, and C = 3.27

Hence,

in the range

The actual power outputs, calculated power outputs and the percentage errors at the given velocities are summarised in the table 4.4.

Table 4.4 Summary of the 300W turbine power outputs and error analysis

Speed, V (m/s)	**Actual power, P_a (W)**	**Calculated Power, P_c(W)**	**%Error,**
3.8	21.49	24.42	-13.60
4.3	69.88	76.50	-9.58
5.0	142.61	152.16	-6.69
5.4	178.99	196.83	-9.97
5.7	212.26	231.03	-8.84
5.9	235.52	254.15	- 7.91
6.1	260.88	277.54	- 6.39

The root mean square percentage error calculated from equation (4.7) is 8.98%

The actual power output and calculated power output are obtained from table 4.4 and plotted on the same graph shown in figure 4.2.

ε

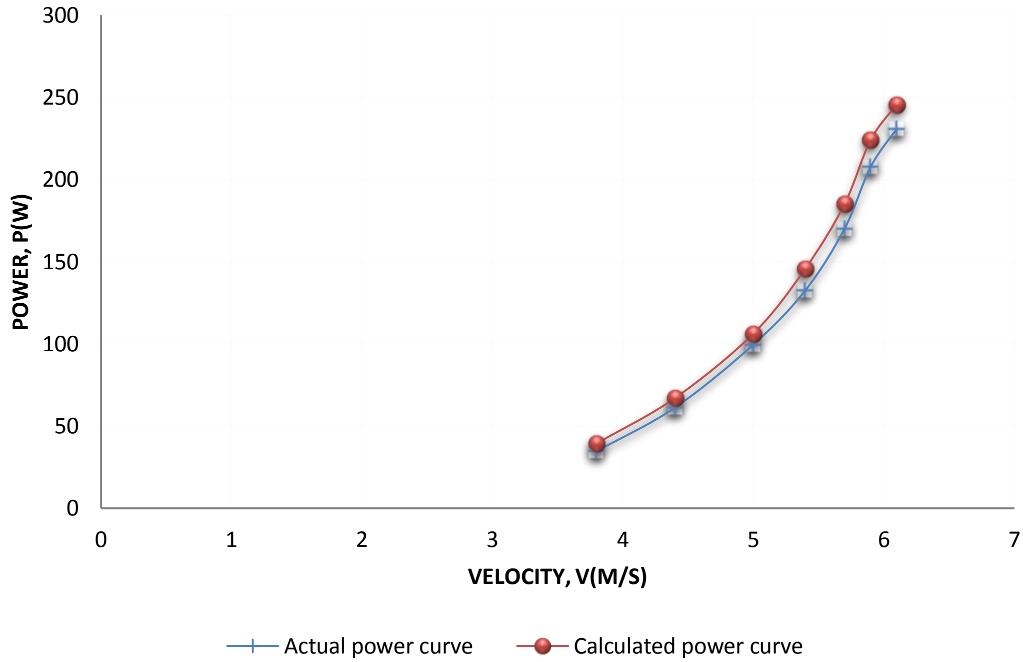


Figure 4.2 Actual and calculated power curves

Figure 4.2 shows a comparison between the actual power output curve and the simulated power output curve. As the velocity increases, the power output increases by a cube of the velocity (Edwin, 1982). Therefore, the slopes of the curves are steep. These curves, which are for the power output between cut in wind speed and rated wind speed for the wind turbine, are similar in shape. This shows that using a second degree polynomial to model the system is satisfactory. It describes very well the nature of the system performance between the cut in wind speed and rated wind speed of the wind turbine.

The rms percentage error, , is 8.98%. This is an indicator that the simulated power output or performance of the turbine is close enough to the actual power output, and shows further that the closeness of fit to the actual characteristics of the wind-powered turbines is satisfactory.

The system was designed for the wind data of Jos, but tested in Zaria. This has significance in the observed output. The wind data for Jos is much more superior to that of Zaria (Pam, 2008). This means the performance, if tested in Jos, would be better. This shows how important it is to design a wind turbine with the observed wind data of the location in which it will be used.

4.5 EFFICIENCY

Zaria has an altitude of 653.9m above sea level and therefore a corresponding air density of 1.147kg/m^3 (Pam, 2008). The overall efficiency, from equation (2.4) is given by

The overall wind turbine efficiency a the prevailing velocity is calculated and tabulated as shown in table 4.5.

Table 4.5 Overall efficiencies of the wind turbine

V (m/s)		

[illegible]%

3.8	21.49	15.1
4.3	69.88	31.61
5.0	142.61	43.97
5.4	178.99	43.81
5.7	212.26	44.17
5.9	235.52	44.19
6.1	260.88	44.29

The average overall efficiency, ‾‾, can be calculated from the table as follows:

(4.9)

The average overall efficiency is 38.16 %

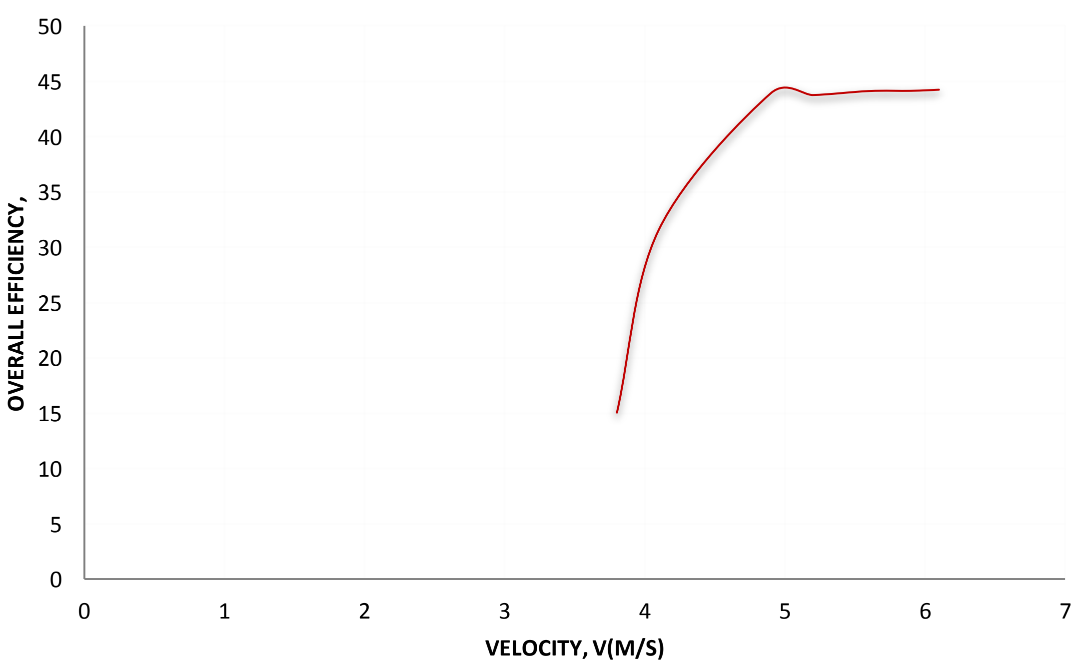


Figure 4.3 Overall efficiency curve.

The overall efficiency curve behaves as expected. The efficiency increases with increase in velocity. As the wind velocity increases, the available power increases by the velocity cubed. This in turn increases the power output of the generator, and hence, the efficiency.

Thus, the highest efficiency of the wind turbine was 44.29%, which occurred at the highest wind speed of the system operation. The average overall efficiency was found to be 38.16%, which is a very good result for a practical situation. Therefore, if this system operates in a region with predominantly rated wind velocity (6.29m/s), it would be practically very efficient most of the time.

4.6 COST EVALUATION

Evaluation of the machine cost is based on material, labour and overhead costs. The material cost involves the detail breakdown of materials summed up costs of all the materials used for the construction of the wind turbine, tower, and accessories. Labour cost is what has been spent in payment for labour and services during the manufacturing process. Most of these costs were incurred by the workshop services offered. Overhead cost involves the transportation and miscellaneous expenses. Table 4.6 and table 4.7 give a detail breakdown of the system cost.

Table 4.6 Material Cost

	COMPONENT	MATERIAL	DIMENSION (mm)	QTY	UNIT	Total Cost(

					COS T (₦)	₦)
1.	Alternator	Copper	-	1	4500	4500
2.	Blades	Wood	3800 x 220 38	1	2250	2250
4	Solid shafts	Mild steel	Φ25 x 600	1	1500	1500
5	Metal sheet	Mild steel	1500 x 800 x 2.5 600 x 300 x2.0	1 1	3500 1500	3500 1500
6	Frame (2x2 angle iron)	Mild steel	4000	1	1500	1500
7	Deep groove single row ball bearing	UTP	Φ22	2	1200	2400
8	Spur gears	Tephlon	Φ200X50	1	10000	10000
9	Bolts, nuts & washers	Grade 4.8 steel			1300	1300
10	Aluminum paint	Oil paint	450ML	1	1500	1500
11	Cast	Gravel:Cement: Sand	99kg:33kg:50kg	1	3000	3000
12	Electric Wires	Copper	Φ5X3000 Φ1.5X3000	1 1	450 200	450 200
13	Battery	Copper		2	200	400

	Terminals					
14	Hollow Pipe	Mild steel	Outer diameter 150, inner diameter 145, length 3000	1	1500	1500
15	Welding electrode		Gauge 10	60	10	600
16	Set Of Spanners & Pipe range	Mild steel		1	1200	1200
17	Tail vane	Ply wood	600 x 600	1	800	800
18	Boom	Rectangular hollow pipe	1500 x 50 x 30	1	500	500

Sub Total = N38,850.

Table 4.7 Labor and overhead costs

S/N	TYPE OF LABOUR	COST(₦)
1.	Cost of cutting /carving the blades	1500
2.	Cost of producing the housing, housing components, tail vane, tower, etc	17000
3.	Cost of casting the machine concrete base	2500
4.	Cost of transportation and other miscellaneous expenses	12000
5	Cost of installing the system	3000

Sub Total = N36,000.

Grand Total = N74,850

The installed capital cost for the 300W wind turbine generator

4.7 DIFFICULTIES

Some difficulties were experienced in the course of carrying out the work. A major one was finding the most suitable alternator. A permanent magnet alternator (PMA), which is the best choice for small wind turbines, was very difficult to find. The only possible option for getting a PMA failed to pull through. Other alternator options, such as dismantling a small domestic generator and using its alternator, were tried and test-run. They did not prove good options, and the car alternator became the last resort. Wood is a very good option for small wind turbine blades, but so many factors restrained the possibility of considering better material options such as reinforced fiber glass. Aluminum could have been a good option for some nacelle parts, but is very expensive.

On more than one occasion, some of the constructions or selection processes had to be done all over again before arriving at the most suitable option.

CHAPTER FIVE

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.1 SUMMARY

The system design was carried out based on long term observed wind data for Jos. The designed calculations were done both manually and with a computer programme developed with JAVA programming language. The designed components of the turbine were carefully constructed using the best available methods and materials. The system was coupled and tested on the roof of the Mechanical Engineering Department of Ahmadu Bello University, Zaria, at a height of 22m. A mathematical model for computing their power output using a second degree quadratic equation, and the power outputs at the velocities recorded were developed. The results were analysed, and performance variables such as power output, root mean square percentage error and overall efficiency were determined. A cost evaluation of the system was carried out.

5.2 CONCLUSIONS

The following conclusions may be drawn from the current work

i. A simulation of the system performance output was carried out using a second degree polynomial model, and it showed that this model satisfactorily represents the actual system performance.

ii. The overall efficiency increased, as the velocity increased which is as expected, and the average overall efficiency was found to be 38.16%.

5.3 RECOMMENDATIONS

The following recommendations would help in improving and easing further research in wind turbine design and construction:

1. Other alternator options should be explored. Permanent magnet alternators still seem to be the best, and maybe the possibility of building them from scrap should be considered. Since the alternator selection has a huge impact on the outcome of the research, it should be sorted out before any work is started.
2. If a car alternator has to be used, research should be done on how to modify them for high efficiency.
3. Grants should be sought for projects of such magnitude. Wind energy research is very expensive, and in most cases cannot be done effectively without grants.
4. In the future, arrangements should be made to carry out testing of constructed wind turbines in the locations they were designed for. This would give a better result.
5. Data loggers should be incorporated in the measurement to ensure long term power output measurements.

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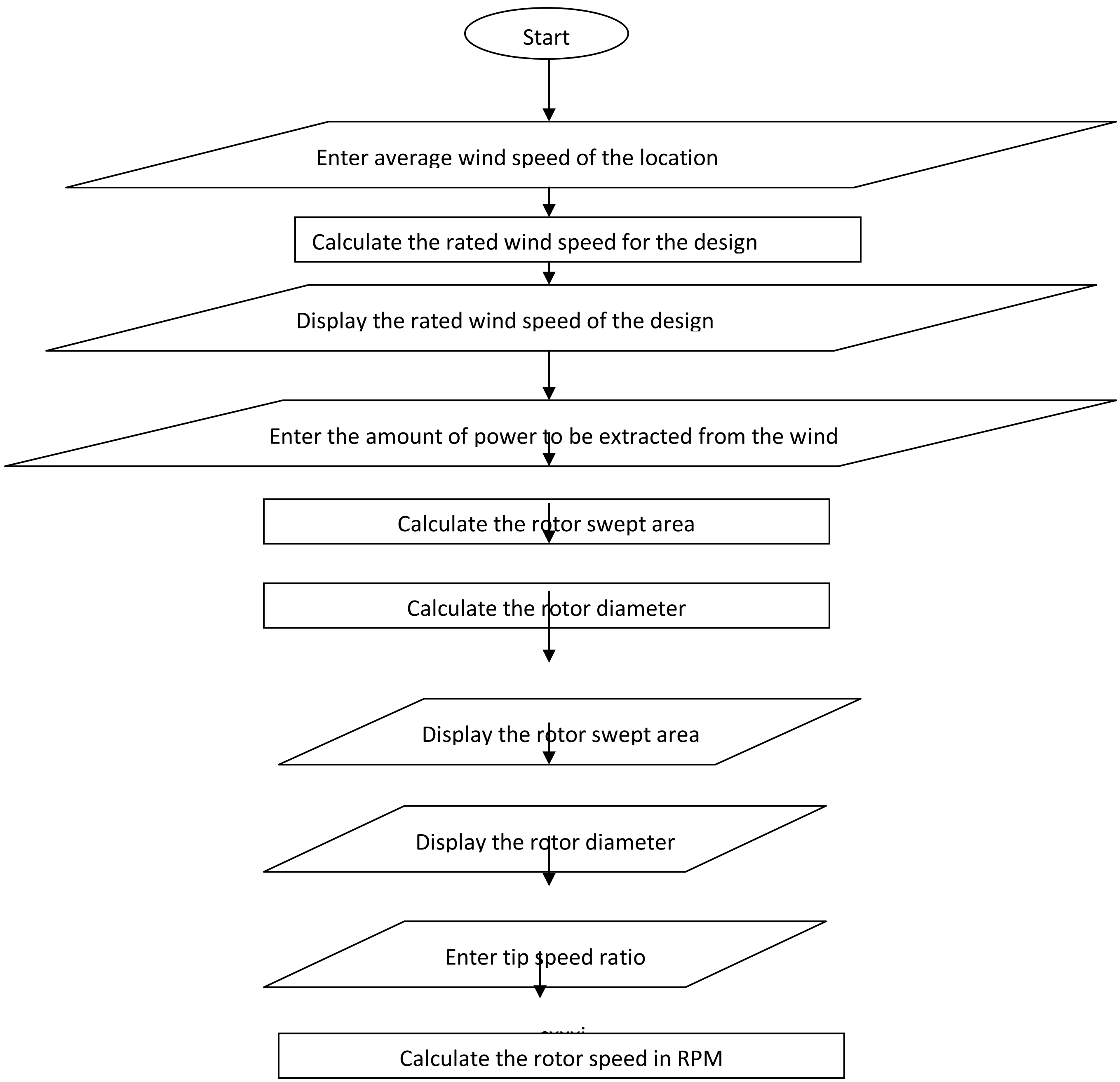
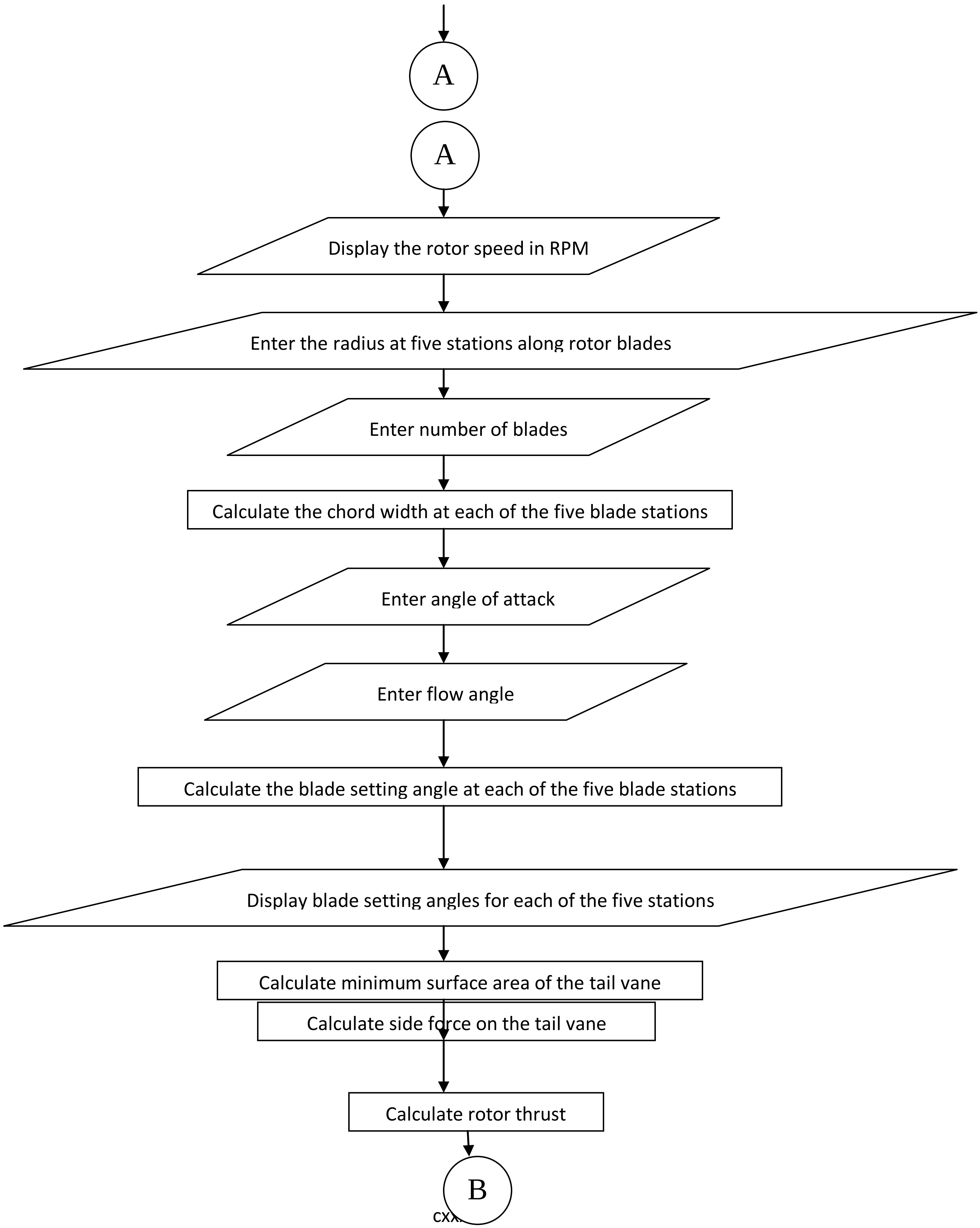
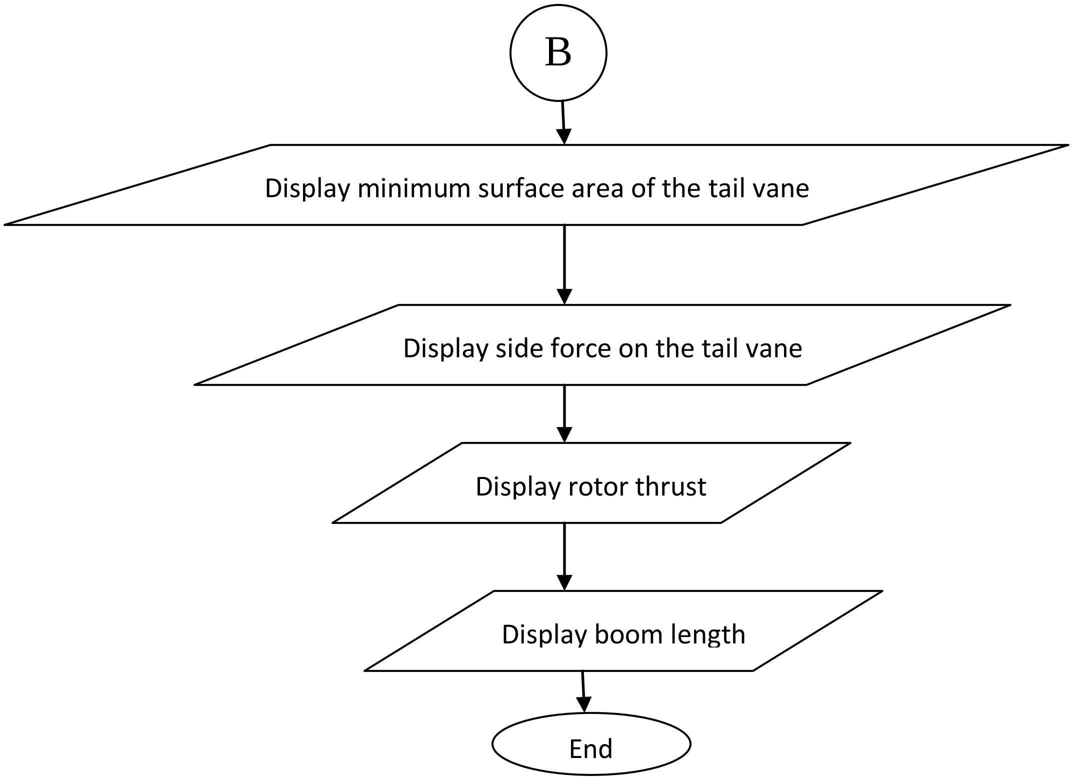
APPENDIX A

A1: FLOW CHART AND JAVA PROGRAMMING CODES FOR THE WIND TURBINE DESIGN




A
A
Display the rotor speed in RPM
Enter the radius at five stations along rotor blades
Enter number of blades
Calculate the chord width at each of the five blade stations
Enter angle of attack
Enter flow angle
Calculate the blade setting angle at each of the five blade stations
Display blade setting angles for each of the five stations
Calculate minimum surface area of the tail vane
Calculate side force on the tail vane
Calculate rotor thrust
B


B
Display minimum surface area of the tail vane
Display side force on the tail vane
Display rotor thrust
Display boom length
End

A2: JAVA CODES

```
/**
 * @(#)WindPower.java
 * @Jesse Mamman
 * @version 1.00 2012/5/23
 */
import java.io.*;
import java.lang.Object.*;
import java.lang.Math.*;
public class WindPower {
public static void main(String[] args) {
java.io.DataInputStream stream = new DataInputStream(System.in);
System.out.println("\n\n\nWIND TURBINE ROTOR DESIGN");
                                                double Um;
                                                double U;
try{
 /*INPUT*/
System.out.println("\nWhat is the mean/average wind velocity of the location in m/s?");
 Um = Double.parseDouble (stream.readLine());
/*PROCESSING*/
                                U = (1.2)* Um;
System.out.format("\nThe rated wind speed of the turbine is "+"%.2f m/s",U);
/*DETERMINATION OF ROTOR SWPET AREA AND ROTOR DIAMETER
*The power extracted from the wind is a fraction of the available power
*/
System.out.println("\n\n\nDETERMINATION OF ROTOR SWPET AREA AND ROTOR
DIAMETER");
```

```
double power;

double swept_area;

double rotor_diameter;                          ;

double Cp = 0.40;

double air_density= 1.225;

double pi = 3.142;

// Where Cp, the Power coefficient (Betz Limit)has its maximum value of 0.593.We assume it to be o.40

/*INPUT*/

System.out.println("\nEnter amount of power to extract from the wind in Watts:");

power = Double.parseDouble (stream.readLine());

/*PROCESSING*/

swept_area = (2.0*power)/(air_density*(Math.pow(U,3.0))*Cp);

rotor_diameter = Math.sqrt((4.0*swept_area)/pi);

/*OUTPUT*/

System.out.format("\nThe rotor swept area is "+"%.2f meters-square",swept_area);

System.out.format("\n\nThe rotor diameter is "+"%.2fm",rotor_diameter);


/*DETERMINATION OF ROTOR SPEED (RPM) AT A GIVEN TIP SPEED RATIO*/

double n_rotor;

double tsr;

double r;

r = (rotor_diameter/2);

// where 'n_rotor' is the rotor speed in rpm, and 'tsr'is the tip speed ratio

System.out.println("\n\n\nDETERMINATION OF ROTOR SPEED (RPM) AT A GIVEN TIP SPEED RATIO");
```

```
/*INPUT*/

System.out.println("\nEnter tip speed ratio:");

tsr = Double.parseDouble (stream.readLine());

/*PROCESSING*/

        n_rotor = (30/pi)*tsr*(U/r); // equation 3.9

/*OUTPUT*/

System.out.format("The rotor speed is "+" %.2frpm",n_rotor);

 /*DESIGN OF BLADE CHORD WIDTH*/

System.out.println("\n\n\nDESIGN OF BLADE CHORD WIDTH AT DIFFERENT SECTIONS");

System.out.println("\nThe chord width would be determined at four sections along the blade lenght/radius." );

/*INPUT*/

 double radius_section1;

 double radius_section2;

 double radius_section3;

 double radius_section4;

 double radius_section5;


System.out.println("\nEnter the radius at each section; section 1 being closest to the hub, section 4 closest to the tip:");

System.out.println("\nThe radius at section 1 in meters is:");

radius_section1 = Double.parseDouble (stream.readLine());

System.out.println("\nThe radius at section 2 in meters is:");

radius_section2 = Double.parseDouble (stream.readLine());

System.out.println("\nThe radius at section 3 in meters is:");

radius_section3 = Double.parseDouble (stream.readLine());

System.out.println("\nThe radius at section 4 in meters is:");
```

```
radius_section4 = Double.parseDouble (stream.readLine());
  System.out.println("\nThe radius at section 5 in meters is:");
radius_section5 = Double.parseDouble (stream.readLine());

/*PROCESSING*/
double chord_width1;
double chord_width2;
double chord_width3;
double chord_width4;
double chord_width5;
double lift_coefficient;
int blade_number;

System.out.println("\nEnter number of blades:");
blade_number = Integer.parseInt (stream.readLine());
//at section 1
chord_width1 = (16*pi*r*(r/radius_section1))/(9*(Math.pow(tsr,2))*blade_number);
//at section 2
chord_width2 = (16*pi*r*(r/radius_section2))/(9*(Math.pow(tsr,2))*blade_number);
//at section 3
chord_width3 = (16*pi*r*(r/radius_section3))/(9*(Math.pow(tsr,2))*blade_number);
//at section 4
chord_width4 = (16*pi*r*(r/radius_section4))/(9*(Math.pow(tsr,2))*blade_number);
//at section 5
```

```
chord_width5 = (16*pi*r*(r/radius_section5))/(9*(Math.pow(tsr,2))*blade_number);

/*OUTPUT*/

System.out.format("\n\nAt secction 1, given a radius of "+"%.2fm, the chord width is %.2fm.", radius_section1,chord_width1);

System.out.format("\n\nAt secction 2, given a radius of "+"%.2fm, the chord width is %.2fm.", radius_section2,chord_width2);

System.out.format("\n\nAt secction 3, given a radius of "+"%.2fm, the chord width is %.2fm.", radius_section3,chord_width3);

System.out.format("\n\nAt secction 4, given a radius of "+"%.2fm, the chord width is %.2fm.", radius_section4,chord_width4);

System.out.format("\n\nAt secction 5, given a radius of "+"%.2fm, the chord width is %.2fm.", radius_section5,chord_width5);

/*DESIGN OF BLADE PROFILE*/

double angle_attack;

double flow_angle;

double setting_angle1;

double setting_angle2;

double setting_angle3;

double setting_angle4;

double setting_angle5;

/*INPUT*/

System.out.println("\n\nEnter angle of attack in degrees:");

angle_attack = Double.parseDouble (stream.readLine());

/*PROCESSING*/

setting_angle1 = (Math.atan((2*r)/(3*radius_section1*tsr)))*57.3 - angle_attack;

setting_angle2 = (Math.atan((2*r)/(3*radius_section2*tsr)))*57.3 - angle_attack;
```

```
setting_angle3 = (Math.atan((2*r)/(3*radius_section3*tsr)))*57.3 - angle_attack;

setting_angle4 = (Math.atan((2*r)/(3*radius_section4*tsr)))*57.3 - angle_attack;

setting_angle5 = (Math.atan((2*r)/(3*radius_section5*tsr)))*57.3 - angle_attack;

//System.out.println("Enter flow angle in degrees;");

//flow_angle = Double.parseDouble (stream.readLine());

/*OUTPUT*/

//System.out.format("The flow angle is " +"%.2f Degrees",flow_angle);

System.out.format("\n\nThe angle of attack is "+"%.2f Degrees",angle_attack);

System.out.format("\n\nTherefore the blade setting angle at station 1 is "+"%.2f Degrees",setting_angle1);

System.out.format("\n\nBlade setting angle at station 2 is "+"%.2f Degrees",setting_angle2);

System.out.format("\n\nBlade setting angle at station 3 is "+"%.2f Degrees",setting_angle3);

System.out.format("\n\nBlade setting angle at station 4 is "+"%.2f Degrees",setting_angle4);

System.out.format("\n\nBlade setting angle at station 5 is "+"%.2f Degrees",setting_angle5);


/*TAIL VANE DESIGN*/

System.out.println("\n\n\nTAIL VANE DESIGN");

double area_vane;

double side_force;

double rotor_thrust;

area_vane = (Math.pow(rotor_diameter,2))/40;

side_force = (area_vane*(Math.pow(U,2)))/16;
```

```
rotor_thrust = (Math.pow(rotor_diameter,2))*(Math.pow(U,2))/24;

System.out.format("\nThe area of vane must be greater than "+"%.2f meters-square",area_vane);

System.out.format("\n\nThe side force on the vane is "+"%.2fkg",side_force);

System.out.format("\n\nThe rotor thrust is "+"%.2fkg",rotor_thrust);

System.out.format("\n\nAs a rule of thumb, the actual boom should be about equal to the length of one blade (half the rotor diameter) i.e about "+"%.2fm",(rotor_diameter/2));

System.out.format("\n\nNOTE:Rotor speed is "+"%.2frpm%n%n",n_rotor);


}catch (Exception e){e.printStackTrace();}


}

}
```

APPENDIX B

OUTPUT OF THE COMPUTER PROGRAM

--------------------Configuration: WIND - JDK version 1.6.0_03 <Default> - <Default>--------------------

WIND TURBINE ROTOR DESIGN

What is the mean/average wind velocity of the location in m/s?

5.42

The rated wind speed of the turbine is 6.50 m/s

DETERMINATION OF ROTOR SWEPT AREA AND ROTOR DIAMETER

Enter amount of power to extract from the wind in Watts:

300

The rotor swept area is 4.45 meters-square

The rotor diameter is 2.38m

DETERMINATION OF ROTOR SPEED (RPM) AT A GIVEN TIP SPEED RATIO

Enter tip speed ratio:

6

The rotor speed is 313.07rpm

DESIGN OF BLADE CHORD WIDTH AT DIFFERENT SECTIONS

The chord width would be determined at four sections along the blade lenght/radius.

Enter the radius at each section; section 1 being closest to the hub, section 4 closest to the tip:

The radius at section 1 in meters is:

0.25

The radius at section 2 in meters is:

0.5

The radius at section 3 in meters is:

0.75

The radius at section 4 in meters is:

1

The radius at section 5 in meters is:

1.25

Enter number of blades:

3

At secction 1, given a radius of 0.25m, the chord width is 0.29m.

At secction 2, given a radius of 0.50m, the chord width is 0.15m.

At secction 3, given a radius of 0.75m, the chord width is 0.10m.

At secction 4, given a radius of 1.00m, the chord width is 0.07m.

At secction 5, given a radius of 1.25m, the chord width is 0.06m.

Enter angle of attack in degrees:

4

The angle of attack is 4.00 Degrees

Therefore the blade setting angle at station 1 is 23.88 Degrees

Blade setting angle at station 2 is 10.82 Degrees

Blade setting angle at station 3 is 6.00 Degrees

Blade setting angle at station 4 is 3.53 Degrees

Blade setting angle at station 5 is 2.04 Degrees

TAIL VANE DESIGN

The area of vane must be greater than 0.14 meters-square

The side force on the vane is 0.37kg

The rotor thrust is 9.99kg

As a rule of thumb, the actual boom should be about equal to the length of one blade (half the rotor diameter) i.e about 1.19m

NOTE:Rotor speed is 313.07rpm

Process completed.

APPENDIX C

AUTO CAD DESIGN DRAWINGS

APPENDIX D

PICTURES OF THE PRODUCTION PROCESSES

Plate 1

Plate 2

Plate 3

Plate 4

Plate 5

Plate 6

Plate 7

Plate 8

Plate 9

Plate 10

Plate 11

Plate 12

Plate 13

Plate 14

Plate 15

Plate 16

Plate 17

Plate 18

Plate 19

Plate 20

Plate 21

Plate 22

Plate 23

25

Plate 24

Plate 25