University of Southern Queensland

Faculty of Engineering and Surveying

DESIGN OF A SMALL WIND TURBINE FOR ELECTRIC POWER GENERATION (1-5kW)

A dissertation submitted by

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Abstract

This dissertation is the documentation of the design and development of a sustainable wind energy conversion system to be employed as a stand-alone electrical energy generator for isolated communities and dwellings.

As our global population increases at an exponential rate and our consumerism grows with it, a sustainable source of energy needs to be developed to meet our power requirements. At this stage wind energy conversion systems (WECS) cannot produce power to the same scale as coal or gas fuelled power stations, but they do however offer the ability to operate as stand-alone power generation systems, reducing the need for long distance power transmission lines.

Stand alone WECS are suitable electricity suppliers for isolated communities, island communities or applications where the cost of grid connection exceeds the installation and maintenance cost of a WECS. Small WECS can be configured to:

- Feed into an existing grid
- Supply charge to a battery bank
- Directly power an appliance

The prototype design incorporates:
- 3 bladed aerofoil rotor
- Adjustable blade pitch
- Self governing speed regulation
- Speed increase gear box
- AC-induction generator – DC conversion circuit.
- Steel tower

The mechanical design was complimented by a functioning prototype of the Hub and rotor demonstrating the effectiveness of the power extraction mechanism. The turbine design was rated as having a power output capacity of 2 kW and is designed to be used in a shunt regulated battery charging circuit.

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CHAPTER 1

PROJECT INTRODUCTION

1.1 Project Outline

This project envisages the design and implementation of a small wind turbine for electric power generation: 1-5 kW. The project encompasses the mechanical design of the wind blades, tower, gearbox, and choice of the proper electricity generator. The ability to provide a feasible and reliable electrical supply shall be emphasized. Connection to electricity networks with the associated proper frequency and voltage requirements and the involved technical modifications is described and discussed. The wind turbine shall be tested under local conditions in Toowoomba and Ipswich.

1.2 Project Introduction:

This project envisions the design and appropriate implementation of a 1-5 kW electricity producing wind turbine. The turbine will ideally be designed for implementation in remote communities to power individual house's electrical needs or to be fed directly into a local energy grid. The aim of the project is to design a wind energy converter comprising of a rotor system, a gearbox and a generator that will successfully produce the specified electrical power. As wind turbines are not new technology the project will be aimed at proving and optimising a system based on existing technology to achieve the desired power output. Considerations are taken in designing the turbine with an effective post life recycling scheme in mind so that there will be minimum wastage of resources once the turbine is made redundant.

Ultimately the aim of this project is to make use of a natural resource to supply mankind's energy requirements in a sustainable manner. If a wind turbine can be designed and constructed so that it can produce more power over its life time than it takes to be produced and maintained over its useful life, then it is a sustainable answer to our global energy requirements. It is obvious now that we are facing an oncoming global energy shortage. Fossil fuel prices are rising in conjunction with the decrease in their stockpiles and it is vital that alternative methods of energy production be investigated and introduced on a global scale to maintain our standard of life. Wind energy has the potential to meet our requirements and several nations have already begun effectively producing and harvesting this form of green energy.

1.3 Project Objectives

As previously mentioned, the electricity producing wind turbine is an already existing technology and this project is focused on redesigning and adapting mechanical and electrical engineering principles to achieve the specified energy output. Realistically the simplest method to achieve the goal in this project would be to scale down an existing turbine until its power output fell into the category of 1-5 kW. However it is vital that a good understanding of the concepts and principles behind wind turbine design is developed so that existing methods of wind energy production can be improved and made more efficient. There are a wide variety of wind energy converters already available on the market and many of these will be investigated throughout the course of the report.

The objectives of the project are:

- To provide thorough background information on wind energy and wind turbines
- To employ mechanical design principles gained over the duration of a BENG Mechanical degree.
- To design a suitable wind turbine to meet the specifications set out in the project outline.
- To develop a sustainable, environmentally friendly alternative to fossil fuel consuming energy production.

The main objective of the design project is to develop a mechanical system that is capable of providing driving force to a generator using only the energy contained in wind. The generator in the system is the mechanical-electrical converter in the wind turbine and the gearbox and rotor blades need to be designed to supply the generator with an input that will yield the desired output power. This being said, a suitable generator first needs to be selected and tested to determine the input speed required to produce 5 kW before any other design goes ahead. Once this has been determined a rotor system and gearbox can be designed to produce the required revolution speed and torque to supply mechanical power to the generator. In selecting a generator consideration needs to be made as to what type of current is being produced and where it will flow to, if it will be stored or if it will be directly applied in an electrical device.

1.4 Consequential effects of project outcomes

In our current global situation, both environmental and economic, it is evident that drastic changes need to be made to the way we treat our planet and each other. Rather than dwell on the problems of the past and present, this research project aims at creating an understanding of a proven environmentally friendly alternative to fossil fuel based power production. Although as yet a wind turbine on its own cannot provide the same scale of power as a steam turbine in a coal fired power plant, it is a technology that will long outlast fossil fuel technology. Aside from its initial construction and ongoing maintenance costs, the wind turbine provides electrical power without any extra input. This project aims at designing a small scale 1-5kW turbine for personal use in isolated areas where grid connection is not available as yet. By supplying wind powered electricity generators to these areas, it alleviates the need for the construction of electrical networking (powerlines) to the specified areas saving both money and resources. In a country like Australia where the population to landmass ratio is relatively low and the majority of the population residing in coastal regions, wind energy converters have been put aside due to the cheap coal and oil prices at the time. Coal fired power stations have been the method of preference due to their high power output capabilities. However coal resources are only finite and therefore it is time to start looking for other viable energy sources such as wind power. A turbine producing 5kW of electrical energy is sufficient to power a refrigerator, a television and a household’s lighting quite comfortably. This being said, a feasible wind turbine design would not only be a demonstration and application of 4 years of study but could potentially spark global change leading to a better future for our planet.

A potential consequence of the success of this project would ultimately be the refinement of the design and future production and commercialisation of the turbine. For the purpose of the project, the design of the turbine is for the demonstration of applied technical knowledge gained over the duration of a mechanical engineering degree. However, particularly in this project there is a great opportunity to continue research and development beyond the timelines and aims mentioned in the project specification.

One of the issues on a social level with wind turbines is the aesthetic appeal of the structure. If every house in a community had a wind turbine in its back yard, understandably there would be an issue with noise and aesthetic appeal. However if the turbines were grouped, as in a wind farm either on land or out at sea the issue could be successfully avoided, however a power distribution network would need to be created. A power distribution network would alleviate the issue of storing the electricity once it has been produced, rather than subsequently having one battery in every household which would see costs increase dramatically, not to mention the environmental effects incurred by the eventual disposal of the batteries.

1.5 Methodology

The process of designing a wind turbine involves the conceptual implementation of a number of electrical and mechanical subsystems to create a machine capable of converting the energy contained in wind to useful electrical energy. This process is constrained by various factors, the most notable being the economic viability of the design. If the machine can be designed and is able to produce energy at a cost less than its opposition of fossil fuels and nuclear energy, then the project is deemed economically viable. However in today's global situation there is also the challenge of environmental and ethical viability to contend with. Renewable energy projects should be prioritised and subsidised by the appropriate government agencies due to the benefits they offer to society. However, along with the majority of design projects, it is a fundamental design goal to keep the energy cost at a lower level than of existing energy producing systems.

Design procedure outline

There are a variety of different approaches that can be taken in wind turbine design and accordingly there are also a number of issues that need to be taken into account. The design procedure outlined in "(*McGowan 2003)"* (p248), sets guidelines for the design of a wind energy converter and has been taken into consideration for application in this project.

Proposed Design Procedure:

1. *Determine application*
   The first step in the design process is determining for what type of application the turbine is being designed for. A large 2 MW turbine will follow different design and implementation procedures as opposed to a small scale 1-5 kW machine. There is also a difference in blade configuration for water pumping wind mills when compared to 3 bladed electricity producing turbines.

2. *Review previous experience*
   This section of the process deals with the review and investigation of the previous design of similar wind turbines. Reviewing previous work helps with troubleshooting and allows the designer to narrow down the available options and gain some direction as to conducting the design process.

3. *Select topology*

   As there are a wide variety of different wind turbine designs, mainly varying with the rotor type and orientation, it is important to identify the most suitable option for the proposed application. The options include:

   (As listed, *Wind Energy Explained : Theory, Design and Application)*

   - Rotor axis orientation: horizontal / vertical
   - Power control: stall, variable pitch, controllable aerodynamic surfaces and yaw control
   - Rotor position: upwind or downwind
   - Yaw control: driven yaw, free yaw, fixed yaw
   - Rotor speed: constant or variable
   - Design tip speed ratio and solidity
   - Hub type
   - Number of blades

4. *Preliminary loads estimate:*

   In the early stages of design it is important to have an approximate idea of what sort of loading the wind turbine will be subject to. This helps in narrowing down the design of individual components and employed techniques such as scaling and 'rule of thumb'. The estimates made in the preliminary stages of design are adjusted throughout the project duration to conform to the required design specifications. This will be done with the use of FEA programs such as ANSYS and COSMOS.

5. *Develop tentative design*

   Once an overall design layout has been determined, the preliminary turbine design can be developed. The design can be broken up into a number of smaller sub systems such as:

   - Electrical Generator
   - Gearing system
   - Drive train
   - Hub
   - Yaw system
   - Rotors
   - Nacelle and tower

Modelling will be conducted using Pro Engineer and SOLID Works.

6. *Predict performance*
   It is important to develop a power curve of the turbine which depicts the performance of the turbine at different speeds. This primarily will relate to the rotor design but also incorporates the type of gear box and generator and the associated losses in each.

7. *Evaluate design*
   Like all engineering designs the structural and mechanical integrity of the proposed wind turbine needs to be thoroughly evaluated to ensure the turbine can operate safely and effectively under various types of loading. As the turbine is exposed to the forces of nature it needs to be designed with irregular weather patterns taken into consideration. The turbine's components will constantly be subject to fatigue loading and an increase in wind speed can cause shock loading to occur which needs to be taken into consideration in the design stages. The turbine will also be subject to static, steady, cyclic, impulsive, stochastic transient and resonance induced loads and will need to be able to withstand these loads under all credible conditions, both normal and extreme. The main loads of concern are those occurring around the rotor and hub. This is a primary area of focus in the design of the proposed wind turbine.

8. *Estimate costs and cost of energy*
   Before the wind turbine reaches prototyping or production stages a careful cost analysis needs to be conducted to determine if the design is economically viable. It is necessary to effectively quote the construction cost of the turbine in both prototyping and production stages and also to then determine a productivity cost, the cost of producing energy. In the prototyping stages relatively high costs can be expected due to the work involved with designing each individual component the associated fabrication and machining costs. In the production stages the individual component cost will drop quite significantly in relation to quantity and the possible off the shelf availability of certain components.

9. *Refine design*
   Once preliminary design, design evaluation and cost estimation has been completed the refinement stage is reached. Changes are made in accordance to the findings of the mentioned evaluation processes. Material selection, component strength and component appearance may be changed to conform with costing, structural and mechanical integrity and also aesthetic appeal. Once the changes have been employed the redesigned turbine will then be subject to re-evaluation to ensure the design still conforms to all safety standards.

10. *Build prototype* ***(If time permits)***
    Once the design process has been completed a prototype should be designed to verify any assumptions made, test concepts and insure that the turbine can be fabricated, installed and operated as expected. Due to the time limit of the project and the nature of the work associated in completing a prototype, this stage has only been partially completed.

11. *Test prototype*
    After installation of the prototype the turbine is subject to a variety of field tests to determine the physical capabilities of the design and to determine the wind turbine's rated power output. Once again due to the time restraints of the project the different subsystems will be tested to determine their individual performance levels.

12. *Design production machine*
    The final stage of the process is to redesign the prototype for a production scenario. This would involve sourcing readily available off the shelf parts and redesigning components so they can be easily mass produced. This stage of the design process does not directly apply to the project but will be pursued in future depending upon the success of the project.

1.6 Initial blade design methodology

The design of the turbines rotors is perhaps the most mathematically involving element of the entire turbine design. The rotors use aerodynamic lift to provide a turning moment and consequently an input torque to the gearbox. The sizing and configuration of the blades is based upon the relative power coefficient of the turbine and the energy in the stream tube. The energy in the stream tube depends on the swept area of the blades and the wind speed. For the purpose of this project, mathematical modelling and analysis is utilised to determine the rotor sizing, however some assumptions have to be made in order to obtain a realistic geometry. The design of the blades used in this project is based on blade element theory and the Betz equation and will investigate the blade shape for ideal rotors with and without wake rotation.

For experimental purposes a set of scaled blades will be created for testing and employment in a small wind turbine to be constructed during the duration of the project, time permitting. The blades will be based on the ideal blade shape for a rotor without wake rotation. The blades will be created using a fibreglass mould which will then be filled with two part expanding foam. The cured foam will take up the shape of the blade and once cured will be glassed to give increased strength and rigidity. Due to the nature of the blade crafting technique it will be very difficult to achieve symmetry in all of the blades and this will ultimately attribute to some dynamic instability. Post shaping blade balancing techniques are employed to ensure that dynamic stability and safety of the rotor.

Blade geometry

The geometry and shape of the wind turbine rotor depends on the size of the turbine and its rated energy output. Typical wind turbines used in energy production such as those on wind farms tend to have rotor diameters between 30 and 80 metres. These turbines include automatic rotor pitching mechanisms which allow the turbine to run safely even in extreme weather conditions and turn out of the wind if running conditions threaten the structural integrity of the turbine. These turbines typically produce around 2 MW of electrical energy. The turbine being designed in this project aims at achieving a power output of 1-5 kW. The rotor diameter for this type of turbine will be around one to two meters based on the relationship between the power output of the turbine and the swept area of the rotor. This value however does also depend upon the efficiency of the gearbox and the type of induction generator used.

Assuming no wake and drag, the maximum achievable power coefficient of a wind turbine was determined to occur with an axial induction factor of 1/3. Under the same assumptions, an ideal blade shape can be determined by using the blade element and momentum equations. This blade shape would approximate a design that would provide maximum power at the design tip speed ratio of a real wind turbine.

Assumptions made for ideal blade design with no wake rotation

- No wake rotation : $a' = 0$
- No drag : $C_d = 0$
- No losses from finite number of blades
- For the Betz optimum rotor, $a = 1/3$ in each annular stream tube

The blade rotor cross section is in the shape of an aerofoil and uses aerodynamic lift to induce rotation in the drive shaft. The forces on the blades of a wind turbine can be expressed as a function of lift and drag coefficients and angle of attack. In analysing the cross sections of a turbine blade it must be noted that drag and lift act parallel and perpendicular, respectively, to the effective or relative wind.

Table 1.1 contains design guidelines for an ideal blade without wake rotation. The initial turbine blade will be designed using these figures as reference.

Twist and chord distribution for a Betz optimum blade

r/R	**Chord, m**	**Twist angle** (deg.)	**Angle of Rel. Wind (deg.)**	**Section pitch** (deg.)
0.1	1.375	38.2	43.6	36.6
0.2	0.858	20	25.5	18.5
0.3	0.604	12.2	17.6	10.6
0.4	0.462	8	13.4	6.4
0.5	0.373	5.3	10.8	3.8
0.6	0.313	3.6	9	2
0.7	0.269	2.3	7.7	0.7
0.8	0.236	1.3	6.8	-0.2
0.9	0.21	0.6	6	-1
1	0.189	0	5.4	-1.6

Table 1.1 Twist and chord distribution for a Betz optimum blade (McGowan, Rodgers, 2003)

The data contained in Table 1.1 are used as guidelines during the preliminary stages of the blade design. The relationship between twist angle and r/R ratio will be employed whilst the corresponding chord lengths will be adjusted to suit the length of the blade where seen fit (R is the total length of the blade. r is the relative length from the blade root). As this is only for the initial stages of design, a simple blade shape will be achieved and then tested to determine where it can be improved and what changes need to be made.

Initial design and shaping of blades

Introduction:

The initial design of the turbine rotors was based upon the Betz equation and the design guidelines for a rotor without any wake rotation. This data was sourced from the text *Wind Energy Explained* and was used to create a computer model for testing and reference during shaping. The initial aim was to create the blade shape using a light weight foam, also commonly used for making surf boards, however due to problems encountered with the foam's structural properties a different material was used.

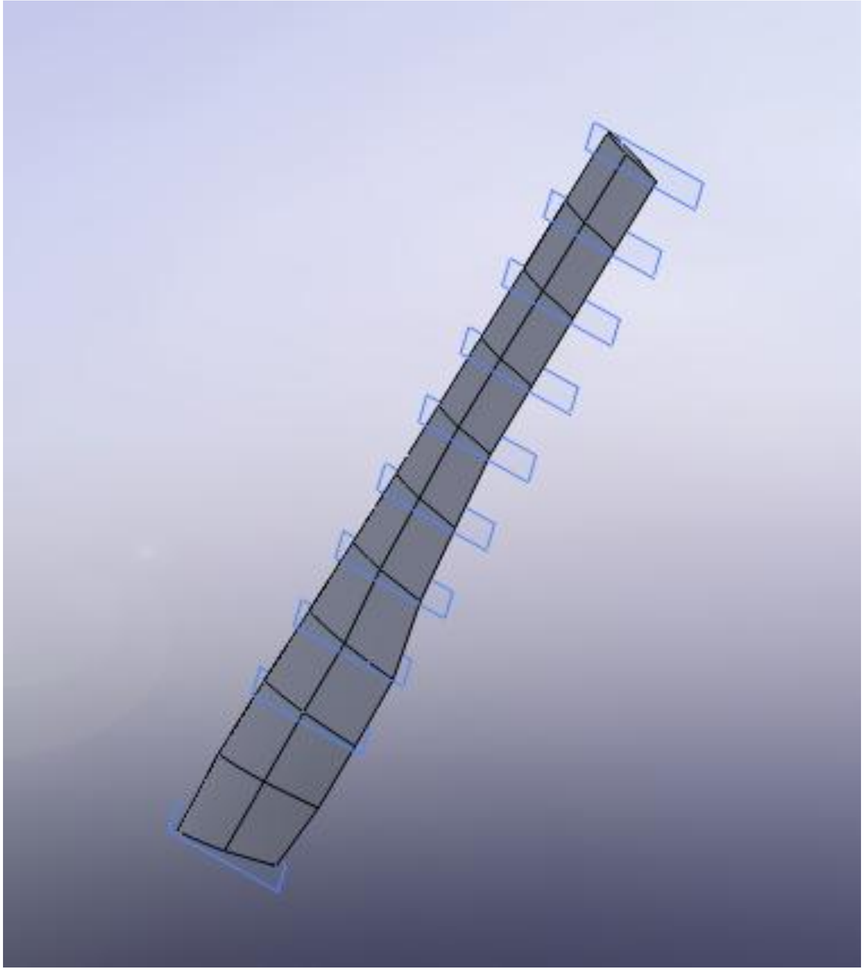


Figure 1.1: Blade profile

The blade shown in Figure 1.1 is a modified version of the optimum design data specified in table1.1. This was done to accommodate for the difficulty in shaping the blade by hand from either foam or wood. The chord lengths varying with distance from the blade root were increased to make shaping easier and to increase the strength of the blade. Note that this is only an initial blade design for testing and modelling purposes and further development was conducted for the final design. The blade incorporates an overall blade twist of 38.2° from root to tip. The majority of the blade twist, around 26 degrees, occurs in the first 400mm of blade from the root and then turns into a gradual twist over the remaining 600mm of the blade.

Initial shaping of the blades

The first stages of blade shaping took place during the mid semester study break between the 4th and 11th of April 2009. Shaping took place in a wood working workshop in Millaa Millaa, Far North Queensland.

At first the aim was to shape the blades out of a large piece of high density foam due to the ease of which the material can be shaped and formed. Initially an aerosol propelled foam in a can type substance was used. The foam was injected into a mould, 1200 x 200 x 100 in dimension, to create a blank for shaping. However once fully cured the foam did not poses the right structural and mechanical properties for further shaping. The foam was spongy and did not sand very easily instead crumbling and breaking off in chunks and the decision was made to discontinue with the material. Due to time constraints the decision was made to continue using timber as a material for creating an initial blade shape. The blade profile was then shaped using Caribbean pine as a base material. The physical blade model was formed predominantly to act as a blank for the future moulding of blades as the blades need to be identical and balanced for the turbine to operate safely and efficiently. Unless CNC profile cutting equipment is available and a uniform lightweight material is used, the precision and accuracy of the blade dimensions is compromised.

During the first shaping process a total of three identical timber blades were created all slightly varying in dimension. The blade twist in all three was maintained at 38 degrees of their lengths conforming to the ideal blade guidelines for a blade with no wake rotation. The three blades will be used for modelling of the rotor assembly and for testing of the aerofoils drag and lift forces.

1.7 Risk assessment

The design and construction of a wind turbine incorporates various risks and hazards that need to be brought to the attention to anyone who is involved in the processing of parts, assembly and operation of the machine. The majority of risks and hazards are common in industry and there is professional training available to prepare individuals for safe operation within a hazardous environment.

The majority of hazards associated with the project are in the construction stage and are identified in the following table:

Table 1.2

Hazard / Risk	**Description / significance/ likelihood/ exposure Consequences/ counter measures**
Fumes	During the fabrication of fibre glass blades/ carbon fibre blades there is a hazard associated with the fumes produced by combining the resin with the catalyst. The fumes can cause nausea and extreme headaches and if exposed to them for extended periods can cause brain damage. If proper breathing masks and eye protection are used during the handling of the chemicals the risk is minimized. Protective clothing and gloves should also be applied to avoid contact with skin.
Machining Fabrication	The machining and fabrication of parts is a hazardous procedure mainly due to the exposure to moving parts and cutting equipment. Interference with the equipment can result in serious injury; abrasions, cuts, bruising. To avoid contact and minimize the risk of these occurring, no loose fitting clothing should be worn during operation of the equipment. Steel toed boots, ear muffs and appropriate eye protection should be worn during the operation of equipment. If possible the work should be carried out under the supervision of professionals.
Electrical	As the turbine is used to produce electrical energy there is an apparent electrical hazard. Interference with electricity can cause significant damage to a person or even death. The amount of energy being produced by the turbine poses a significant risk to anyone who comes into contact with it. This being said only professional electrical technicians should conduct any work on the generator, the transmission and the storage unit. All wiring and connections must be effectively insulated and tested on a periodic basis to avoid short circuiting which could cause damage to the electrical network.
Construction	The construction of the turbine will involve the use of a crane lifting the nacelle and rotor in position some 6-10m above the ground. Objects falling from such heights can cause significant damage to anything they come into contact with. Hard hats and steel toed boots should be worn during the assembly and erection of the turbine.
Operational	Once in operation the rotors of the turbine are in constant motion. There is a slight contact risk for personnel conducting maintenance on the turbine. The rotors must be stalled before any maintenance is conducted on the turbine to avoid contact. Contact can result in cuts, bruises, breaking of limbs and may cause a fall from a height that could be fatal.

1.8 Resource Requirements

Design

As the project deals mainly with the design and implementation of a wind turbine and actual construction is only a secondary project objective that will only be conducted if time permits, the majority of resources will be in the form of software and literature.

The design of the wind turbine will be based on existing technology which will be investigated in the literature review. This will provide the background knowledge and aid in optimising the technical design parameters of the project; materials, geometry, structure, electrical generator selection etc... The University Library will be the primary source of information aiding the design procedure along with private publications from industry.

The geometric and physical design and modelling will require a CAD package such as PRO Engineer or SOLID Works. The software is available for use at the university along with ANSYS for finite element analysis of the design and testing of individual components.

Construction, fabrication

If construction of the turbine is to take place a wide variety of machinery, tooling and additional tooling is required. These are listed below:

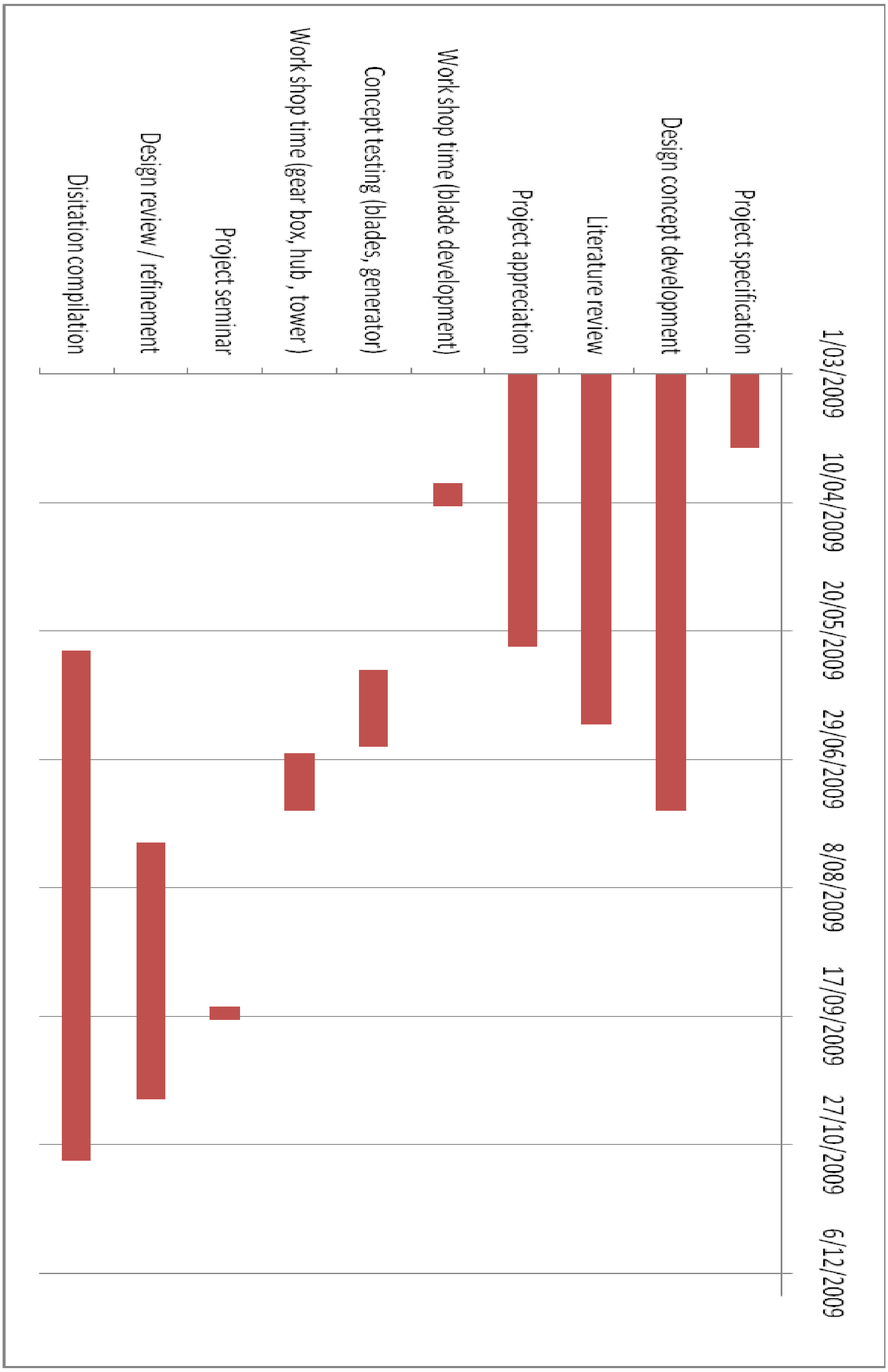
- Milling centres (tooling)
- Metal lathe (tooling)
- Welding equipment (TIG, MIG)
- Workshop equipment (general tooling)
- Fibre glassing equipment
- Testing facilities (Tensile, impact, fatigue, wind tunnel)

Material

- The blades will be optimally constructed using either carbon fibre or fibre glass coated timber.
- The mechanical parts within the Hub and gear box will be machined from high tensile steel (4140, 4340) to ensure wear resistance.
- The base and housing of the nacelle will be machined and fabricated from aluminium stock.
- The tower will optimally be fabricated from appropriately sized steel tubing.

1.9 Project timeline

The project time line is a time management too that acts as a guide to ensure tasks are planned and completed on schedule. Figure 1.2



CHAPTER 2

REVIEW OF LITERATURE

Review of available literature

The content of this chapter is an overview of the available literature and information on wind turbine design that will ultimately be used as a foundation throughout the design project.

The chapter aims at:

- Providing an overview of the history and development of wind turbines
- Identifying the need for wind turbines
- Identifying the most effective type of wind turbine for the proposed application

This project aims to include and further develop the methodologies previously employed in wind turbine design to produce a 1-5kW turbine for electrical energy production in isolated areas. A wind turbine utilises naturally occurring wind flow to turn wind power into electrical energy via a mechanical medium.

2.1 Brief history of wind mills

Wind energy converters are not a new technology and have been utilised for mainly mechanical applications such as grain crushing since 644 A.D. (first reliable information from historical sources; as cited ‘Hau, 2000’) Windmills were first utilised in the ancient area of Seistan (Persia, Afghanistan) and primitive machines are still being used today in the region for grain processing. The first wind mills were vertical axis turbines which used sails around a pivot to create mechanical power. Centuries after the Persian wind mill technology was documented news of the Chinese utilising wind mills to drain their rice paddies of water reached Europe. Whether or not the Chinese had already been utilising the windmill or a run-off of a wind mill before the Persians can no longer be determined with certainty today.(‘Hau, 2000’) Interestingly, the Chinese wind mill was also a vertical axis bamboo structure with sails, similar to the Persian system.

The classical or horizontal axis wind turbine can be confidently attributed to European designers independent of the oriental vertical axis systems. The first documented historical evidence of horizontal axis wind mills dates back to 1180 which tells of a wind mill called a *post* or *trestle mill* present in the Dutch Normandy. From there on the post mill quickly spread throughout Europe and was then further developed into the tower mill two centuries later. In the 16th century the Dutch wind mill was developed in Holland which composed of a mill house with a rotating tower cap and rotor blades. This design is still in practical use today throughout the Netherlands and other European countries for traditional milling processes.

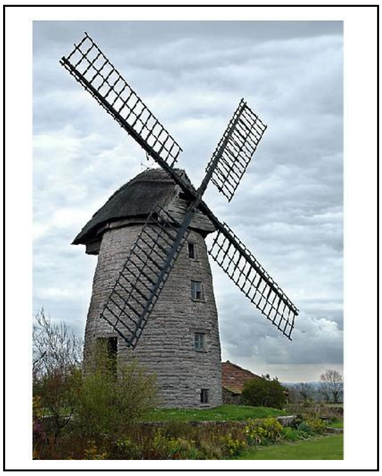


Figure 2.1 Dutch Tower mill

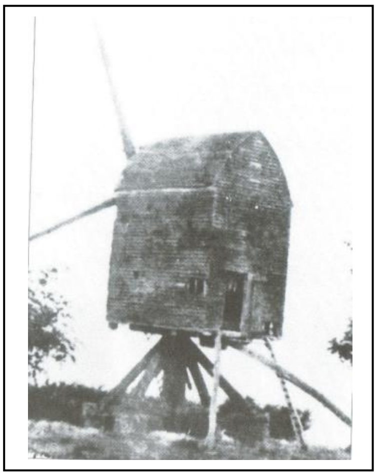


Figure 2.2 Pillar Mill

2.2 The American wind turbine (Halladay design)

When windmill technology was reaching its peak in Europe in the Early 19th century, windmill design and construction had also spread to what we now refer to as the United States of America, particularly on the British and Dutch inhabited East coast. In the mid west of America there was a need for the extraction of artesian water to provide the settlers with a source to sustain their crops and livestock. The first suitable solution to the water extraction problem came in 1850 when a mechanic from Connecticut called Daniel Halladay invented a self regulating wind turbine that was safe from destruction even in violent wind storms. Halladay developed a blade system that was not directly connected to the shaft but suspended on a ring collar which allowed for the free movement of the blades and self adjustment to the pitch angle of the blades to operate safely in the prevailing wind conditions. The movement of the ring was triggered by centrifugal forces and the pitch angle of the blades increased

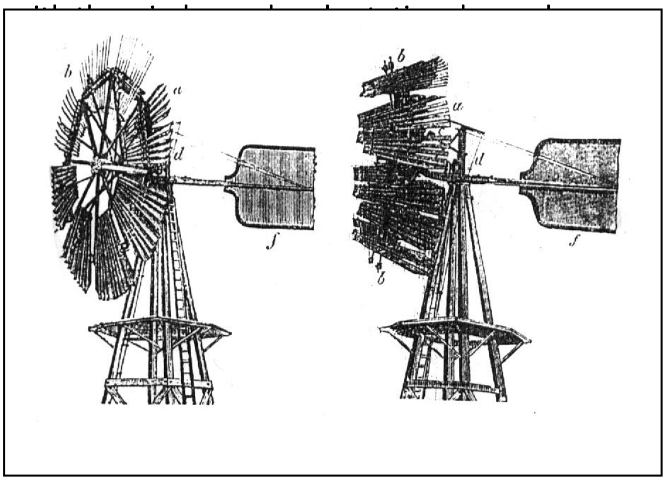


Figure 2.3 Halladay design wind mill

2.3 Initial stages of electrical power production from wind

In 1882 the world's first power plant was built in New York and produced around 500kW of electrical power for utilisation in the cities developing electrical distribution network. In 1891 three-phase current was introduced and power plant technology developed rapidly and yielded a progressively increasing output capacity. By the Early twenties most large cities in industrialised countries had been supplied with electricity. Supplying rural regions with electricity however proved to be a very slow process due to the large distances between the power plants and receptive areas. Whilst waiting for the arrival of electricity to the mid western region, farmers of the area began to make attempts at driving electrical generators with their windmills which were actually designed for water pumping.

The first systematic development of a wind mill for purely electricity generation took place in Denmark by the Dane Poul La Cour. La Cour built an experimental wind turbine driving a dynamo in 1891 under the encouragement of the Danish government in the hope of supplying electricity to the rural regions of Denmark. At the same time La Cour tackled the issue of storing the electricity produced as he used the direct current produced for electrolysis and stored the hydrogen gas produced during the process. La Cour's wind turbines were the beginning of a new era of electricity production and his success was highlighted when the Lykkegard Company started to industrially evaluate his developments. Lykkegard began the production of electricity generating wind turbines modelled after the developments made by La Cour at his testing station at Askov. The rising fuel prices encountered during World War 1 brought about an acceleration in the production of the wind turbines and by 1918 about 120 electricity producing wind turbines were in operation around Europe.

The La Cour Lykkegard turbines were produced in a range of sizes with power production ranging from 10-35 kW . The design incorporated fan blades with shutters which made it possible to remain below a certain critical rotational speed limit and operate at a safe level and yawing was managed by two fan tails. The electrical generator was positioned at the base of the tower and was connected to the rotor shaft by a vertical drive shaft and intermediate gearbox.

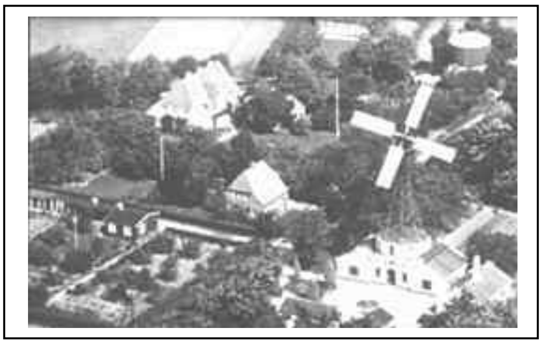


Figure 2.4 La Cour Lykkegard Turbine positioned on building.

The La Cour Lykkegard electricity producing wind turbine achieved an overall efficiency of around 22% and at a highly productive site the annual energy yield amounted to around 50 000 kWh.

2.4 The need for development of renewable energy sources

A study on the environmental impacts of wind energy projects*, Environmental Impacts of Wind-Energy Projects (2007, National research council(US)),* highlights some important positive factors that support the development of wind energy farms. Wind turbines are a viable medium of energy production in that they can produce our energy requirements in place of other methods and do not have the same harmful effects on the environment. Wind turbines do not pollute our air or water with polluted or toxic bi-products of energy production. Directly, their operation only affects the wind speed directly behind the rotor blades. Other organisations have however drawn attention to some adverse environmental affects. These include the visual effect they have on humans, the interference on the ecosystem; birds and bats – rotor blades, and the increase in transport infrastructure and power lines to the wind farm site.

Renewable Electricity and the Grid : The Challenge of Variability*(Godfrey, 2007)* states that, *"It is shown that modest amounts of input from sources such as wind pose no operational difficulties because they do not add significantly to the uncertainties in the prediction of the supply-demand balance."* It also predicts that the integration of wind energy into the grid on a global scale would be around £2 per MWh with 10% wind energy, rising to £3 for 20% wind energy. Weighing up the benefits of wind energy against the incurred cost, it is evident that wind energy would be not only a sustainable alternative but also economically viable.

Australia is one of the world's highest per-capita consumers of fossil fuels. This primarily can be attributed to the vast distances between our major centres and community hubs. Along with this Australia has been identified as the developed country most vulnerable to climate change and its adverse effects on our environment and ecosystem. *Energy Revolution- A sustainable Australia energy outlook (Teske, Vincent(2008),* an article published by Greenpeace International draws attention to the current crossroads faced by humanity in terms of our changing climate. Since the industrial revolution our planet has warmed by 0.74° C primarily due to the burning of carbon-intensive fossil fuels. The challenge faced today is the avoidance of "runaway" climatic change. According to climate experts, if a global increase of 2° is reached it would trigger the release of even more emissions inevitably taking global warming out of our control.

Figure 2.5 is a representation of the world's naturally occurring energy resources. All natural energy sources combined provide 3078 times the current global energy needs.

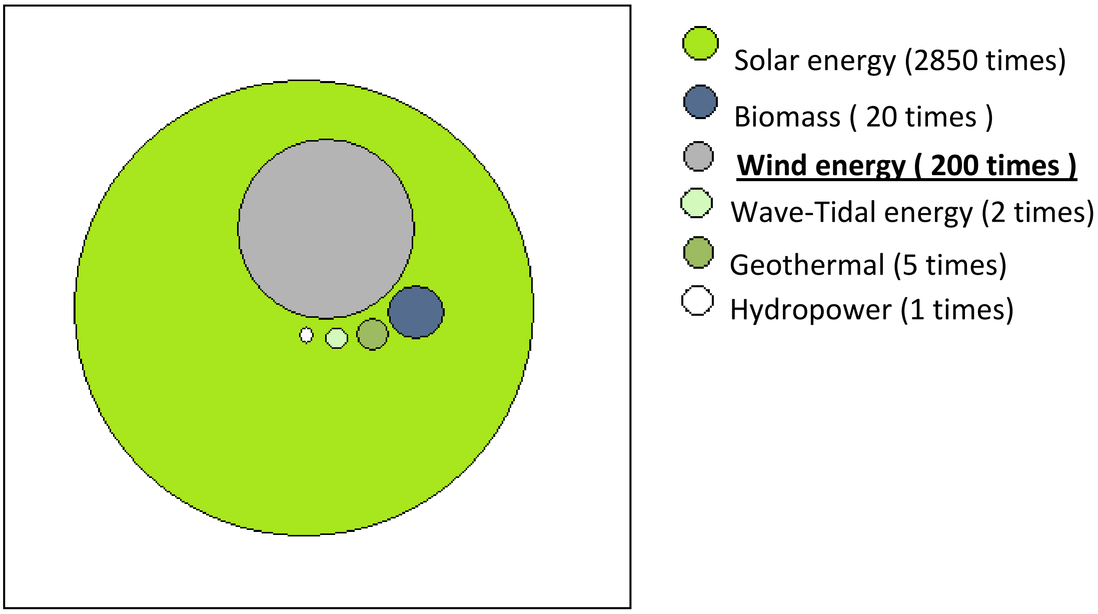


Figure 2.5 Naturally occurring Energy resources of the world (Source : Dr. Joachim Nitsch (Greenpeace))

Taking Figure 2.5 into account, it is a wonder that we are still burning fossil fuels at all. With the current available technology we can access 5.9 times the global demand of energy, all from natural sources. Wind energy is the 2nd largest available form of accessible renewable energy and with current technology can provide half the world's energy requirements.

2.5 Basic concepts

Wind turbines come in a variety of different designs with varying outputs and efficiencies but all convert the kinetic energy contained in an airstream into mechanical work. The most common type of wind turbine is the Horizontal axis wind turbine with blade numbers generally ranging from one to three. (Hau(2000) ; Gipe(2004) and McGowan & Rogers(2003) all state that the three bladed horizontal axis wind turbine is the most suitable to standard wind conditions and is also the most aesthetically pleasing of the wind energy converters.

There are also a wide variety of vertical axis wind turbines being utilised for the purpose of electricity production however none can achieve as high a power coefficient as the horizontal designs. Vertical axis wind turbines were initially designed to be used as purely drag type rotors however later on engineers redesigned the systems to also incorporate aerodynamic lift as a source of rotation. The most common type of vertical axis wind turbine is the Darrieus rotor which can be best described as a turbine resembling the “spinning rope” principle. The specific advantages associated with the vertical axis wind turbine are generally related to the simplicity of the design. The gearbox and generator can be placed at ground level which also prevents the need for a yawing system to be incorporated in the design. However the advantages of the vertical axis turbine are also accompanied by some major disadvantages such as the low tip-speed ratio produced, the inability to self-start and also the inability to control the power output by self pitching of the blades.

Another variation of the Darrieus rotor is the H-rotor which utilises straight blades connected to the vertical axis by struts as opposed to curved blades. Yet another design and perhaps the most basic is the Savonius rotor which uses 2 or more wind cup like blades. The Savonius rotor was most commonly used for mechanical applications such as to pump water or as a ventilation mechanism for train carriages. As this type of rotor does not utilise any type of aerodynamic lift, the maximum achievable power coefficient is a value of 0.25. In general due to their simplicity there are a large variety of different vertical axis rotors but due to their low power coefficients the economy of this type of mechanism is questionable. (McGowen & Rogers (2003). At present vertical axis rotor concepts are generally not competitive with horizontal axis wind turbines.

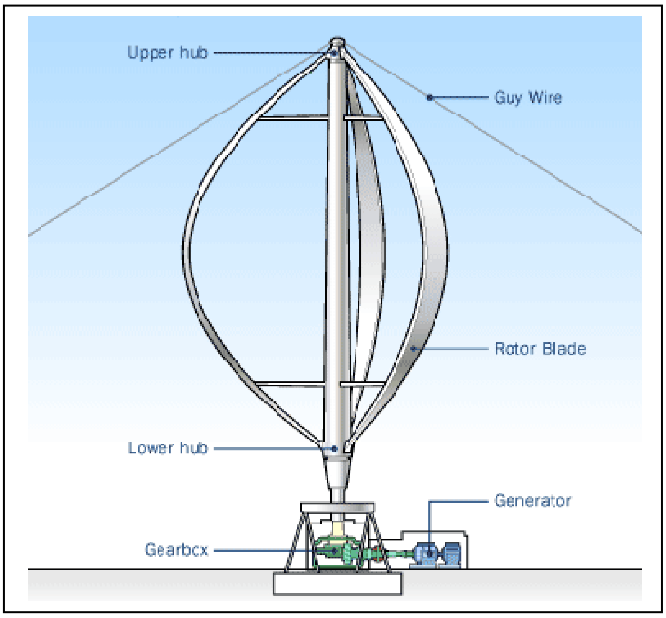


Figure 2.6 Darrieus rotor (courtesy *Photobucket Inc 2009*)

The most effective and common type of wind turbine found today is the horizontal axis wind turbine which can be most easily identified by its propeller like rotor design.(Hau(2000) ; McGowan & Roberts(2003) ; Gipe(2004) ; Heier(1998)) This concept developed from the European wind mill now dominates the wind energy industry in terms of design, efficiency and achievable power factors. The main characteristics which lead to the superiority in design over their vertical axis counterparts are:

- The ability to control the rotor speed and power output of the turbine by self pitching the blades around their longitudinal axis which ensures their safe operation and also survival in high winds and extreme weather conditions.
- The aerodynamic design of the rotor blades play a major role in achieving a higher power factor and based on this aspect alone can achieve twice the efficiency of most vertical axis turbines at similar wind speeds.
- The turbine incorporates a yawing system in its design which allows it to judge and adapt to the wind direction to ensure maximum energy absorption from the wind.

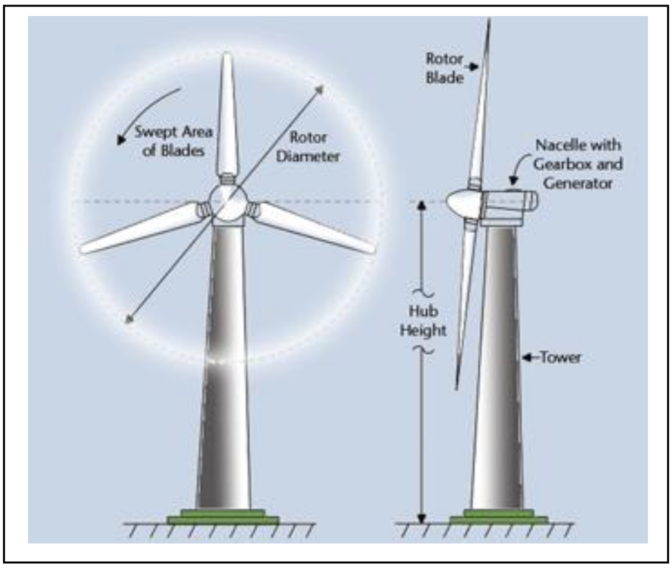


Figure 2.7: 3 bladed wind turbine. (courtesy *Photobucket Inc2009*)

The three bladed vertical axis wind turbine is the most common type of energy producing wind turbine in use. Vertical axis wind turbines however need only one slender blade to capture the energy in the wind (Gipe,2004). To effectively sweep the rotor disk, single bladed turbines need to rotate at a higher velocity than their 2 and 3 bladed counterparts. This reduces the gearing ratio required for transmission and subsequently the mass and cost of the gearbox. Proponents argue that since one blade costs less than 2 or three, single bladed rotors will deliver optimal engineering economy.

Cost effectiveness however is not the only factor to consider. Two bladed turbines are often used for reasons of static balance (Gipe,2004). Three bladed turbines are preffered over single or two bladed turbines as they give greater dynamic stability. Rotors using three blades are also more efficient than single or two bladed turbines due to the aerodynamic losses at the tip of the blades (Gipe, 2004 ; Hau, 2000). Below is a comparison of the overall efficiencies of differnet types of turbine designs. At too high a tip speed ratio the operation of the 2 bladed turbine and Darrieus rotor becomes uncontrolable and dangerous. It can be seen that the three bladed wind turbine gives the highest efficiency at controllable wind speeds.

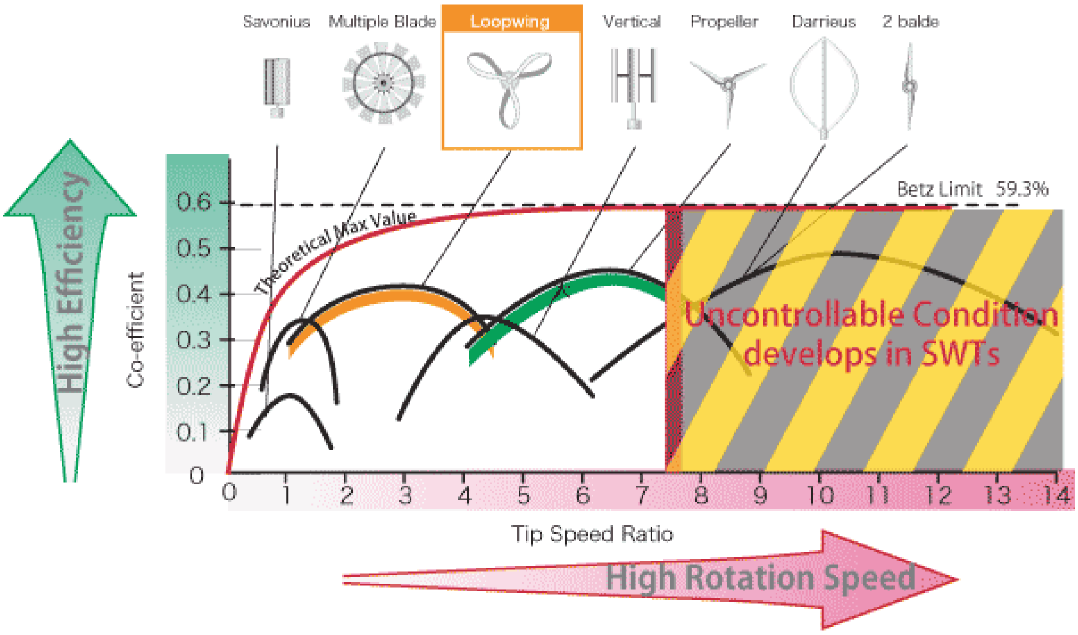


Figure 2.8 Comparison of various wind turbines maximum efficiencies (source : Loop wing)

It is evident that for achieving maximum attainable efficiency, the three bladed rotor system is the most effective option. Taking this into account, the design of the 1-5 kW wind turbine will be based upon the technology used to develop the three bladed system. Preliminary design will incorporate a rotor system comprising of three aerofoil shaped rotors driving a suitable electric generator using a gearing system to effectively generate the required torque and rotational speed.

CHAPTER 3

WIND BEHAVIOUR, CHARACTERISTICS AND POWER

3.1 Introduction

Wind is a naturally occurring form of fluid-kinetic energy that is in constant motion across the earth's surface and can be attributed to pressure differences caused by relative temperature variation. Another example of naturally occurring fluid-kinetic energy is the tidal movement in our oceans which is caused by the relative position of the moon in its orbit around the earth.

Turbines are an effective method of converting linear fluid-kinetic energy into rotational motion and have been employed in various electricity producing power plants including, coal fuelled steam plants, hydroelectric plants and wind farms. Steam plants are an effective method of producing high volume energy at a controlled rate and are currently the most common form of electricity producing plant in Australia.

The process of burning fossil fuels to boil water and create steam is an unnecessary process because there is already an abundant amount of naturally occurring fluid-kinetic energy in motion waiting to be harnessed. Converting the energy contained in wind to mechanical and then electrical energy is a sustainable method of supplying our energy requirements.

This chapter investigates naturally occurring fluid-kinetic energy, wind characteristics and behaviour, energy extraction and conversion theory.

The topics covered include:

- Wind characteristics, loading and effects on structures
- Wind speed and characterisation
- Control volume and linear momentum
- Energy conversion theory

This chapter aims to emphasise the importance of site selection and describe the process of wind extraction and conversion to mechanical power.

3.2 Wind – Characteristics, loading and effects on structures

Common atmospheric circulation patterns

The general global flow circulation pattern previously described is a basic generalised model assuming that the earth is smooth spherical surface. In reality the Earth's relative surface roughness varies between locations due to large natural formations such as land, sea and mountains. The earths land formations can considerably affect the air's flow regime due to their resulting relative pressure fields, solar radiation absorption characteristics and the relative humidity.

The ocean is a perfect example of a land formation affecting the flow circulation. The ocean is a huge energy sink and the flow of air over its surface is often linked to and dependent upon the flow characteristics of the water.

The local geography and land formations in an area are responsible for creating what is known as a localised wind or regional winds. Fluctuation in the local temperature of a region can cause localised wind to occur on a seasonal or even daily basis including sea breezes or mountain winds.

Small scale atmospheric circulation can be divided into two groups, secondary and tertiary circulation (Rohatgi and Nelson 1994). Secondary circulation occurs in centres of high or low pressure caused by the heating and or cooling of different atmospheric levels the effects of which include:

- Hurricanes
- Monsoon circulation
- Extra-tropical cyclones

A prime example of this can be witnessed in the tropical region of far north Queensland during the summer months of the year also known as the wet season. Monsoonal troughs and combining low pressure systems can cause circulatory patterns known as cyclones which exhibit wind speeds of up to 200 km/h which can have devastating effects on the local infrastructure and ecosystem.

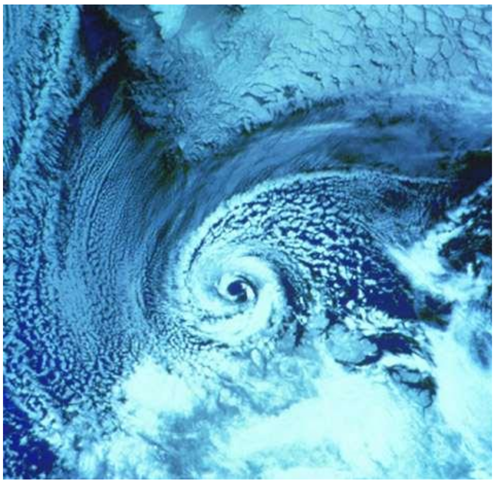


Fig 3.1 - satellite image- tropical cyclone caused by secondary circulatory patterns

Tertiary circulations a smaller scale local circulation pattern which contribute to the following:

- Land and sea breezes
- Valley and mountain winds
- Monsoon-like flow
- Foehn winds
- Thunderstorms
- Tornadoes

(Mcgowen and Rodgers, 2002)

An example of tertiary circulation can be depicted as valley and mountain winds. Valley and mountain winds are subject to dramatic change with a variance in temperature. During the daytime where the temperature at ground level is generally much higher than the air temperature at higher atmospheric levels; the relative temperature difference causes a natural localised convection cycle. The warm air of the mountain slopes rises and replaces the cooler air higher above it on the mountain. During the night the direction of flow reverses. The cold air drains back down the mountain slope and stagnates in the valley floor.

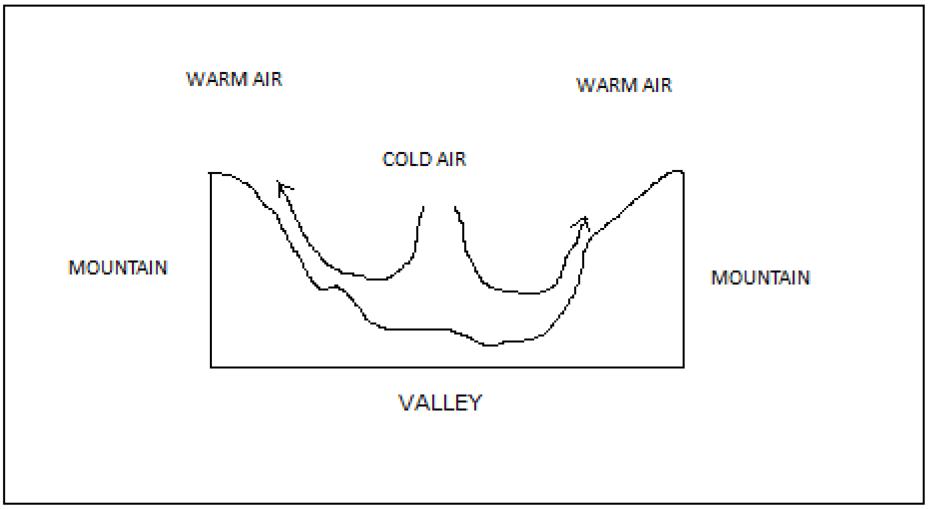


Figure 3.2 - Diagram of diurnal valley and mountain wind during the day. Direction of flow reverses at night.

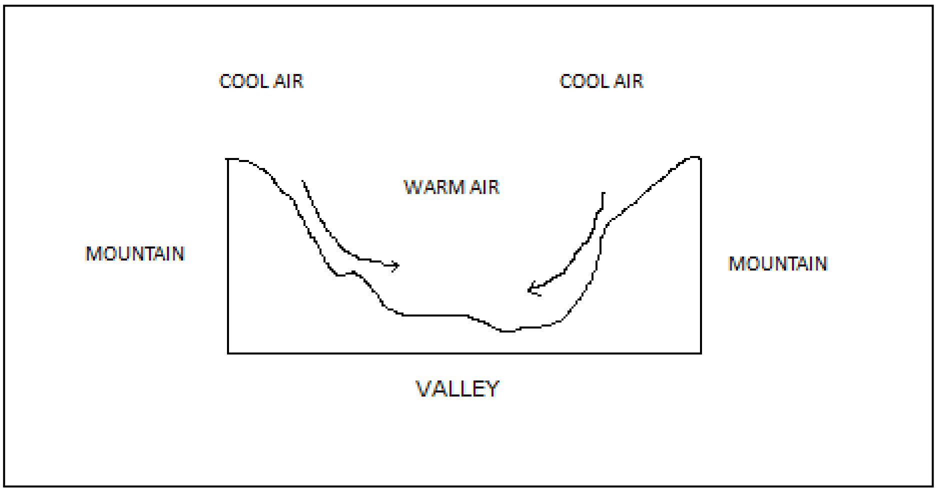


Figure 3.3 - Represents the space time scale of the different categories of atmospheric circulation as applied to wind energy production. Wind speed and consistency generally varies

with height and time but its flow characteristics are heavily depends upon the global and local geographical conditions.

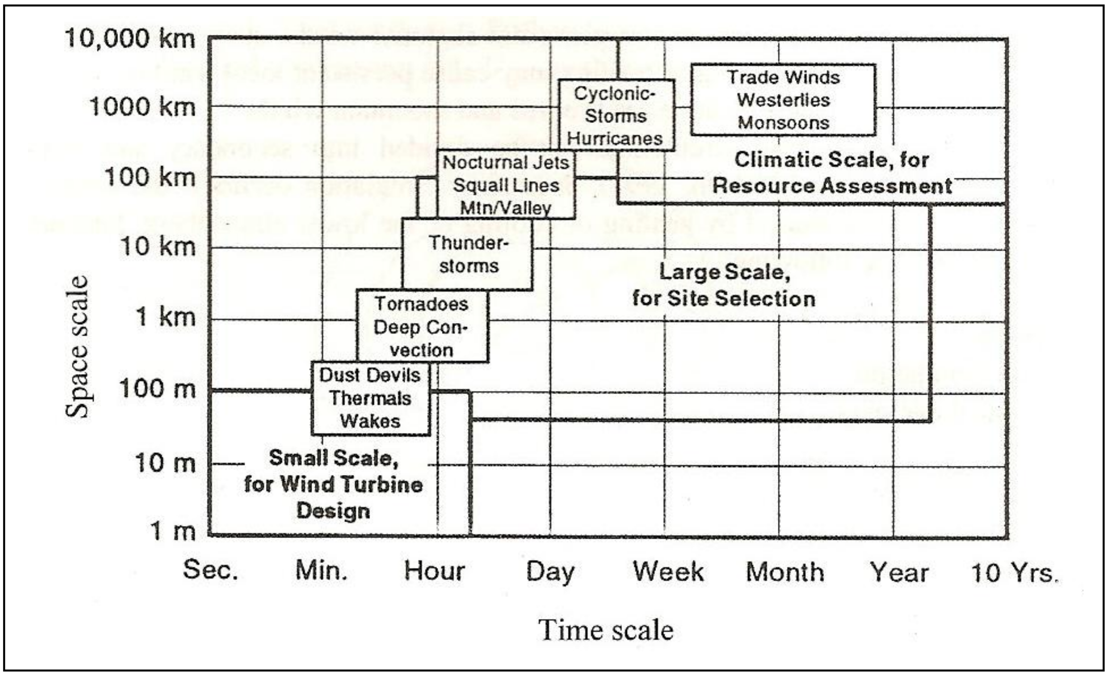


Figure 3.4 - Time and speed scales of atmospheric motion (McGowan and Rodgers, 2002)

Categories of wind variation with respect to time:

Inter-annual – Inter annual time variation refers to wind speed variations that occur over time scales greater than one year. Inter annual wind variation is the main factor to consider when selecting a long term wind energy production site. To determine the viability of a long term site for wind energy production, the proposed site’s long term values of wind speed and climatic activity are reviewed in order to determine an average wind speed to determine expected energy production.

Annual – Annual variation refers to the wind speed variation over the period of a season or year. The average seasonal wind speed varies from location to location depending upon their relative local geography and climatic conditions. As previously discussed, far north Queensland experiences a heavy monsoonal trough during the summer months which can produce fierce low pressure systems which cause higher than average winds.

Diurnal- Diurnal variation refers to the variation of wind on a time scale of 24 hours. Figure 3.2 illustrates the flow characteristics of diurnal flow variation between the daytime and night time in a valley/mountain scenario. Another typical characteristic of diurnal flow variation is an increase of wind speed during the day time with the lowest speeds being experienced during the hours between midnight and sunrise.

Short term- Short term wind variation refers to the instability of wind speed at a given location. Generally naturally occurring wind is described as having an average velocity. It does however fluctuate a considerable amount due to turbulence and gusts and the average velocity does not give a true representation of the actual flow characteristics.

Terrain classification and its effect on wind speed and behaviour

Terrain in its most basic form can be classified as either flat or not flat. Non flat terrain is any terrain where the terrain's surface formation or characteristics has a significant effect on the flow over the considered plain. Non-flat terrain generally refers to the following:

- Mountains
- Valleys
- Depressions
- Plateaus
- Ridges
- Cliffs
- Significant structures (Large buildings etc)

Flat terrain refers t the following sorts of formations:

- Open Plains
- Plains with relatively even forestry
- Masses of water
- Terrain with small irregularities

To classify as flat terrain the following conditions must be met. (Some conditions depend upon the wind turbine relative geometry.

- Elevation differences around the wind turbine sight do not exceed an absolute value of 60 m within an 11.5 km diameter circle of the proposed site.
- No land formation has an aspect ratio greater than 1/50 within 4km upstream or downstream of the site. (The aspect ratio is the ratio of Height : Width)
- The height of the lowest point of the rotor disk is at least 3 times larger than the difference between the maximum peak and trough of the land formations within 4 km upstream of the turbine.

The wind profile changes with height and is affected by the relative geometry of the terrain over which it flows. Figure 3.5 illustrates the flow profile of wind passing over a group of trees considered to be flat terrain. The region directly downstream and up to the tree top height is sheltered from the oncoming flow.

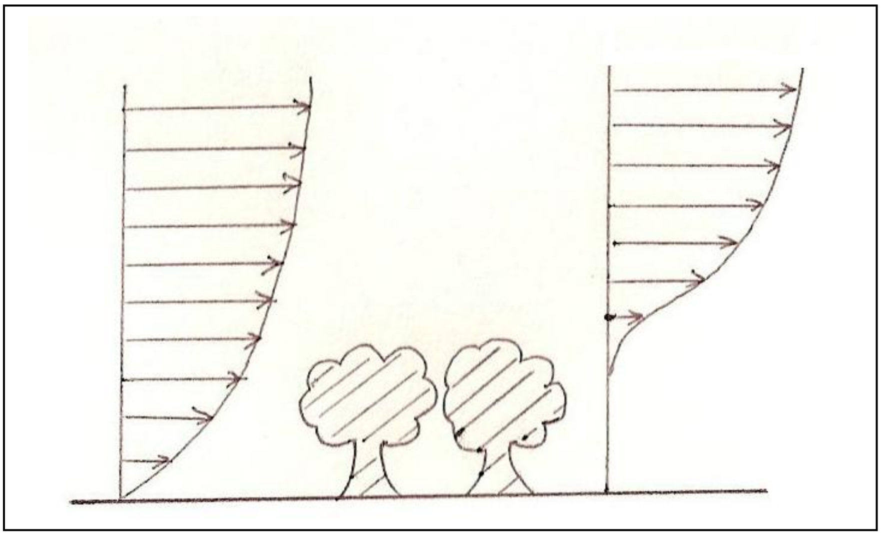


Figure 3.5

Figure 3.5 illustrates the topographic profile and relative configuration to oncoming flow of various ridges. Ridges are elevations of heights up to 600m that do not have a flat area at their summit. For wind turbine site selection the ideal ridge should be perpendicular to the oncoming flow. Concavity perpendicular to the direction of flow is also favoured as it increases the wind speed at the foot of the ridge.

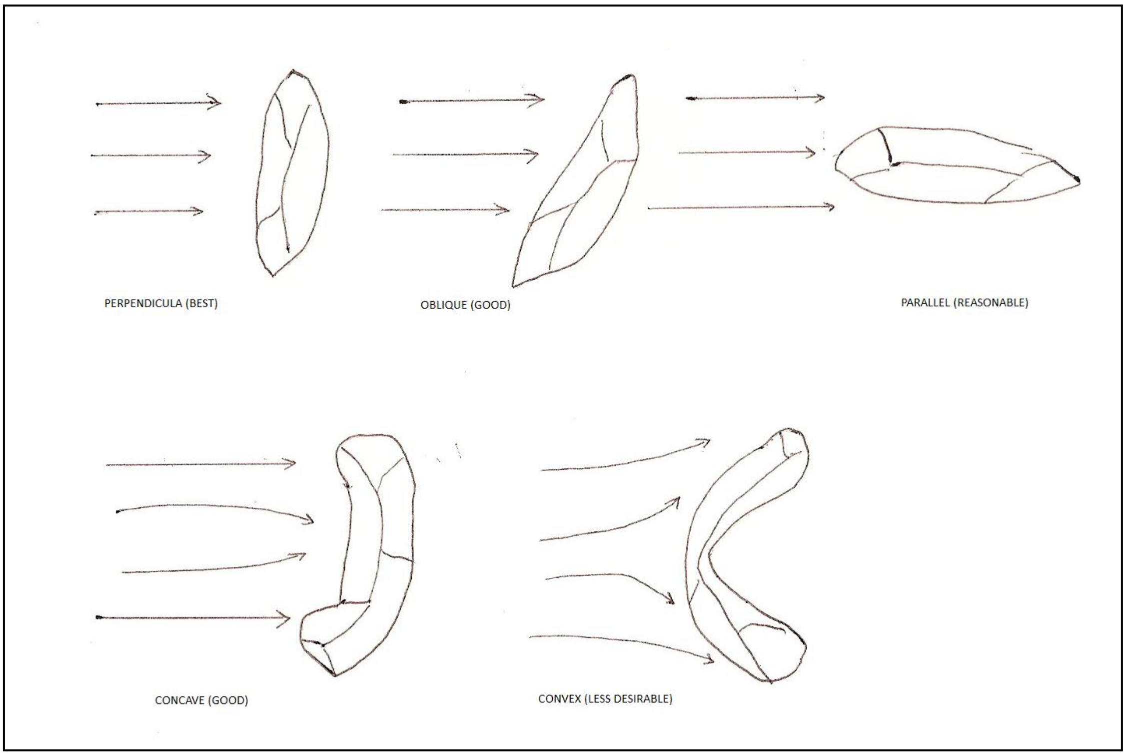


Figure3.6 - Ridge configuration to oncoming flow

Loading and effects on structures

The effects of wind loading on structures play a major role in the design faze of buildings, bridges, towers and Wind energy conversion systems. In areas of high wind aspects such as the configuration of the structure relative to the wind plays a huge role in ensuring the long term structural integrity of the building.

"*When an undisturbed air flow approaches a building, it is forced around and over the building. This creates areas of pressure or suction on the building facades, gables and roof. Pressure and suction refer to air pressure above and below barometric pressure levels respectively.*" (Dyrbye and Hansen, 2002, P50.)

Aerodynamic lift is a topic referred to quite heavily in wind turbine design as it is the main contributing factor in generating torque and rotation. On structures such as the buildings however, it is an undesirable effect and the structure should be designed to minimise lift and drag forces. Lift can cause catastrophic failure in static structures and it is important to design with minimal potential for lift force creation.

Wind turbine towers can be best analysed as tall cylindrical towers of uniform circular cross section. Cylindrical towers produce minimal lift as they display no surfaces that with an angle of attack that can produce a significant pressure difference. Like all structures cylindrical towers create a stagnation zone and produce a wake region at their trailing section. Flow visualisation techniques such as hydrogen bubble dispersion in a fluid flow environment are an effective way of demonstrating the streamlines and wake region around a bluff object such as a cylindrical tower.

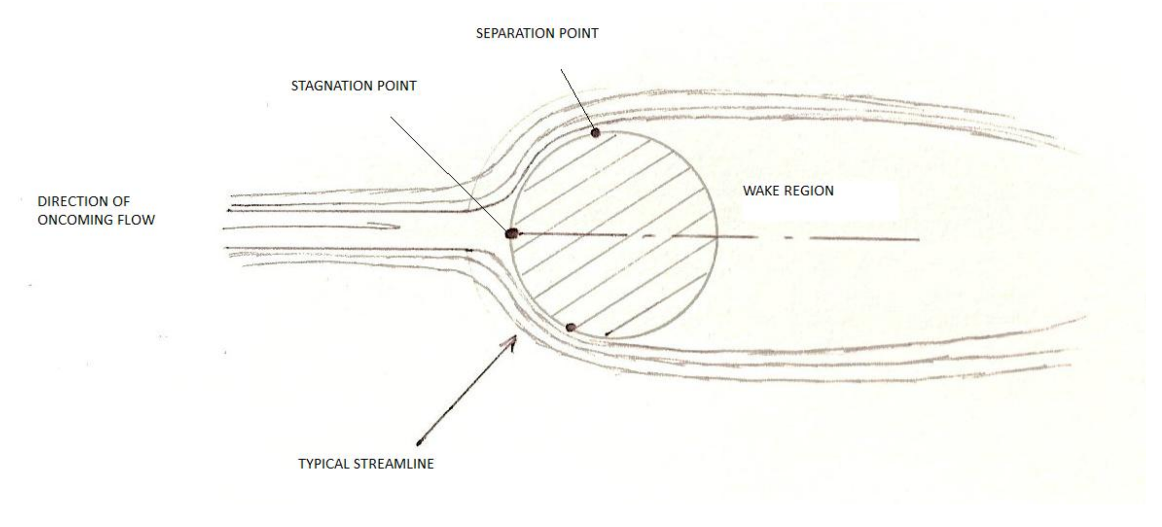


Figure 3.7 - Flow visualisation around a cylindrical object

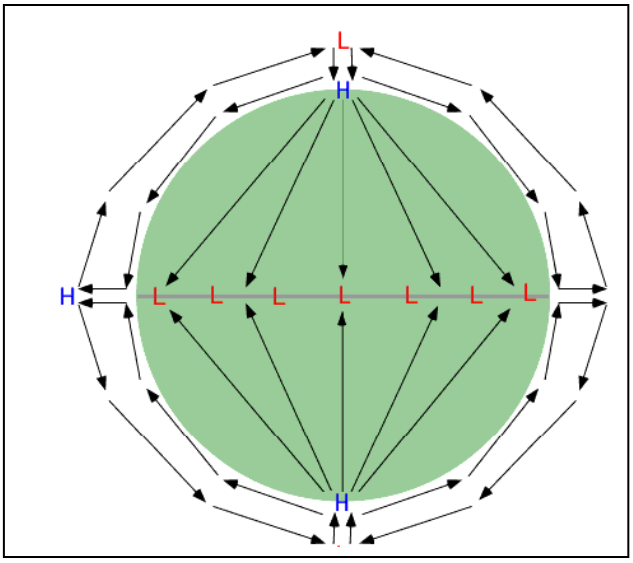
3.3 Wind speed - Wind characterisation

The wind speed at the location of proposed installation is one of the main determining factors as to what type of turbine will be designed; vertical axis, horizontal axis, blade configuration etc. For example, in an area where the average wind speed is relatively low a Halladay type multiple fan system may be implemented as opposed to a 3 bladed rotor due to the fan's better performance at a lower tip speed ratio.

Not only the average wind speed should be considered when selecting a particular type of design but also the distribution of wind speeds over an extended period of time. We also need to consider that the wind speed varies with height in order to properly asses possible sites and also the particular type of turbine suitable for that site.

Global winds are caused by a difference in absorption of solar radiation across the entirety of the Earth's spherical surface resulting in a pressure difference. Wind flows in the direction of high to low pressure, much the same as heat does from high to low temperature. The Earth absorbs a greater amount of solar radiation at the equator than at its poles. The variation of incoming radiation produces areas of convective activity in the troposphere, the lower region of the atmosphere. The resulting flow produced circulates winds rising at the equator and sinking toward the poles. The circulation of the atmosphere is greatly influenced by the rotational speed of the earth along with seasonal variation in solar distribution.

The variation in temperature that causes the warm air to rise at the equatorial regions is counteracted by the gravitational force acting upon it. This results in wind travelling in predominantly the horizontal plane and responds to the varying horizontal pressure gradients. Along with atmospheric pressure and gravitational forces, the behaviour of atmospheric wind is influenced by the friction of the Earth's surface, the inertia of the wind and the rotational speed of the Earth.



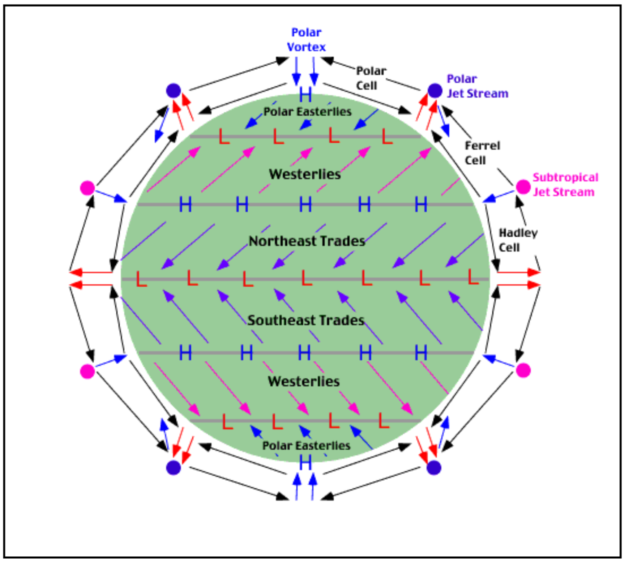


Fig 3.8, 3.9 , Images courtesy of : http://www.physicalgeography.net/fundamentals/7p.html

As previously mentioned wind speed varies with height and can be reasonably approximated in the following relationship:

$$\boldsymbol{u} = \boldsymbol{V}\ \mathbf{ln}\ (\frac{\boldsymbol{z} - \boldsymbol{d}}{\boldsymbol{z0}})$$

$u = horizontal\ velocity$

$z = height\ in\ metres$

$z0 = roughness\ length$

$d = zero\ plane\ height$

$V = characteristic\ \ velocity$

Wind speed measurements are often made from a reference height. The following power-law expression can be used to relate the wind speed at a particular height to the reference speed at a particular reference height.

$$\boldsymbol{u} = \boldsymbol{u_{ref}} \left(\frac{\boldsymbol{z}}{\boldsymbol{z_{ref}}}\right) \boldsymbol{b}^{'}$$

$u_{ref}\ = velocity\ at\ reference$

$z_{ref}\ = reference\ height$

$b^{'}\ =\ \ interference\ factor\ (\frac{1}{7} for\ open\ sites\ )$

3.4 Control Volume and linear momentum

Considering the control volume for a turbine rotor, the sum of forces acting on the fluid is given by the following linear momentum expression:

$$\sum \boldsymbol{F_x} = \int_{cs} \boldsymbol{u\rho\bar{u}}\,.\,\overline{\boldsymbol{dA}}$$

$$= \boldsymbol{\dot{m}(u_2 - u_0)}$$

Subscripts 0 indicates upstream velocity, 2 indicates downstream velocity

$\rho = fluid\ density$

$\dot{m} = mass\ flow\ rate\ (\frac{kg}{s})$

The stream tube passing the turbines rotor system expands, as opposed to the contraction that occurs at a propellers interface. The force experienced by the turbines rotors will be in the direction of the flow stream (wind direction) and will be equal to the axial force experienced by the fluid,

$$\boldsymbol{F_A = \dot{m}(u_0 - u_2)}$$

The mass flow rate of the fluid is denoted by the following relationship:

$$\boldsymbol{\dot{m} = \rho_0 u_0 A_0 = \rho_1 u_1 A_1 = \rho_2 u_2 A_2}$$

In this case the density of the fluid is maintained at a constant throughout the stream. Note that subscript 1 indicates the characteristics at the turbine rotor interface.

Power can be expressed as force X velocity and the power extracted by the turbine can therefore be expressed as:

$$\boldsymbol{P_T = F_A u_1 = \dot{m}(u_0 - u_2)\, u_1}$$

3.5 Energy Equation

The energy equation for an incompressible fluid is given by:

$$\boldsymbol{\frac{p}{\rho}+\frac{1}{2}u^2+\ gh = constant\ along\ stream\ line}$$

If there are any energy losses the relationship can be rewritten

$$\frac{p_0}{\rho}+\frac{1}{2}u_0^2+\ gh_0 =$$
$$p2\rho+12u22+\ gh2+specific\ energy\ removed\ from\ streamline$$

As energy is absorbed by the rotor blades and converted to mechanical power the following relationship represents the power removed from the stream tube:

$$\boldsymbol{specific\ energy\ removed\ from\ stream\ tube = \frac{1}{2}\ (u_0^2 - u_2^2)}$$

In terms of power:

$$power\ removed\ from\ streamtube = \ \frac{1}{2}\boldsymbol{\dot{m}\ (u_0^2 - u_2^2)}$$

Combined momentum energy equations

The power removed from the stream tube and hence the power of the turbine can be written as :

$$\boldsymbol{P_T = \dot{m}\ (u_0 - u_2)u_1 = \ \frac{1}{2}\dot{m}\ (u_0^2 - u_2^2)}$$

$$\boldsymbol{u_0^2 - u_2^2 = (u_0 + u_2)(u_0 - u_2)},\quad This\ indicates\ that,$$

$$u_1 = \frac{1}{2}(u_0 + u_2)$$

The interference factor (*a*) is the fractional change in wind speed at the turbine station. This factor is defined as:

$$a = \frac{u_0 - u_1}{u_0}$$

The power of the turbine can also be expressed as a function of the area swept by the blades, the wind speed and the density of the fluid, in our case the density of the air.

$$P_T = 4a(1-a)^2 \frac{1}{2} \rho A_1 u_0^3$$

This can also be written as,

$$P_T = C_p P_0$$

$$C_p \text{ Is the power coefficient of the turbine}$$

$$C_p = 4a(1-a)^2$$

P0 Is the kinetic power in the undisturbed stream tube with the area expressed as A1:

$$P_0 = \frac{1}{2} \rho A_1 u_0^3$$

Turbine Thrust equations

The axial force or thrust that acts on the turbine is obtained by combining the wind speed with the swept area of the turbine and the air density along with the interference factor in the following relationship:

$$F_A = 4a(1-a) \frac{1}{2} \rho A_1 u_0^2$$

$$F_A = C_F \frac{1}{2} \rho A_1 u_0^2$$

Where C_F is the coefficient of axial force,

$$C_F = 4a(1-a)$$

Torque

The maximum torque occurs when the maximum thrust is applied to the turbine rotors, the tips of which are at a radius *R* from the hub centre. The maximum force or axial thrust occurs when the interference factor $a = 0.5$, $C_F = 1$ and $F_A = \frac{1}{2} \rho A_1 u_0^2$. The maximum torque is expressed as:

$$T_{max} = \frac{1}{2} \rho A_1 u_0^2 R$$

$$T_{max} = \frac{1}{2}\rho A_1 u_0^3 \frac{R}{u_0}$$

$$T_{max} = P_0 \frac{R}{u_0}$$

The actual torque developed by the rotors is less than the maximum torque and can be obtained by multiplying the maximum torque by a torque coefficient. The torque coefficient is dependent on the type of design and rotor system being used.

$$T = C_T T_{max}$$

Where C_T is the torque coefficient.

The mechanical power being produced by the turbine can be related to torque being generated,

$$P_T = T\omega$$

$$P_T = C_T T_{max}\, \omega$$

ω is the angular velocity of the turbine expressed in (rad/s).

3.6 Aerodynamics in Rotor Design

The design of the turbines rotors is perhaps the most mathematical element of the entire turbine design. The rotors use aerodynamic lift to provide a turning moment and consequently an input torque to the gearbox. There are many different standardised aerofoil profiles varying in cross-sectional profile and can be most recognisably characterised by their camber, thickness and chord length. The design of the blades used in this project will be based upon blade element theory and the Betz equation and will investigate the blade shape for ideal rotors with and without wake rotation.

The following terms are used to characterise an aerofoil:

- *Mean camber line* – The locus of the points half way between the upper and lower surfaces of the aerofoil profile.
- *Leading edge* – The most forward point of the aerofoil cross section
- *Trailing edge* – The tail end of the aerofoil cross section (feather edge)
- *Chord line* – The chord line connects the leading edge to the trailing edge. The chord line is a straight line and its distance is known as the chord *c* of the aerofoil.
- *Camber* – Camber is the distance between the chord line and the locus that represents the mean camber line measured perpendicular to the chord line.
- The thickness of the aerofoil at any point along its chord line is the distance between the top and bottom surface measured perpendicular to the chord line.
- *Angle of attack (α)* - The angle of attack is the angle created between the chord line and the relative wind direction.
- *Span* – The term span refers to the length of the aerofoil perpendicular to the cross section. In terms of a wind turbine the span of the blades make up the swept diameter of the turbine minus the hub diameter.

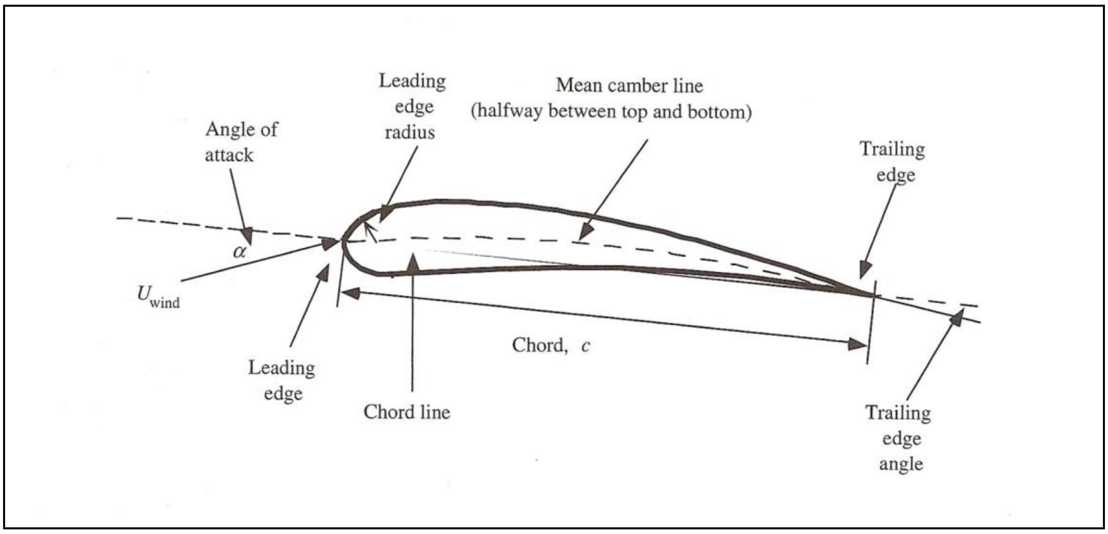


Fig 3.10 - Airfoil nomenclature (McGowan, Rogers (2002), Wind Energy Explained)

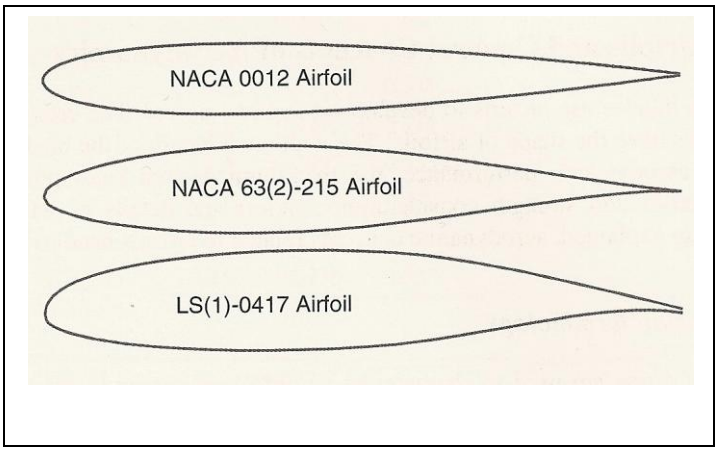


Fig 3.11 -, Airfoil profiles (McGowan, Rogers (2002), Wind Energy Explained)

The aerofoil profiles shown in figure 3.10 are three of the most common aerofoil cross sections used in for wind turbines. NACA is the National Advisory Committee for Aeronautics and designs aerofoils for aircraft wings, some of which also find use as suitable turbine rotor cross sections.

The NACA four digit numbering system is a method of classifying an aerofoil design based on its camber, chord and thickness.

For example NACA 2320 (theoretical number) has a maximum camber of 2% at a distance of 30% of the chord length from the leading edge with a maximum thickness of 20% of the chord. NACA 0012 shown in figure 3.10 is an asymmetric aerofoil. The first two digits are 0 meaning it has no camber, the 12 represents a maximum thickness of 12% of the chord length.

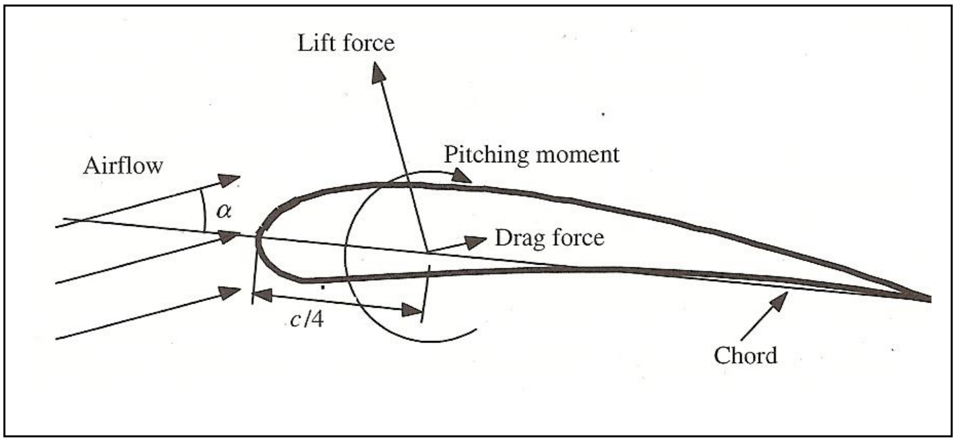


Fig 3.12 - Drag and lift forces (McGowan, Rogers (2002), Wind Energy Explained)

Lift and drag are the forces that are responsible for the rotating the blades and creating mechanical energy. When air flows over the cross section of an aerofoil it produces an uneven distribution of forces over the aerofoil surface. The air flow over the convex (upper) surface moves at a higher velocity than the air flowing across the concave (bottom) surface. The increased velocity of the flow over the convex surface results in a lower pressure creating suction on that side of the aerofoil. The slower moving air on the concave side, the pressure side, imparts a positive force on the aerofoil surface which also adds to the lift created by the suction side.

Lift force can be best defined as force acting perpendicular to the direction of oncoming flow. Lift is the resultant force of a pressure difference between the upper and lower boundaries of the aerofoil

cross section. Drag force is the force acting parallel to the direction of oncoming flow. Drag force is the resultant of viscous friction forces created at the boundary layer of the aerofoil and also the pressure difference that exists between the leading and trailing edges.

Many flow problems can be characterised by non-dimensional flow parameters. The Reynolds number, which indicates the whether a flow system is turbulent or laminar is the most important dimensionless parameter. The force and moment coefficients are generally a function of the Reynolds number and can be defined for both 2 and 3 dimensional objects. Rotor design usually involves 2 dimensional design coefficients as the span of the aerofoil can be broken up into several cross sections which are separately analysed. Sections of the aerofoil are commonly tested in wind tunnels with varying angels of attack and flow speeds, ultimately effecting the Reynolds number.

Dimensionless coefficients:

$Re = \frac{UL}{v} = \frac{\rho UL}{\mu} = \frac{Inertial\ force}{Viscoua\ force}$	Reynolds number: Characterises the degree of flow
$C_l = \frac{L/l}{\frac{1}{2}\rho U^2 c} = \frac{Liftforce/unit\ length}{Dynamic\ force/unit\ length}$	Lift coefficient: Coefficient of force perpendicular to direction of flow
$C_d = \frac{D/l}{\frac{1}{2}\rho U^2 c} = \frac{Dragforce/unit\ length}{Dynamic\ force/unit\ length}$	Drag coefficient: Coefficient of force parallel to direction of flow
$C_m = \frac{M}{\frac{1}{2}\rho U^2 Ac} = \frac{Pitching\ moment}{Dynamic\ moment}$	Pitching moment coefficient: Coefficient of moment induced by flow on projected aerofoil area
$C_p = \frac{p - p_\infty}{\frac{1}{2}\rho U^2} = \frac{Static\ pressure}{Dynamic\ pressure}$	Pressure coefficient
$\frac{\varepsilon}{L} = \frac{Surface\ roughness\ height}{Body\ length}$	Surface roughness ratio

Table 3.1

Cambered aerofoils:

Cambered aerofoils have a curved chord line which allows them to produce lift at zero angle of attack. Cambered aerofoils generally have higher maximum lift/drag ratios than symmetrical aerofoils for positive angles of attack which make them favourable for application in wind energy converters.

For this reason a slight cambered aerofoil will be applied in the design to ensure maximum lift generation and effective power extraction from the stream tube. The aerofoil design chosen was based upon NACA4412, a commonly used aerofoil cross section in wind energy conversion.

CHAPTER 4

INDUCTION GENERATORS AND POWER DISTRIBUTION

4.1 Induction Generator Theory

Induction generators are by far the most common form of electrical generator used in stand-alone power generation systems. The induction generator began its employment as an electrical generator early in the 20th century but almost completely fell out of fashion in the 1960's. However, a dramatic rise in petroleum prices in the 1970's saw the swift return of the induction generator.

It's no secret that on earth we are running out of natural resources used in our current fossil fuel powered electrical power plants. There is a growing opportunity for the development of new, effective, more efficient environmentally friendly energy conversion systems such as the wind turbine or hydroelectric turbine. Induction generators have been traditionally favoured for small rotating power production units as they are low maintenance, exhibit simplified controls, are robust and are relatively small in size per kW of energy converted.

Energy conversion systems can be classified as either direct or indirect.

Direct conversion systems are systems that do not have an intermediate energy conversion system, for example:

- Photovoltaic panel (electromagnetic)
- Chemical reactions (batteries)

Batteries are fuel cells that convert chemical energy into electrical energy. Batteries normally contain two electrodes separated by an electrolyte solution.

Direct energy conversion systems are generally favoured due to their silent operation and low pollution. They are however generally much more expensive than indirect conversion systems and not as efficient.

Indirect conversion systems incorporate one or more intermediate energy conversion systems. For example:

Wind turbine:

Wind (naturally occurring)----- Rotor(mechanical)----- Generator(Electrical)

Rotating generators:

The electric generation in a rotating generator is based upon the relative movement between a coil and a magnetic core. The rotation of a coil between a pair of poles (field) of an electromagnet or permanent magnet creates either an alternating current or a direct current depending on the configuration of the generator:

Alternating Current machine (AC)	Direct Current machine (DC)
- Slip ring configuration - Requires a DC power supply to excite field windings, sometimes sourced from smaller DC generator located on same generator shaft.	- Segmented commutator instead of slip rings - Requires DC power supply to excite field windings - Some DC machines are self exciting

- Synchronous or Asynchronous - Synchronous if the frequency is an integer multiple of the grid frequency. - Asynchronous – frequency is not a fixed value.	(shunt, series, compound) needing only a small amount of residual magnetic flux in the core of the machine to start the excitation process.

Table 4.1

Induction motor/generator theory

Both synchronous and DC machines can be used as either generators or motors and in the same way induction motors can be made to operate as an induction generator. Since the energy crisis of the 1970's engineers and scientists have developed uses for induction motors as generators particularly in wind energy converters as they are a suitable mechanism for transforming mechanical energy into useful electrical energy. Induction generators are also referred to as asynchronous generators as the rotor does not operate at synchronous speed.

When a voltage, V, is applied to the stator winding of an induction motor, a current made up of two components flows into it. The two current components are the magnetizing component and the real power component. The magnetizing component lags the applied voltage by 90° and is responsible for creating the magnetic field or rotating flux (rotating stator field) . The real component is in phase with the applied voltage and supplies the real or active power (watts) to the induction motor. This component consequently induces rotation to the shaft of the motor and is responsible for the mechanical output and internal losses.

If the real load is removed from the system the motor continues to draw the same magnetizing current. However the real power current becomes very small. If at this point mechanical power is added to the rotor shaft causing additional rotation and an increase in speed to a point where it is rotating above synchronous speed the once induction motor begins to operate as an induction generator.

In this conversion, the value of slip becomes a negative number. The rotor conductors are consequently moving at a speed higher than that of the rotating flux meaning that the motion of the rotor conductors relative to the flux will change in direction. As a consequence the direction of the rotor current will change causing a reversal in the electromagnetic flux (emf) generated in the stator winding. This means that the electric power will now flow out of the stator windings resembling an electric generator.

The machine does however continue to draw the same exciting current from the ac supply lines as the induction generator is not self-exciting and the rotating flux requires constant supply. The once present internal losses of the induction motor are now supplied by the prime mover which in this case is the rotation provided by our wind turbine. The frequency of the generated stator voltage is dependent upon the rotational speed of the magnetic flux and therefore will be of the same frequency as the applied exciting stator voltage.(Emanuel , Pericles John, 1985, *Motors, Generators, Transformers and Energy*, Prentice Hall Inc., Englewood Cliffs, New Jersey

4.2 Induction generator/motor mechanical design

An induction generator is made up of two major components, the stator and rotor. The stator is a stationary series of laminated steel plates mounted on a frame that ultimately forms the 'cage' which is the inside diameter of the housing assembly. The laminations of the stator are mounted on the inside frame in such a way that they form slots as in a synchronous machine. The rotor can come either in the wound form or cage form and for the purpose of this report the cage form will be investigated. The cage rotor consists of a series of bars of conducting material, typically copper alloy, which are embedded into the rotor slots. The rods are shorted at the two ends of the rotor by the conducting rings which are brazed to the rods. Cage type rotors are more favourable for small to medium type power applications as they are very rugged and not as expensive as a wound rotor.

For the purpose of physical analysis a 750 W induction motor/generator was disassembled to give physical representation of an induction machines internal components.

The machine investigated was a Brazilian made WEG- EFF E2 induction motor.

Induction motor specifics:

3 phase

V	**Hz**	**kW**	**RPM**	**A**	**cosφ**
220 DELTA	50	0.75	910	3.47	0.74
380 Y	50	0.75	910	2.01	0.74
230 DELTA	50	0.75	920	3.37	0.72
400 Y	50	0.75	920	1.94	0.72
415 Y	50	0.75	930	1.92	0.70
440 Y	60	0.85	1110	1.96	0.74
460 Y	60	0.85	1120	1.92	0.72

Table 4.2 Generator statistic

Figure 4.1- The induction motor/generator investigated.

The housing of the machine is made of cast aluminium making it relatively light weight. The design incorporates cooling fins which extrude from the outside of the stator housing that are responsible for effectively removing heat from the system.

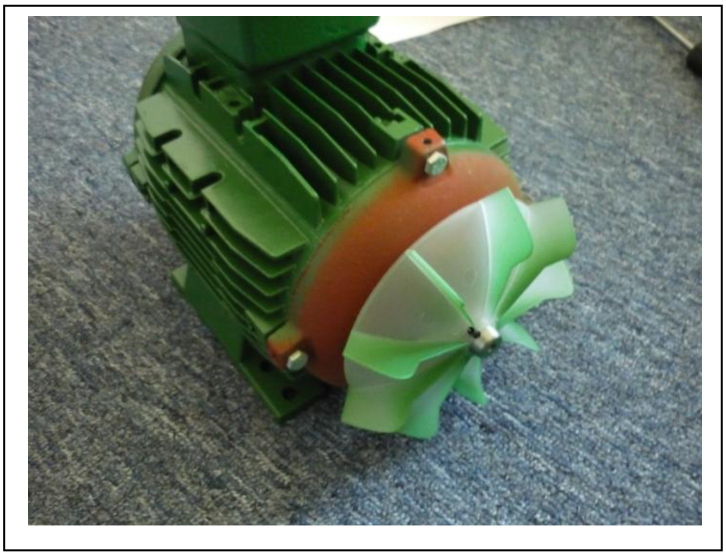


Fig 4.2

An impellor is mounted onto the same shaft as the rotor which creates a forced convective cycle to effectively remove heat from the cooling fins and hence keeping the machine at is rated running temperature of 40°C.

The mechanical design of an induction generator refers to the appropriate sizing of and selection of the various mechanical components within the induction generator. This process includes the selection of bearings, inertia calculations, the definition of the critical rotational speed, noise generation and avoiding vibration that may cause stresses and deformations. Centrifugal forces on the rotor experienced at high speeds must be maintained below the critical operating limit to ensure safe operation. The mechanical design also incorporates the winding configuration.

Induction generator design is commonly divided into two distinct levels: 100 kW > , <100 kW.

The size of generator being dealt with in this project falls into the > 100 kW category. In general, induction generators with an output power of less than 100 kW consist of a single winding stator configured for low voltages and a rotor with a cast aluminium squirrel cage.

Fig 4.3 -Generator rotor, shaft , and bearing

Fig 4.4- generator circuit box

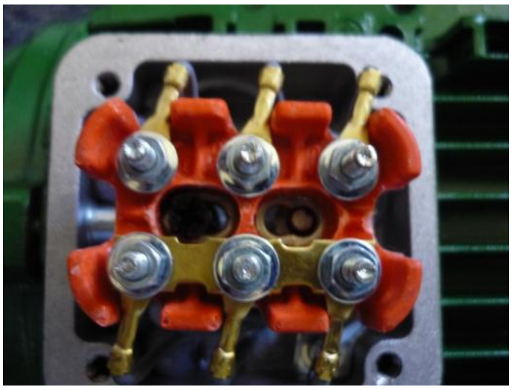


Fig 4.5- Close up of circuit box

Fig 4.6- Cage and rotor

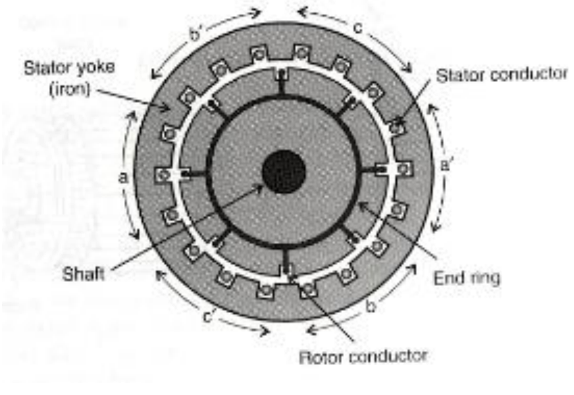


Fig 4.7- Cage and rotor (reference)

The figure 4.6 shows the complete assembly of the rotor within the stator. The diagram in figure 4.7 is a cross sectional view of the assembly of a three phase stator and rotor. In the diagram each winding occupies the contiguous slots within a 120° spacing. The laminates that make up the stator core are made of steel and silicon and have slots in integral multiple's of six that are roughly parallel with the machine shaft. The Slots are sometimes angled in relation to the longitudinal axis to reduce cogging torque, vibration and noise and to smooth over the generated voltage.

Stator yoke: The steel laminations that make up the cage.

Stator conductor: The windings of the stator

Rotor conductor : Conducting material incorporated in the laminations of the rotor

End ring :

Shaft: Suspended in bearings allows free rotation of the rotor.

Fig 4.8 -Generator Rotor assembly

Fig 4.9

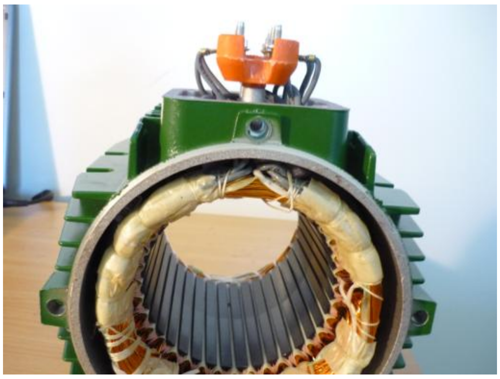


Fig 4.10

Machine sizing:

The developed torque in an induction motor/generator depends upon the following equation.

$$T = \frac{\pi}{4} D^2 l_a J_{sm} B_{rm} \sin(\emptyset)$$

$$D = stator\ bore\ diameter$$

$$l_a = stator\ core\ length$$

$$T = output\ torque$$

$$\emptyset = rotor\ power\ factor$$

The following relationship is true given the air gap volume and the stator winding J_{sm} current density in addition to the assumed air gap B_{rm} flux density.

$$\frac{D^2 l_a \emptyset}{T} \cong constant$$

Power is the resultant product of torque and speed. The coefficient C_0 can be used for determining the size of electrical AC generators.

$$C_0 = \frac{kVA}{D^2 l_a \omega}$$

4.3 Converter circuits

The variable output produced by renewable energy induction machines means that power conditioning and control needs to be conducted in order to transform the produced voltage, current and frequency into an AC or DC form that can be used by general electrical appliances. The particular transformation of interest for this type of application is AC-DC conversion. The renewable energy converter, in this case the wind turbine performs at different levels depending on the magnitude of wind which varies seasonally and at different times of the day. A 1-5 kW turbine would be most useful at supplying charge to a battery bank which then can distribute DC power as required by the appliances.

Before defining the required circuitry to transform AC to DC, some important terms and equipment need to be discussed.

Regulator

A regulator is a battery charge controller that is used to protect the battery bank from overcharging and over-discharging. The simplest method of regulation is to simply turn off the supply when the battery is fully charged and then to turn it on again when the battery reaches a minimum level of voltage. There are three main groups of regulators used in battery bank charging circuits: shunt, series and chopper.

- Shunt: This system dissipates the power from the renewable source, the wind turbine, across a dump load once the battery is fully charged. This method is most common with wind turbines.
- Series: the supply is automatically switched off once the battery is fully charged.
- Chopper: This is a high frequency switching operation which turns the supply to the battery on and off; once the battery is fully discharged the charging circuit is fully turned on. When the battery reaches a higher level of charge, the charging circuit switches the control on and off in proportion to the level of charge of the battery.

Inverter

Wind turbines that use induction generators for electrical energy production produce an AC current. The AC supply is then rectified into a low voltage, direct current. “ An inverter is an electrical device that changes direct current into alternating current.”(Farret, 2004, *Renewable energy systems*). Inverters are the electrical tool that enables standard house hold items to use the power supplied by the renewable energy system. Un-directional inverters are used when power is to be simply supplied from a generator to a load like a battery or a kettle. If an inverter is to supply power to something like a motor it needs to be bi-directional. If the source is to be connected to a grid, the inverter must supply power at a similar quality to that of the grid.

AC to DC conversion

The following parameters are required to design a circuit for AC-DC conversion.

- Evaluation of AC input limitations
- Average output voltage
- Output ripple voltage
- Efficiency
- Circuit load, output power
- Regulation to input voltage variation
- Regulation to output load variation
- Power flow direction if required, AC to DC

In the conversion from AC to DC a wave rectifier circuit needs to be employed. Half wave rectifiers are generally limited to applications lower than 100 W due to their lower power factors, their bulkiness and transformer inefficiencies. Because of this full wave rectifiers are used in practice.

4.4 Energy storage systems

As wind energy conversions systems rely on the naturally occurring winds to produce electrical energy the consistency and quality of the energy fluctuates with the behaviour of the wind. The majority of energy used in a household is during the evening hours, a time where there is generally not as much wind as during the morning or midday hours. Because of this there is an excess of energy during the day and a shortage at night when it is needed. Because of this energy storage systems are employed to ensure there is always a constant power supply.

There are many different methods for storing the energy produced by wind energy conversion systems. The three main types are thermal storage, mechanical storage and chemical storage. Thermal storage converts the electricity produced by the generator into heat using an electric-resistance heater. This method of storage requires an insulated containment chamber that can capture the heat energy for an extended period of time.

Mechanical storage usually encompasses using the energy converted by the turbine to move a mass to a greater height where it posses greater gravitational potential energy. A prime example of this is mechanically pumping water into a raised reservoir. The water can then be released from the reservoir and then be directed through a hydro-turbine to produce electrical energy when required.

The area of storage that receives the most attention is chemical storage. Chemical storage can be achieved in two ways. The first method uses the electrical power produced by the turbine to perform electrolysis on a compound such as water, separating it into its hydrogen and oxygen gas constituents. The hydrogen gas is captured and can be stored in canisters until it used as a fuel source to provide thermal energy.

The most common form of chemical storage is the traditional battery storage device. Rechargeable batteries are the only type of battery currently being considered for storage purposes in wind energy conversion systems. The metal plates inside the battery act as receptors for the atoms that plate out of the electrolyte solution as a charging current is being applied to it. When the battery is being discharged the metal ions return to the electrolyte. This process releases electrons and generates a direct current at the battery poles.

The most common, well developed and successful battery is the lead-acid cell. Lead-acid cells have a wide variety of uses and are most commonly used for supplying electrical energy to automotive vehicles or industrial equipment in limited range service as stand-by power. The most common types of lead-acid cells are of a 12V size ranging from very low to a few hundred watt hours capacity. A high capacity lead acid cell has a useful charge-discharge cycle life of approximately 1000 cycles after which it no longer effectively gains or holds charge.

Cell configuration:

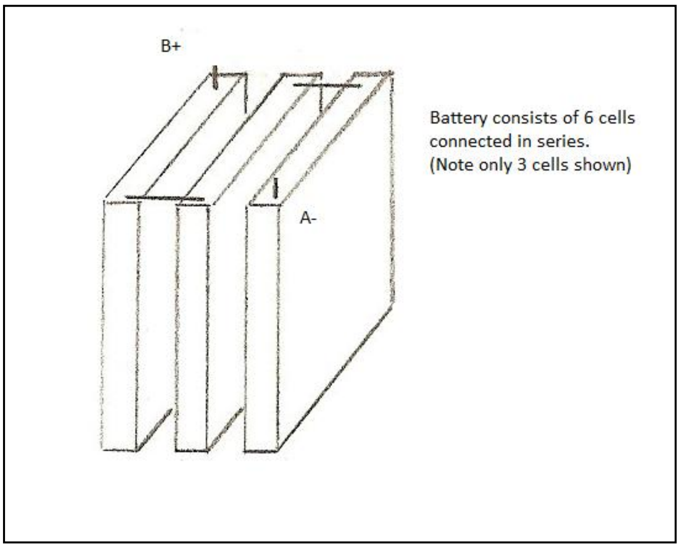


Fig 4.11

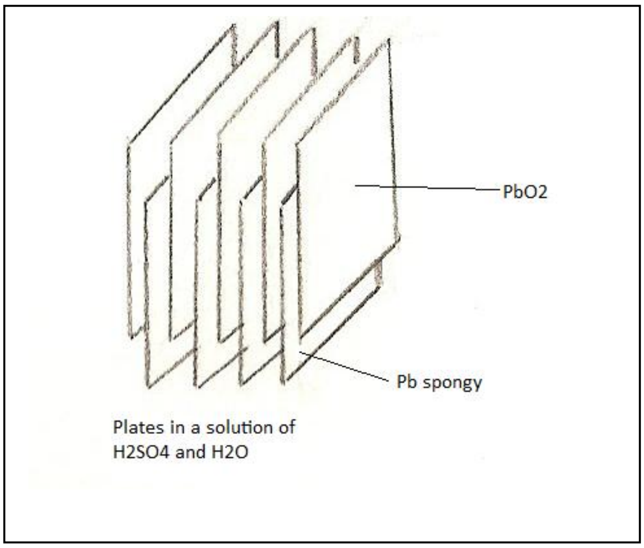


Fig 4.12

A lead acid battery consists of a number of cells connected in series to form a DC power supply. Each cell consists of a number of positive and negative charged electrodes made of pure spongy lead and lead oxide. Connected in parallel, the electrodes are submerged in an electrolyte solution of sulphuric acid and water.

The operational capacity of a battery:

“ The ideal capacity of a cell or battery is obtained from consideration of chemical energy content in the battery. This capacity decreases with increasing power or current demand in a manner that is modelable as an exponential decease of capacity with current draw, or its inverse, the time to decrease the capacity to a small value. The peak power demand that might be placed on a battery system depends on the depth of discharge (dod). Typically, the peak power available decreases from a value at 10% dod to about 0.8 and 0.65 of that value at dod’s of 50 and 75% respectively. These values are dependent on the kind of chemical system under consideration and its physical design. (P174. Decher, 1997)

As the wind energy conversion system is being designed for application in remote isolated communities that may not be connected to a utility grid and rely on stand-alone generation, battery storage is the most practical method of controlling the energy being produced. It is expected that the turbine will produce a varying power supply due to the climatic conditions and varying regional and local winds. Because of this the battery bank will receive charge when the wind is effectively driving the turbine and will be discharged when ever power is required.

A shunt regulator will be used to control the charging of the battery bank and the dumping of excess energy once the battery bank is fully charged. The excess energy being produced once the battery bank is full will be diverted to a dump load like a hot water heater or a refrigerator which will convert the electrical energy to thermal energy.

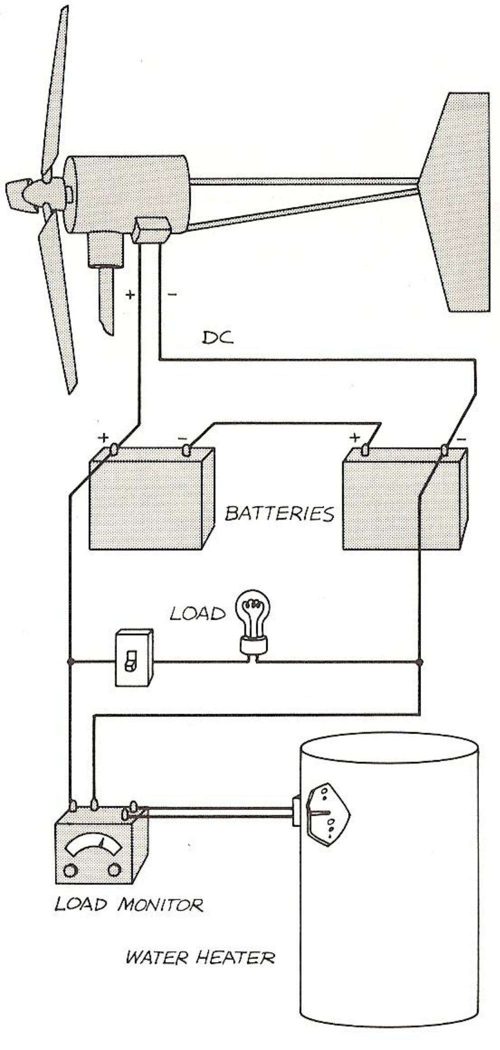


Figure 4.13 shows a similar circuit using a shunt regulator to distribute the excess energy to a hot water service. The difference between the circuit shown in figure 3.24 and the circuit that will be employed in the design is that the circuit creates AC power then transforms it to DC using an inverter. The DC power is then supplied to the battery bank where it is used to charge the cells. The excess energy is then distributed over a dump load.

Fig 4.13- Battery charging circuit with shunt regulator (Park, 1981)

4.5 Testing Of 500 W electrical generator

Introduction:

The mechanical-electrical converter in a wind turbine is the generator. The generator is coupled directly to the input shaft or to the output shaft of a gearbox depending on the rotational speed required by the generator to produce its rated power output.

A 500W AC generator was sourced and tested to determine the performance of the generator at different rotational speeds. The generator was previously mounted to a hydro-turbine and its operating conditions were unknown.

Generator specifications: Micro hydroelectric generator *MHG 500* – Phoenix resources Ltd.

Rated Voltage	**Frequency**	**Rated Power**	**Poles**
220 V	50-60 Hz	500 W	6

Table 4.3

This particular model had previously been adapted to be directly plugged into an electrical appliance for operation.

Resources :

- MHG 500 Micro hydroelectric generator
- G-clamp
- Digital Multimeter- frequency meter
- CY-S2060-B Metal Lathe
- Safety glasses

Safety Hazards:

The generator was suspended with its input shaft held in the jaws of the vice. The vice rotated at speeds of up to 1500 rpm. Due to the high rotational velocity there was a danger of the generator releasing form the fixture and becoming a projectile. Precautions were taken to ensure that the jaws had been locked effectively. The generator housing was then also firmly clamped to the tool post of the lathe ensuring that even if the jaws opened unexpectedly, the body was still effectively constrained.

The generator's rated voltage and power are 220 V and 500 W respectively. This is almost the equivalent to the power obtainable form a standard household wall socket. The generator was earth tested before the operation to ensure the machine would not short circuit and pass a current through the machine, damaging circuitry or electrocuting operators.

As always, the required workshop safety equipment was worn; safety goggles, steel toed boots, sufficient protective clothing.

Testing Method

The generator was clamped in the chuck of the lathe and supported by a freely rotating centre on its centre axis. The clamp supporting the generator was fixed to the tool post of the lathe to stop the generator housing spinning along with the shaft once torque was applied.

Fig 4.14- *Generator mounted in jaws of lathe chuck*

The lathe was set to the desired revolution per minute. Due to the design of the gearbox, the lathe's rotational speed was limited to 12 speed variations (see data for details).

The multimeter was set to its dual setting of frequency (Hz) and voltage (V) and the positive and negative probes placed in the sockets corresponding terminals.

The lathe was then turned on, spinning the generator's input shaft within the internal windings. The machine was left running long enough for the field to stabilise and produce a constant voltage.

The values for both voltage and frequency were tabulated.

Data collection: Results: Discussion:

The data collected during the experiment was recorded and is tabulated in Table 4.4

Speed (rpm)	Frequency (Hz)	Voltage (V)
15	1	1
25	5	2.3
35	6	4.3
60	9	9.3
95	14	15.5
140	21	24
175	26	30
275	41	51
400	59	74
660	160	123.1
1050	252	193
1500	362	277

The data collected shows a steady increase of Voltage with speed, however as the generator has a rated frequency of 50 – 60 Hz it raises some concern to the effective function of the generator.

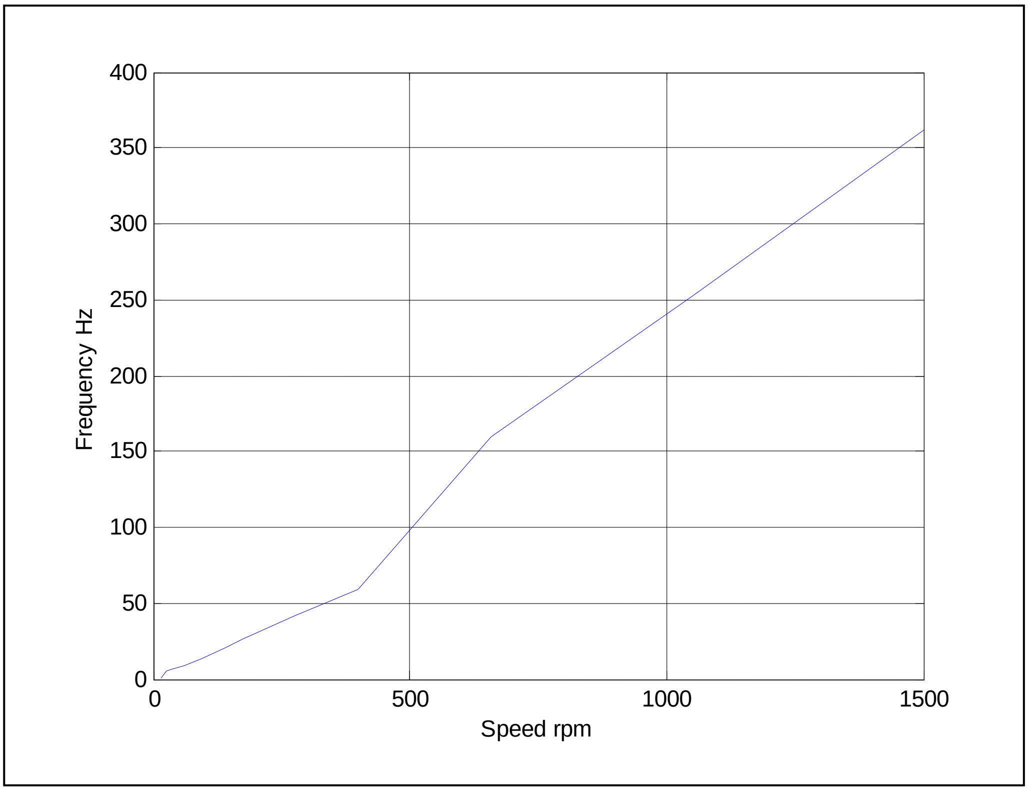


Figure 4.15

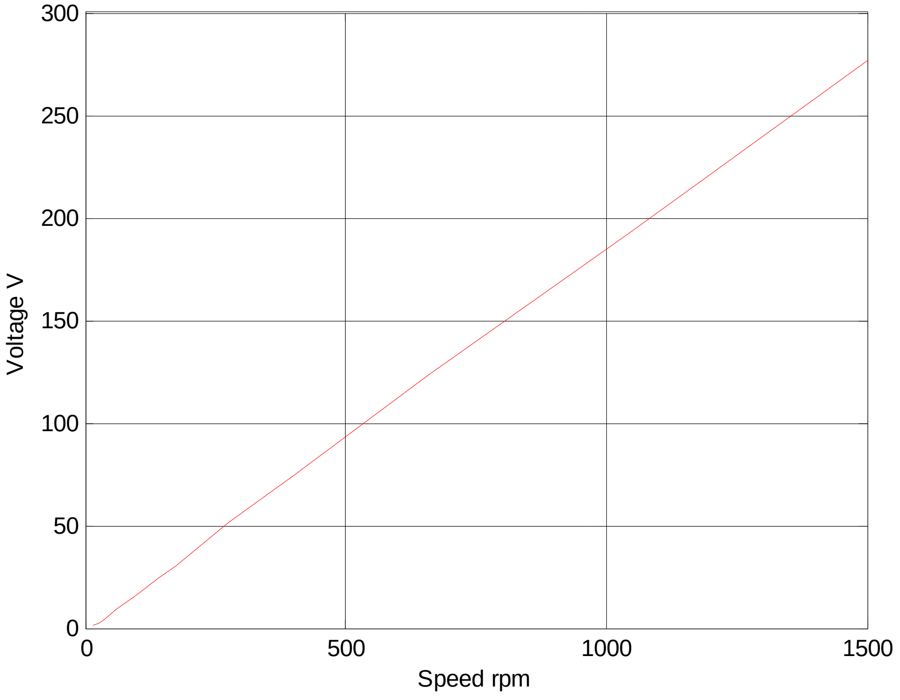


Fig 4.16

CHAPTER 5

PROTOTYPE MECHANICAL DESIGN

5.1 Hub : Blade : Drive shaft prototyping.

During the formation of the project specification, “manufacture a prototype wind turbine” was included. Due to the availability of the resources required to build a prototype, this goal was pursued during the winter university recess.

Prototyping is the process by which an initial design is manufactured. The prototype is then used for testing and further development until a production design is finalised. During prototyping all components that are not available off the shelf need to be designed and then manufactured using various manufacturing techniques. This is generally a relatively expensive process as the parts usually need to be manually machined and the design is often subject to change depending on the effective functionality of the part as it is added to the main assembly.

For example :

A part designed to a certain tolerance may need to be re-machined because the surface finish produced during machining caused interference with a concurrent part affecting the functionality of the assembly.

One of the most common processes used in prototyping which featured quite heavily in this prototyping exercise is machining. Machining is the process of removing material from a billet to achieve a specified geometry. Machining typically incurs an overhead cost of around $70-$100 an hour and therefore is relatively expensive to pursue. Once a production design is produced, processes such as casting are used as opposed to machining as it incurs a far lower production cost per part. Casting is not practical fro prototyping as the part is subject to change and this means that the mould would need to be modified every time a change is made to the part.

The parts manufactured were the hub assembly, blades and drive shaft. The hub and drive shaft were machined whilst the blades were shaped out of laminated timber slabs until they achieved the desired shape.

Figure 5.1

Solid works model of the Hub assembly including the rotors.

The project design specifications state that a 1-5 kW turbine is to be designed. For the purpose of prototyping a turbine of this magnitude would not be feasible due to the available time and funding. Therefore a scaled model was designed aimed at producing 500W of electrical energy. The rotors, hub and drive shaft were all manufactured during the 3 week winter recess in a machining workshop in Malanda, Far North Queensland. These components were chosen for production as they would physically demonstrate the effectiveness of the rotors at extracting energy from the wind and converting it to mechanical power by rotating the drive shaft. This would ultimately prove the overall effectiveness of the particular rotor design for the application.

During the above mentioned time period a 500W electric generator was tested to determine its optimum running speed and the mechanical input to produce the generator's rated power. Using the information collected from the generator trial it is possible to determine the design specifications for the rotor system and gearbox.

The majority of horizontal axis wind turbines are designed to incorporate a self pitching mechanism that governs the rotational speed of the rotors at high wind speeds. The prototype was not designed with a self pitching mechanism due to the time and extra operations involved in manufacturing the extra components. It was however designed in such a way that the blades could manually be adjusted to any desired pitch. This was aimed at determining the optimum pitch angle for various operating conditions during the testing of the rotor system. The design has also made allowances for future incorporation of a self pitching mechanism if it is to be pursued further.

Components

Hub- Front

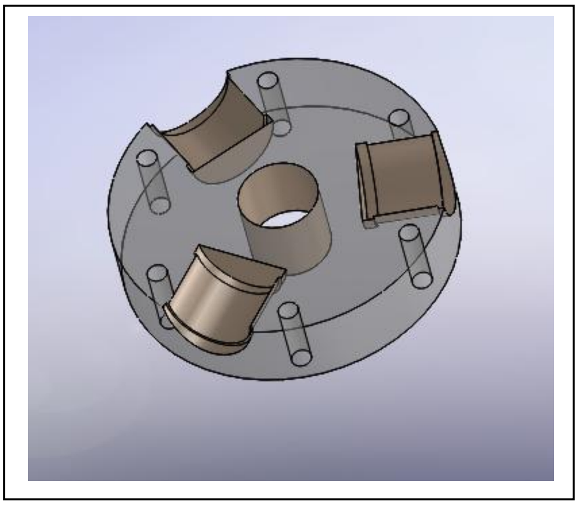


Fig 5.2- Solid work model

Fig 5.3 - Machined component

The hub acts as the mounting platform for the rotors to the drive shaft. The hub was designed using clamping force as the method for constraining the individual rotors in their desired position. The part was machined from a solid ø220 mm nylon block, due to the materials relatively light weight and availability at the time of manufacture. The components were first parted off (front and back of hub) then mounted on a spigot where the outside diameter was machined down to its finished size. The spigot with the hub still attached was then mounted to a horizontal axis dividing head where the cylindrical profile was bored into its periphery at 120 degree intervals. The 6 x ø 10.5 mm holes were then drilled through the entirety of the hub to accommodate the 6 x M10 bolts responsible for providing the clamping force to the assembly.

The gearing system and machine elements

Typically a large energy producing wind turbine's rotor speed is 25-50 rpm, this varies however depending on the size of the turbine. Induction generators for application in wind energy converters operate at speeds of 750-3600 rpm. A gearing system needs to be employed to provide the required rotational speed to the rotor of the induction generator for effective energy conversion to take place.

The type of gearing system and configuration depends upon the selected induction motors synchronous speed. The lower the synchronous speed the better, as this will require a lower gearing ratio and will consequently result in a lower input torque requirement. In gearing reduction systems there is a high speed input with a low speed high torque output. As we are reversing the cycle and gearing-up to achieve higher rotational speeds, torque will be the primary factor that will attribute to the effective functionality of the gearing system. The drive train of a wind turbine consist of a combination of various machine elements that act as a mechanical power transmitter to the generator. This section presents a brief overview of the various machine elements that constitute the drive train of the wind turbine and outlines their function in the mechanical system.

Shafts

Shafts are cylindrical components designed to rotate and transmit torque between machine elements. Shafts are present in various sections of the wind turbine structure and mechanical drive train. The hub of the turbine rotates about the rotor shaft which transmits torque to the gearbox. There are several shafts in the gearbox that carry different sized gears for the purpose of increasing the rotational speed that is transmitted to the generator in which another shaft operates. This shaft is the rotor of the induction generator and its rotation is directly responsible for producing the rated electrical output power. All mentioned shafts are under constantly under torsional loading and fatigue stresses must be taken into consideration during the design process for this machine element. Due to the nature of the rotation of the shafts they have resonant natural frequencies at 'critical speeds' and operation near these speeds should be avoided to prevent excessive vibration. Shaft material varies depending upon the shafts application and loading but in general shafts are made of a high tensile steel such as 4140 and then heat treated and surface hardened to ensure the shafts mechanical integrity.

Bearings

Bearings are mechanical components designed to reduce the friction between two components in relative motion to one another, generally in rotation. Bearings come in a wide variety varying in design depending upon the relative direction and magnitude of loading. The majority if bearings in use in a wind turbine can be found acting upon the various shafts in the gearbox and drive train. Bearings for high speed applications such as this are generally ball bearings, roller bearings or tapered roller bearings and are designed to accommodate for radial loads and also approximately 30% axial loading. There are however other types of bearing in use in the machine such as the axial thrust bearing which supports the nacelle and its rotation about the turbine tower. Axial thrust bearings allow for low speed rotation under high axial loading conditions.

Bearings reduce friction between two elements in relative motion by reducing the contact area between the two surfaces. For example a ball bearing consists of a number of polished hardened steel spheres (balls) that rotate between an inner and outer race on each of which is a groove that directs and constrains the balls motion to two dimensional rotation. The balls are spaced evenly by a metal cage which ensures they do not come into contact and impede each other’s motion.

Couplings

Couplings are machine elements designed to connect two shafts together for the purpose of transmitting torque between them. Couplings are used in wind turbines to connect the rotor shaft to the gearboxes input shaft and again to connect the gearbox’s output shaft to the generator rotor. Couplings come in various designs: Bolted flanged couplings, keyed sleeve couplings, Dampened flexible couplings, clutch couplings and splined couplings to name a few. The coupling of choice depends upon the loading and upon the nature of torque transmission; constant, varying, shock loading etc...

Springs

Springs have various applications in wind turbines particularly in passively actuated systems such as spring applied brakes, return springs for blade pitch linkages, teeter dampers or as bumpers in coupling mechanisms. Springs act as tension springs, compressions springs or torsion springs and attain their name from their natural tendency to return to their initial state when force acts upon them. This tendency is due to the nature of the spring material. Generally spring wire is used and coiled into a helical form to attain the desired shape and spring coefficient for its application.

Clutch and braking mechanism

Clutches are torque transmission mechanisms that are activation dependant. Clutches are therefore optional mechanisms that activate certain functions of a machine. One of the more common types of clutching mechanisms is the pad clutch. This type of clutch operates by initiating contact between a rotating surface and the clutch’s pads. The pads are typically made from a material with a relatively high surface friction coefficient and temperature resistant properties. The high levels of friction between the two surfaces cause the two elements to link and cause the clutch side to adopt the drive side's behaviour of motion. For example: A clutch may be used in a wind turbine to activate a blade pitching mechanism when the rotational velocity of the turbine reaches a certain speed. The clutch then engages and activates the blade pitching mechanism causing the turbine to continue under safe operating conditions. Clutches are typically applied via spring pressure and in wind turbines are generally activated by an electromechanical mechanism: eg. Excessive speed recorded by shaft rotation sensor triggering a solenoid and engaging the clutch.

Brakes are also used in wind turbines to regulate the rotational speed of the turbine. These can be in the form of mechanical friction brakes or even drag brakes located at the tip of the rotor blade. Mechanical blades are activated by a clutch and apply a force restricting the speed of the rotor shaft. Drag brakes are generally in the form of flat plates that are adjusted in a manner that increases the drag force on the rotor blade reducing the rotational speed of the turbine.

The gear box

The expected operating speed of the rotor system at its rated wind speed of 12m/s is approximately 180 rpm. The generator being used has a rated running speed of 1000 rpm. Therefore a speed increase gear box was designed to provide the generator with its rated running speed.

Gears are defined as toothed members that transmit rotary motion from one shaft to another. Among the various methods of power transmission, namely gears, belts and chains, gears are the most rugged and durable. Gears have a transmission efficiency of around 98% and do not suffer from any slippage like belt transmissions. Gears however are usually the more costly option out of the above mentioned transmission mechanisms. This is due to the material cost, the relatively large machining cycle time and also the machining tolerances that need to be adhered to ensuring the effective function and power transmission capability.

The basic requirement of gear tooth geometry is that the angular velocity ratios provided at all points of the toothed circumference are exactly equal. A deviation from the ratio will lead to mechanical interference, a failure to mesh, which ultimately leads to increased wear and catastrophic failure. The geometry of a gear tooth is described on a modular basis derived from the relative size and configuration of the involutes used in constructing the gear tooth profile.

The module of a gear is defined as the pitch circle diameter in millimetres divided by the number of teeth. (number of millimetres of pitch diameter per tooth)

The gear box was designed to increase the speed of rotation from around 180 rpm to around 1000 rpm. It was understood that the input to the gearbox would not always be 180 rpm, hence the output would not always be exactly 1000. However based on the expected rated speed, the decision was made to create a 1:6 geared speed up box.

Gear box components:

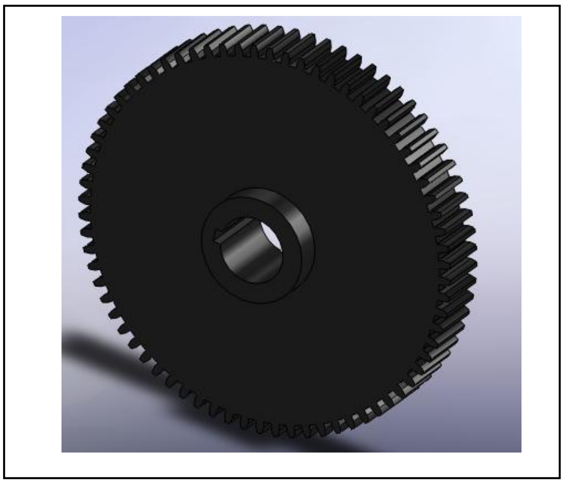


Fig 5.4- 72 tooth spur gear

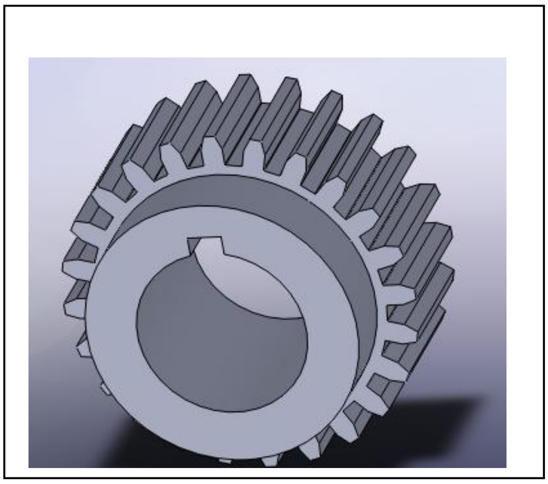


Fig 5.5- 24 tooth spur gear

The gears chosen were two different sized module 2 gears. The gearing ratio between the two gears is 1:3, meaning 1 revolution of the large 72 tooth gear rotated the small 24 tooth gear 3 times. The gears were designed with an internal diameter of 25.0 mm to consequently run on 25.0mm diameter parallel shafts. A 6 mm key way is incorporated to mechanically transmit the rotation to the shaft and lock the gears in their relative positions on the shaft. The gear material is 4140, a high tensile heat treatable steal. Once the gears are machined to their finished tolerances, the gears are through hardened, a heat treating process that ensures the gear has uniform harness throughout its entirety. After through hardening, nitriding, a surface hardening technique, is employed to increase the components surface hardness and resistance to wear.

The gearbox housing is just as important as the gears itself and in this design emphasis is placed on the tolerances of the geometry specified in the manufacturing drawings. The gearbox not only encapsulates the gearing system, protecting it from debris that will contaminate the lubricant, but it also is the frame work to which the bearings are mounted. The bearing centres are a critical factor in the gearbox design. Miss-alignment of the bearing centres greatly affects the efficiency of the gearbox and will also cause premature failure of the bearings themselves. Not only will miss-alignment create uneven loading on the bearings but it will consequently effect the meshing of the gears on the transmission shaft. The spur gears are designed to contact at one point only during operation. Miss-alignment would cause the point of contact to be on a particular point on the gear tooth rather than being distributed over the width of the tooth. This would cause uneven wearing and if it became severe enough cause tooth failure. Tooth failure ultimately results in further failures as the broken off pieces of metal interfere with the meshing of the gears and result in jamming or tooth fracture.

To ensure that miss-alignment is minimised, a tolerance of ±0.01 mm is adopted on all the components that constitute the gear box housing.

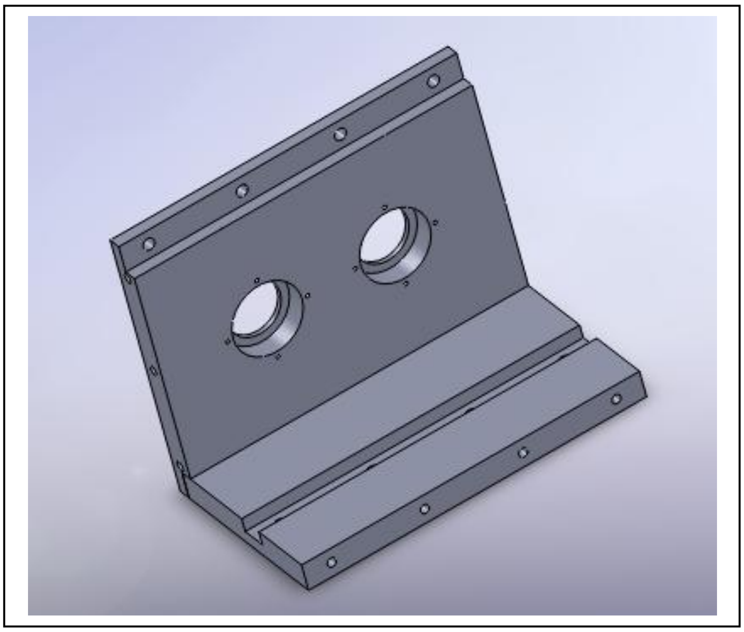


Fig 5.6

In the initial stages of prototyping the gear box housing will consist of a number of flat aluminium plates that are assembled in a way that creates a housing complete with the required bearing housings machined into the appropriate plates. The plates will be machined from solid aluminium incorporating the bearing housing, the threaded holes that act as the anchoring for the bearing retainers and the threaded holes and shoulders that will act as the assembly reference points for the complete box assembly. Aluminium has a high strength to weight ratio and is weather resistant therefore making it a suitable selection for the gearbox housing. If the design goes to a production stage the gearbox housing will be redesigned to a cast design, reducing the overall production cost of the unit.

The bearing retainer is a component that locates the bearing axially and prevents it from sliding out of the bearing housing. Bearings housings are generally machined to the same size as the bearing outer diameter, sometimes even to a slight interference fit. If the interference is too great then it will ultimately affect the bearings life due to the preloading on the bearing. A size on size fit generally ensures that the bearing is held adequately without it sliding in and out of the housing. However to ensure that this does not occur, the bearing retainers will be incorporated. Bearing retainers are generally in the form of circlips, however this design will incorporate a nylon washer that is fastened on the outer surface of the bearing housing which also acts as a seal.

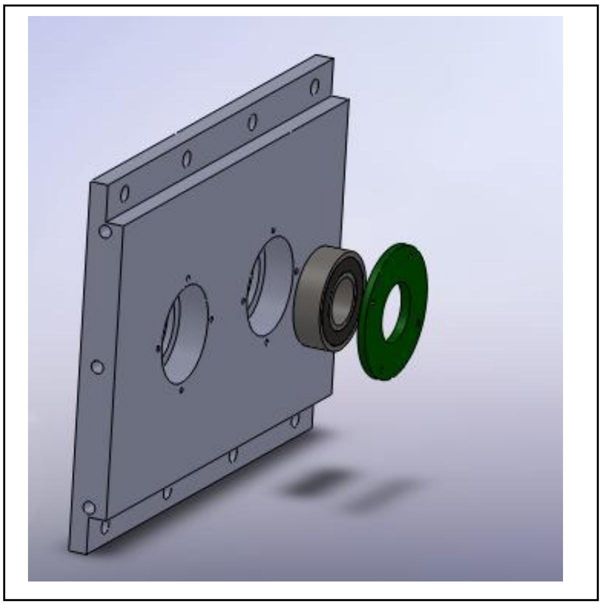


Fig 5.7- bearing and retaining plate/seal

Centrifugal breaking system

The centrifugal breaking system is the speed control mechanism for the rotor and drive train. The rated speed of the turbine rotor is 180 rpm which results in a revolution speed of 1080 rpm at the generator rotor. It is expected that the losses associated with the gearing and the loading of the generator will rarely see the generator speed exceeding 1000 rpm, however the break is there to ensure the rotor does not exceed its rated speed and fall subject to catastrophic failure.

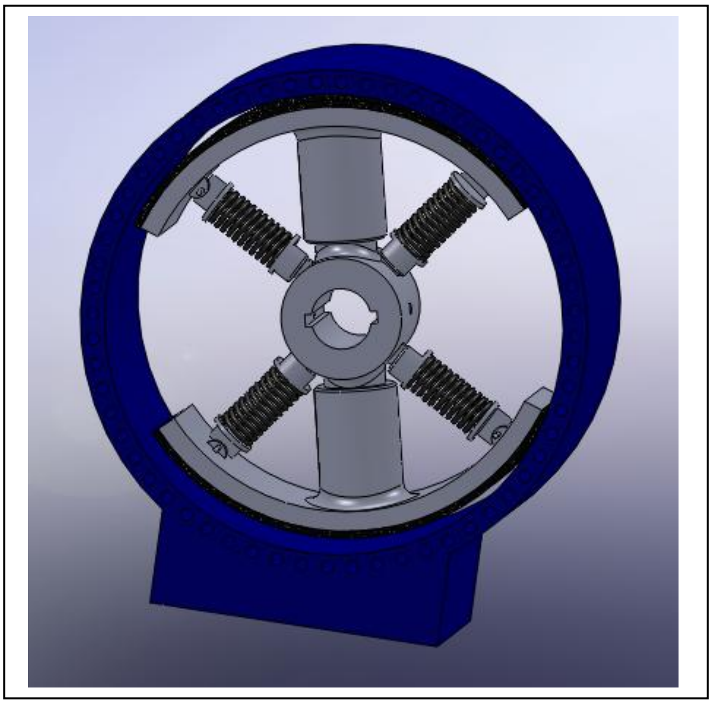


Fig 5.8 - Centrifugal breaking system

The breaking system operates between the gearbox and the generator on the output shaft of the gearbox. At a stationary position the brake pads are positioned 5mm from the break housing, radialy. Holding the brake shoes in position are four tension springs. When the unit begins rotating the centrifugal force that exists due to the mass of the brake shoes puts the springs in tension. As the revolution speed increases so too does the tension in the springs. The Break shoes are free to slide in and out from the central hub being restricted only by the tension springs. The unit has been designed so that when a revolution speed of 1000 rpm is reached the brake shoes will make contact with the brake housing causing frictional contact and essentially maintaining the speed of the output shaft at 1000 rpm.

The friction during breaking causes the break housing to heat up. To counter the heating effect and effectively dump the heat energy, the nacelle cover was designed to incorporate air intakes that direct the flow of the oncoming air directly to the break drum. The forced convection cycle will remove the heat from the drum and dump it through the mesh enclosure plate at the tail of the turbine.

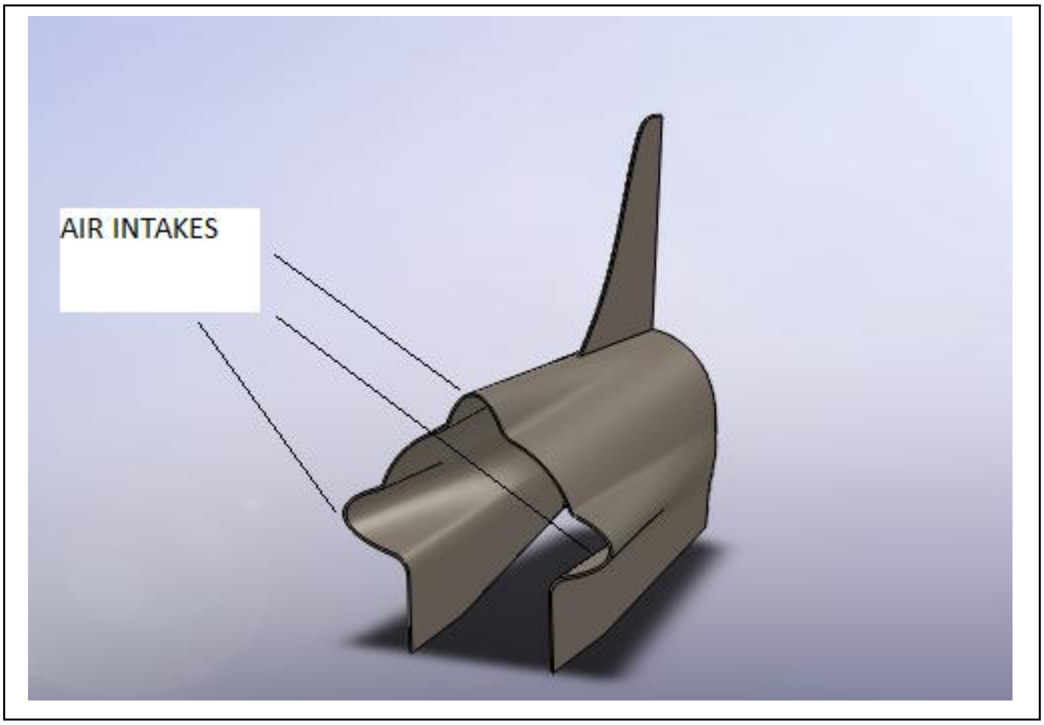


Fig 5.9 - Nacelle cover with air intakes for effective cooling of breaking system

The nacelle cover is a fibre glass enclosure, moulded using biaxial mesh cloth. Biaxial mesh cloth provides strength in two directions and is a common material used in the reinforcing of surf boards. Incorporated into the nacelle housing is the tail of the turbine. The tail or fin is responsible for controlling the yawing of the nacelle. Yawing is the turbines ability to adjust to direction of oncoming wind and position the rotor directly in its path. The cover is bolted directly to the gearbox housing giving it a rigid fixation to the chassis of the turbine.

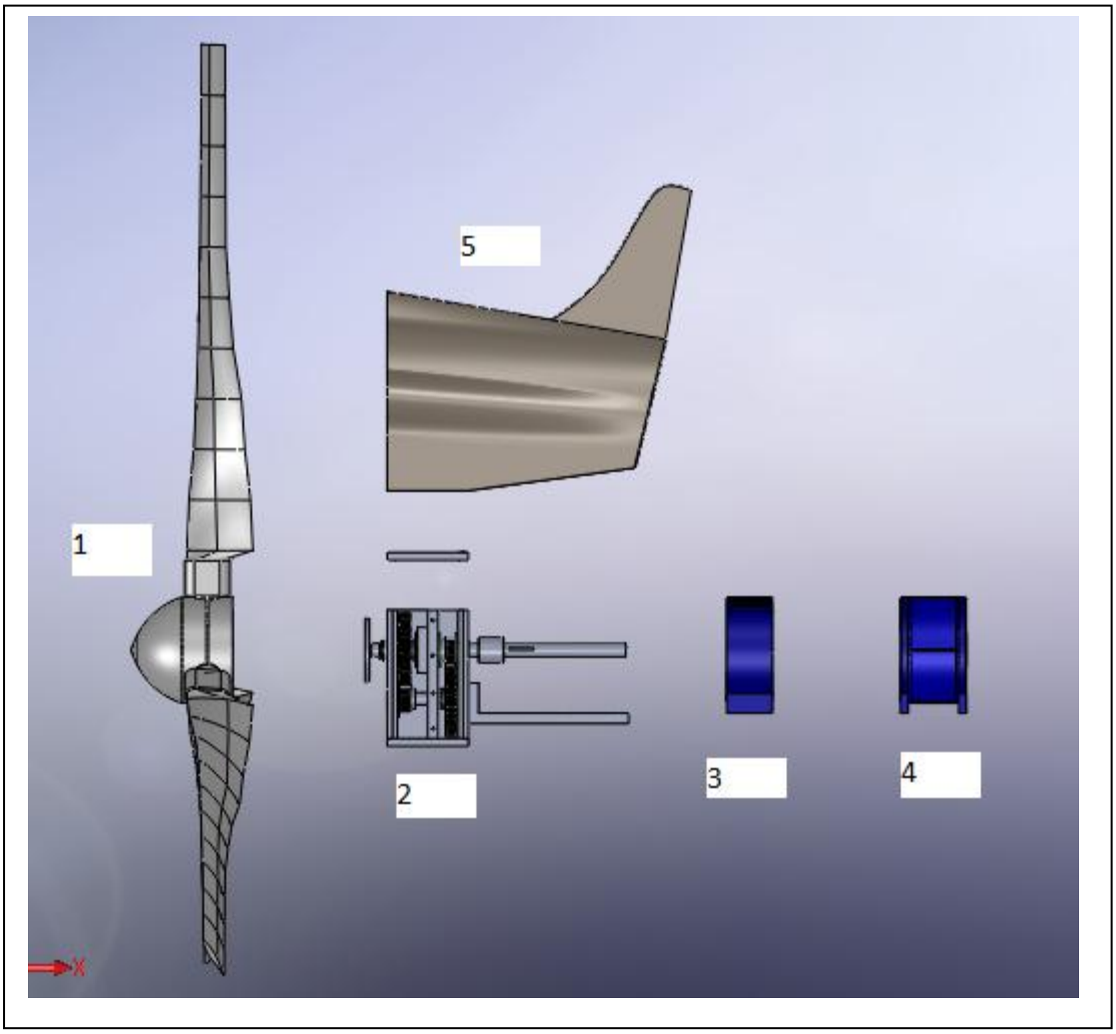


Fig 5.10- Nacelle and mechanical subsystems

1. Rotor system- primary fluid-kinetic to mechanical converter
2. 1:6 speed up gear box and drive train
3. Centrifugal over-speed controller
4. Induction generator
5. Nacelle cover

Tower

Due to the relatively small size of the turbine, it is able to be mounted on various existing structures such as roof tops, rain water tanks and observation platforms. The purpose of the tower is to provide the blades clearance from the ground and to position the turbine in an uninterrupted stream tube.

Small scale turbines are generally mounted on structural towers much like those used for water pumping wind mills as they can be assembled from the ground up and are relatively cheap. The downside to this sort of tower however is its aesthetic appeal. Large scale energy producing turbines are generally placed on large tapered concrete or steel pillars. The pillars are much more optically satisfying and in the author's opinion will play a large role in marketing the design and distributing it throughout the community.

The tower used in this particular design is a tapered coated steel tower attached to the ground by a flange plate which anchors it to its concrete foundation. The tower provides protection for the electrical transmission lines from the generator to the inverter at ground level by passing the wiring through the tower's core.

It was chosen to create a tower that could be mounted into a foundation rather than onto an existing structure. Designing a tower that mounted onto an existing platform would be subject to the design of the platform and would be completely situation dependant.

The tower material was chosen as coated mild steel due to the materials availability and relatively low price. The preferred material however is a fibre composite material with a high strength to weight ratio and resistance to harmful climatic effects.

Fig 5.11- Turbine tower

The tower pole will be mechanically fastened to its concrete foundation using a series of 16 M20 studs that protrude from the foundation.

The tower is designed using coated mild steel as it is relatively inexpensive compared to other grades of steel, its coating makes it weather resistant and it posses the mechanical properties to support the turbine even under extreme loading conditions.

It was hoped to design the tower using a fibre composite making it completely corrosion resistant, non-conducting and much easier to erect due to its light weight properties. Included in the appendices are material property recommendations that should be adhered to if selecting a fibre composite material to manufacture the tower.

Footings and foundation

The design and recommendations made for the foundation and footings of the turbine are based upon the principles of foundation and shaft design specified in *Das 2007.* The design for the turbine foundation is for a broad spectrum of soil and terrain types and was chosen due to its simplicity and adequacy for the turbine and tower design.

Firstly the shaft (hole in which foundation is poured) is drilled rather than piled. Drilled shafts are formed by excavation or by the use of an auger to remove soil from the ground and form the shaft cavity. Pile foundations are used for relatively deep foundation applications where steel members are driven into the soil anchoring the foundation to the earth. The drilled shaft foundation was chosen because it exhibits many advantages for this particular application, namely:

- Single shaft may be used as opposed to a group of piles and a pile cap
- Constructing drilled shafts in deposits of dense sand and gravel is easier than driving piles
- Because the base of the drilled shaft can be enlarged it provides greater resistance to the uplifting load.
- More economical than using pile driving equipment
- Provide high resistance to lateral loads.

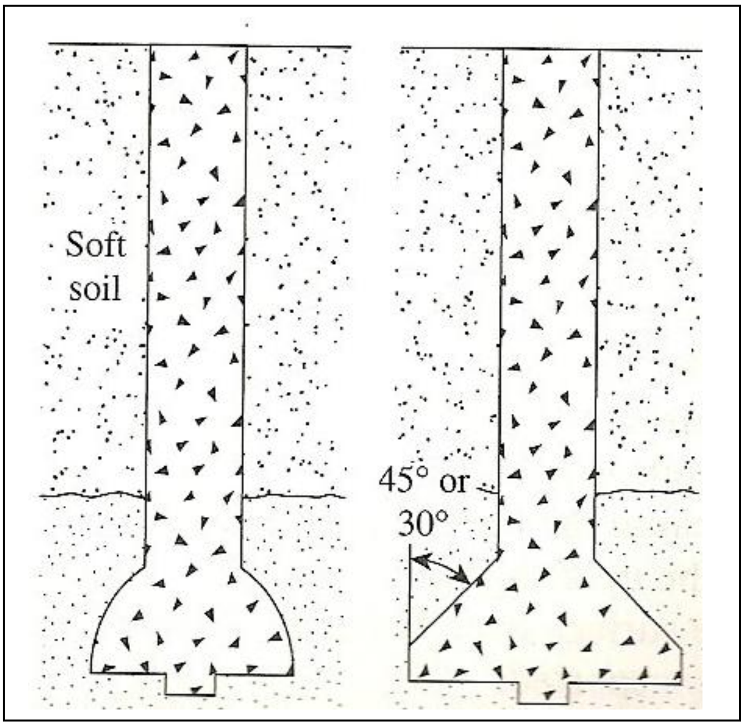


Fig 5.12 -Drilled shaft foundation with bell bottom, P592, Das 2007

The foundation is a concrete/ aggregate mixture with a 30° bell bottom to increase the resistance to lateral force and uplift. The shaft diameter is 700mm and contains steel reinforcing and a steel ring to which the M20 anchor studs are welded to. This provides an anchoring point for the tower.

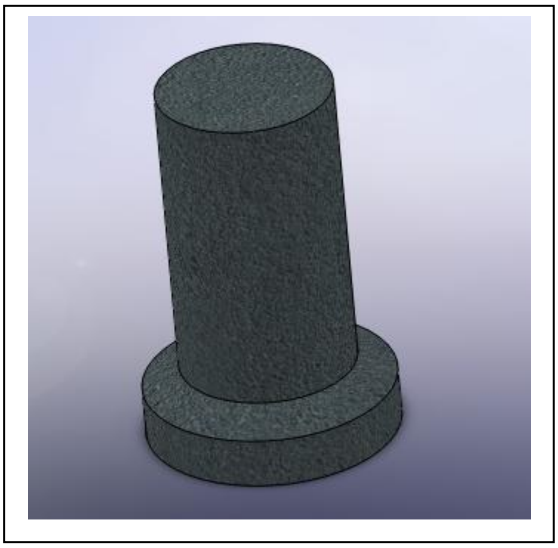


Fig 5.13 -Concrete foundation

Fig 5.14- Steel reinforcing and anchor studs

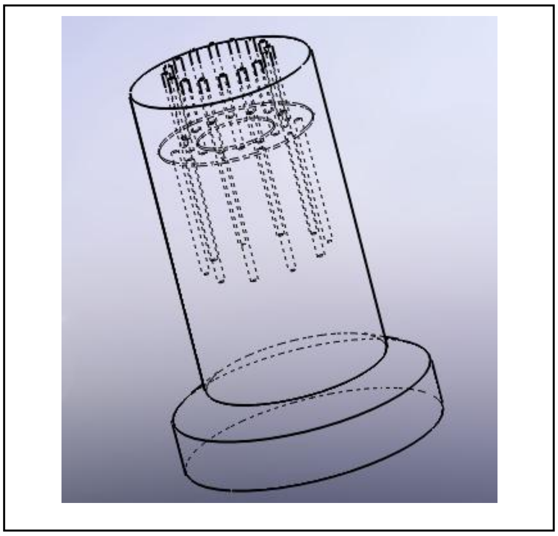


Fig 5.15- Foundation with reinforcement

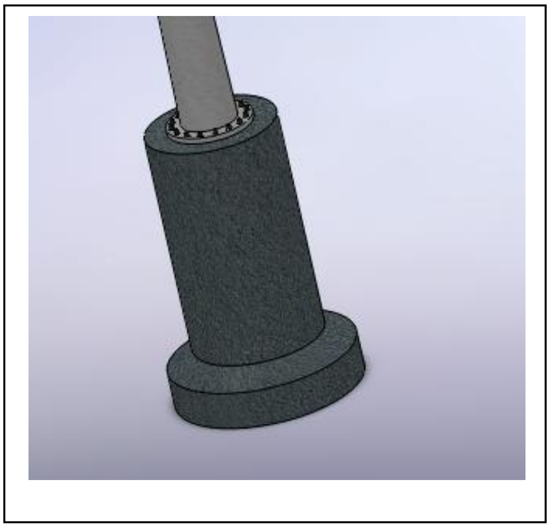


Fig 5.16- Foundation + Tower

The foundation type may vary due to location. The drilled circular shaft with a bell bottom undercut is a simple and effective foundation for structures such as a small wind turbine.

5.2 Carved timber blades

One of the focal points of the project was to design the turbine with an effective post life recycling scheme in mind. Common production turbine blade materials are fibre glass and carbon fibre, both of which are not easily recycled or disposed of after a component has reached its useful life. In addition they require an expensive and poisonous resin and catalyst mixture to maintain the blade's desired shape.

Timber has been a material that has been quite frequently used in turbine blade manufacture. Timber is a natural material that is relatively easy to shape and handle and is completely recyclable. Various timber species have been trialled in turbine blade applications and have shown promising results.

Timber for high efficiency small wind turbine blades (Peterson P.; Clausen P.D. 2004) Investigated the operation of two different 1 m long soft wood species machined turbine blades under 20m/s wind speed . The two timber species used were radiata pine and hoop pine, both of which are commonly found on the market in Australia. The results gathered from fatigue testing showed that hoop pine was 25% stronger and 6% more fatigue resisting than the radiata pine. It also predicted unlimited fatigue resistance for the hoop pine blade at its tested design wind speed of 20 m/s.

Timber was therefore found to be a cheap and effective material for use in wind turbine rotor systems.

The particular timber species used in the prototype rotor system was Neuguinea rose wood, a hard wood sourced from Papua Neuguinea due to its high decay resistance and workability. Neuguinea rose is categorised as a class one timber; a timber of the highest natural durability which may be expected to resist both decay and termite attack for at least 25 years.

The timber was selected on referral by two master timber craftsmen, Mr. Harry Ward, and Mr. David Linton. The timber exhibits variable grain structure making it easy to shape and sand. It also is known for its strength and flexibility.

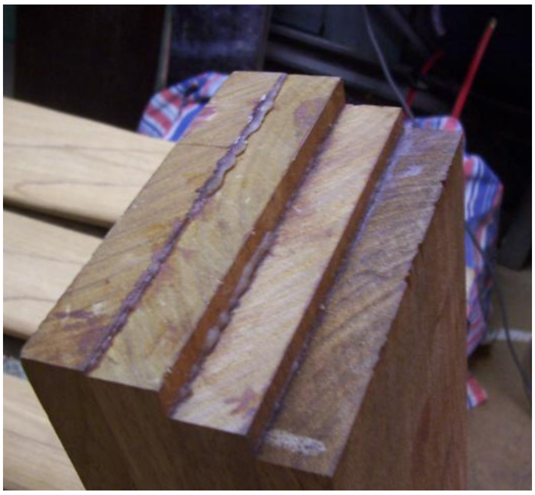


Fig 5.17- Laminated New guinea Rose wood

Fig 5.18- Carved timber blades (bottom)

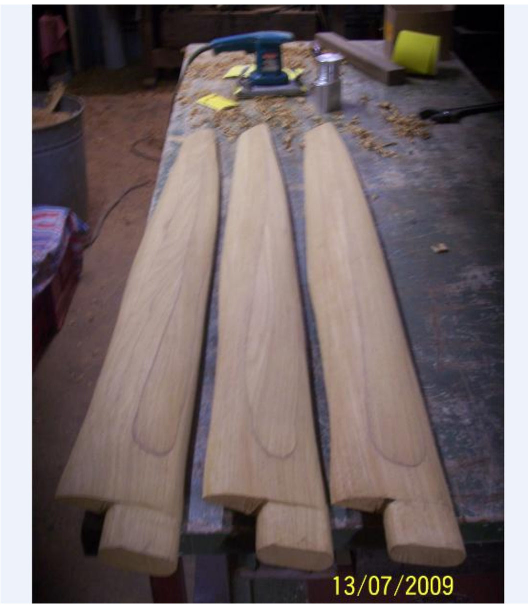


Fig 5.19- Carved timber blades (top)

Load estimates were taken on each blade at its maximum extreme operating conditions to ensure the blades mechanical integrity under expected operational loading.

The material properties were taken as those of oak, a timber of similar characteristics.

Density: 750 kg / m^3

Modulus of rupture: 180 Mpa

Modulus of elasticity: 19.7 Gpa

The blade was modelled as a 25 x 150 x 1250 mm board, constrained at one end (representing the hub) with a uniformly distributed load acting upon its 150mm x 1250 face. In general operation the blade is not subject to the full loading as experienced in this model due to the variance in the twist angle of the blade. It was chosen to determine an extreme scenario to ensure the blade was of a sufficient standard.

Drag force calculation $F_D = C_D\, 0.5\, \rho U^2 A$

$$C_D = 2.05\ (\, drag\ coefficient - table\ 9.3\ (Fox, McDonald, Pritchard 2003)$$

$$\rho = 1.21\ (air\ at\ 20°\ C)\ \ , U = velocity\ , A = Surface\ area$$

$$F_D = 2.05 * 0.5 * 1.21 * 20^2 * 0.1875$$

$$F_D = 93\ N$$

The blade was modelled as a cantilever with one end fully constrained and a uniformly distributed load of 93 N applied on its upper surface.

$$I = \frac{bh^3}{12} \quad = \quad 150 * \frac{25^3}{12} = 195312.5$$

$$Z = \frac{bh^2}{6} \quad = 150 * \frac{25^2}{12} \quad = 15625$$

$$Max\ deflection = \frac{WL^4}{8EI}$$

$$Max\ deflection = \frac{93 * 1250^4}{8 * 19.7\ x10^9 * 195312.5}$$

$$Max\ deflection = 0.00737\ m$$

$$Stress\ at\ support = \frac{WL}{2Z}$$

$$Stress\ at\ support = \frac{93 * 1250}{2 * 15625}$$

$$Stress\ at\ support = 3.72\ Mpa$$

The stress experienced at the blade root is 3.72 Mpa. The modulus of rupture for the material is 180 Mpa , therefore the blade will easily withstand the loading being applied to it by 20 m/s wind speeds.

Twist and chord distribution for a Betz optimum blade

r/R	Chord, m	Twist angle (deg.)	Angle of Rel. Wind (deg.)	Section pitch (deg.)
0.1	1.375	38.2	43.6	36.6
0.2	0.858	20	25.5	18.5
0.3	0.604	12.2	17.6	10.6
0.4	0.462	8	13.4	6.4
0.5	0.373	5.3	10.8	3.8
0.6	0.313	3.6	9	2
0.7	0.269	2.3	7.7	0.7
0.8	0.236	1.3	6.8	-0.2
0.9	0.21	0.6	6	-1
1	0.189	0	5.4	-1.6

Table 5.1 -Blade twist and chord distribution used for shaping timber blades (McGowan, Rodgers, 2003)

Blade shaping by the material removal process of carving and sanding is a relatively slow and imprecise method of production unless a computer numerical controlled production mill is used. Using a solid CAD model of the blade as a basis for computer aided machining, intricate shapes can be produced accurately with infinite reproducibility.

The prototype wood blades were hand shaped and relied on detailed drawings, tables and stencils to accurately produce an acceptable blade shape. The chosen NACA4412 aerofoil cross section was drawn on paper; both a root profile and a tip profile (variance in chord length and thickness). The stencil was then projected onto the laminated timber blank and used as a basis for shaping the blade profile. The stencil for the tip of the blade was adjusted to the maximum angle of twist of 38.2° at the opposing end of the blank.

The shaping process was an operation that involved constant reviewing of the twist and chord distribution table (Table 5.1), comparison with stencils and cross sectional thickness measurement. To be dynamically balanced the blades needed to be of the same geometry and have the same mass distribution. Being unbalanced would cause excessive bearing loading and vibration which would accelerate the failure of the system. During the shaping process the blades were shaped to within 70g mass difference. To counter act the effects of dynamic unbalance, counter weight s were glued into the ends of the blades to ensure an even weight distribution.

CHAPTER 6

EXPECTED TURBINE PERFORMANCE

6.1 Expected turbine performance

This section details the expected rotor, drive train and generator efficiency based on the control volume, linear momentum and energy equations as well as some of the results gathered during the testing of the rotor system.

As previously discussed in chapter 2, the power coefficient of the rotor system can be derived using the interference coefficient :

$$a = \frac{u_0 - u_1}{u_0}$$

The interference coefficient is the measure of the rotors effectiveness at absorbing the energy within the stream tube. To attain the interference factor of the turbine the velocity of the speed upwind and downwind of the rotor system must be attained at a given point in time.

For the turbine to effectively absorb the maximum amount of energy from the stream tube, no air must pass through the disc created by the rotor system without being deflected by the blades. If a volume of air passes through the area swept by the blades without being deflected, then the amount of energy extracted by the turbine would be zero.

From the equation relating the interference factor to the power coefficient:

$$C_p = 4a(1-a)^2$$

The power coefficient C_p is found to be at a theoretical maximum of 0.593 when the interference factor a is equal to 1/3.

The overall performance of the turbine can be characterised by the degree of variation in the three main indicators – power, torque and thrust – at a range of different wind speeds. Normally the performance of the turbine is expressed in non-dimensional graphs from which any turbine's performance can be estimated, regardless of its operational situation; constant rotation, variable rotor speed etc. Most commonly the power coefficient C_p, thrust coefficient C_T and the torque coefficient C_q are listed as a function of the tip speed ratio λ.

The tip speed ratio is described as the ratio of the tip speed of the turbine rotor to the speed of the oncoming wind.

The Cp: λ performance curve for a three bladed horizontal axis wind turbine.

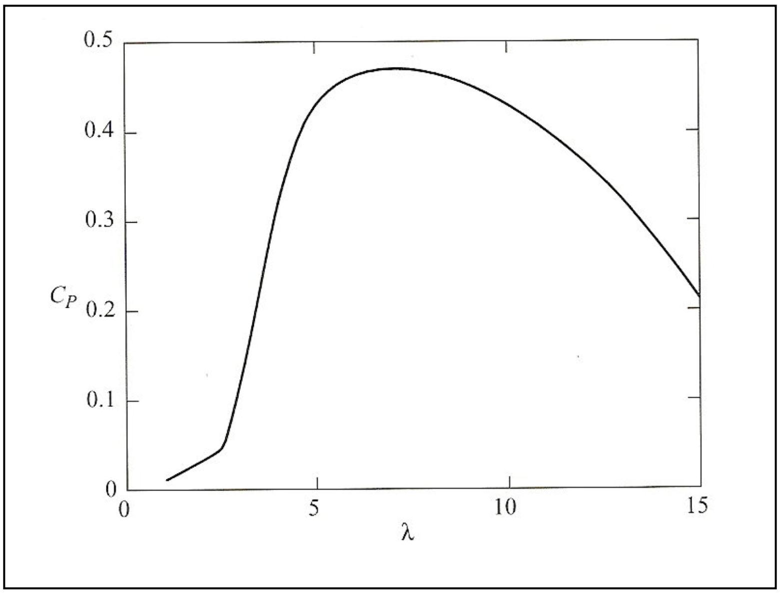


Fig 6.1- performance curve for a horizontal axis 3 bladed turbine (P174,Burton, 2001)

Figure 6.1 shows the achievable power coefficient at varying tip speed ratio's. The maximum attainable power coefficient is 0.47. This factors in the aerodynamic tip losses due to stall and drag. Figure 6.1 shows the power curves for a rotor with no losses at all, all losses included and no drag or stall losses. The Betz limit of 0.593 is achieved when there are no losses at all at a tip speed ratio of 7. However in reality there will always be losses due to the imperfections arising from design and manufacture.

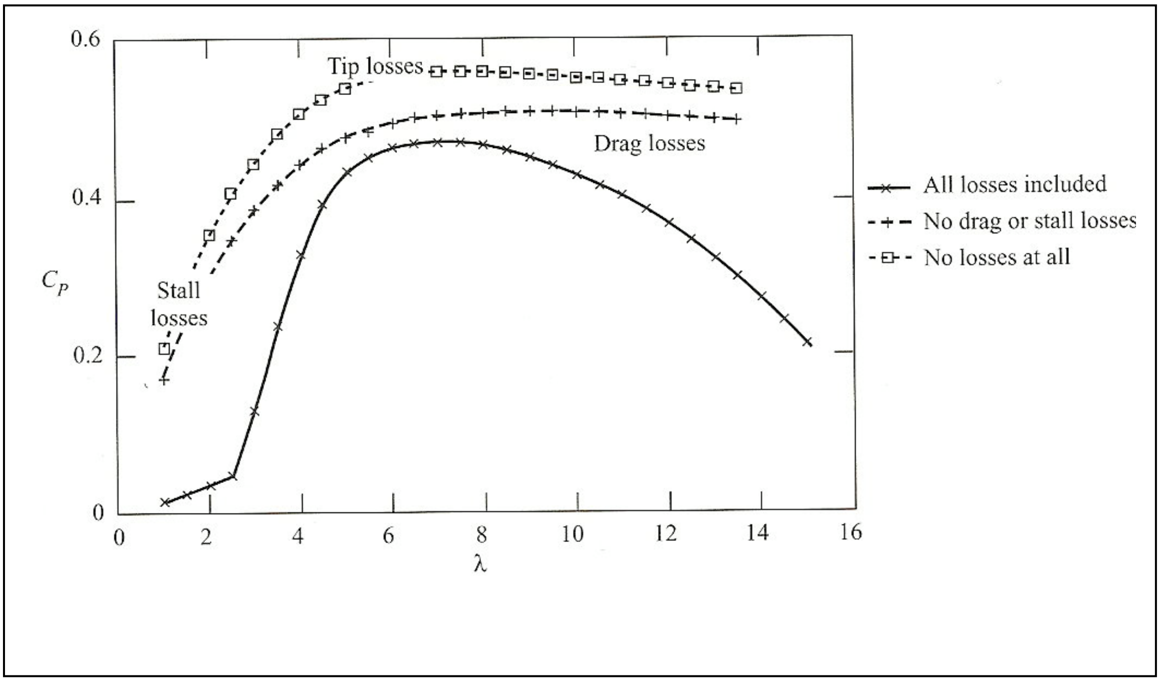


Fig 6.2 -Cp: λ performance curve showing losses. (P174,Burton, 2001)

Another parameter affecting the performance of the wind turbine is solidity. Solidity is defined as the area of the blades divided by the swept area of the blades.

Solidity can be increased by increasing the number of blades in the rotor system. It can also be changed by increasing the chord length of the aerofoil.

Figure 6.3 depicts the effects of solidity on the power coefficient of the turbine.

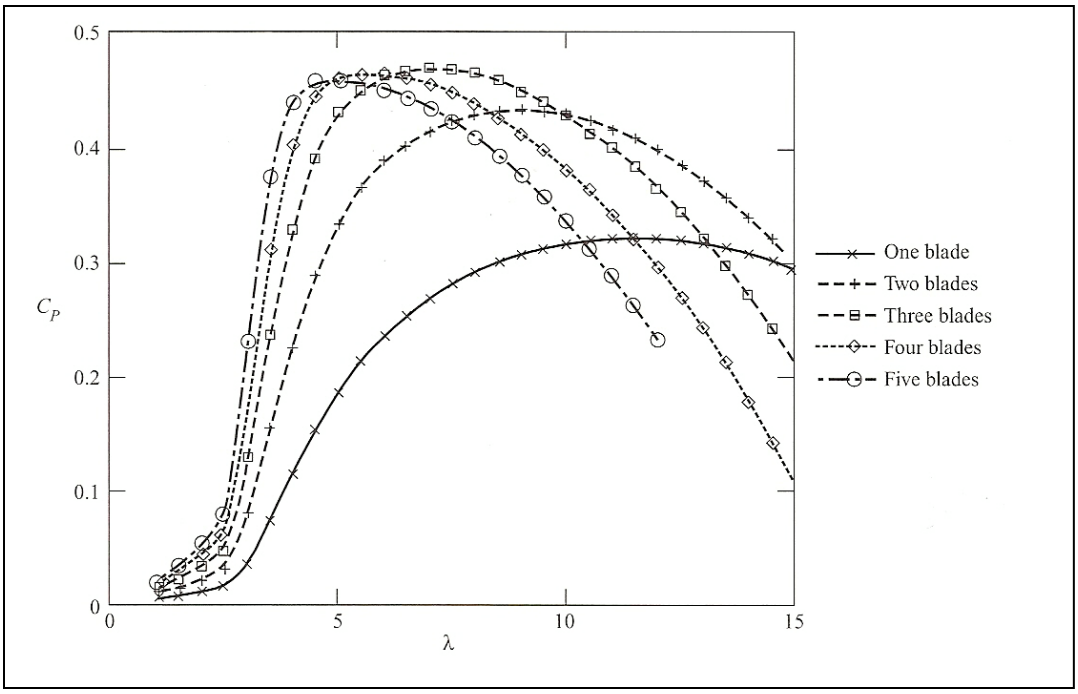


Fig 6.3 - Effect of solidity on power coefficient (P175,Burton, 2001)

Low solidity causes a low flat curve which means that the power coefficient does not vary much with increasing the tip speed ratio.

High solidity creates a sharp peak at low to medium tip speed ratios meaning the turbine is very sensitive to changes in the tip speed ratio.

From (Burton, 2001), it seems the optimum solidity is achieved with 3 blades as the power coefficient remains stable for an increase of 4 of the tip speed ratio after achieving its peek value.

The two turbines that require a high solidity are mechanical turbines used for water pumping and very small turbines used for electric battery charging. Both of these turbines require a high start up torque which is attainable only with a high solidity. It also allows small amounts of power to be produced even at low wind speeds which is also beneficial for battery charging applications.

The torque coefficient C_Q is not useful for assessing the performance of the turbine, it is simply used for determining the type of gearbox that is used in the mechanical transmission system. The torque coefficient is determined by dividing the power coefficient C_P by the tip speed ratio λ.

For electrical power generating turbines, low torque coefficients are favourable as high rotational speed is the primary focus. However for turbine requiring a high start up torque, a higher torque coefficient is favourable. A higher torque coefficient is favourable for this particular design as it is a geared system that is used primarily for battery charging. Its high torque coefficient allows it to generate electricity even at low wind speeds. At low wind speeds the generator will “trickle” charge the battery whilst at high speeds it will produce a constant, useful supply of energy. Due to the nature of the shunt regulator being used in the charging circuit, once the battery bank is fully charged the excess energy is supplied to a hot water system or another existing dump load.

Expected performance of design

The rotor prototype was taken to a location in Toowoomba on a day for testing to determine the tip speed ratio at the particular wind speed on that day. Due to the lack of an adequate anemometer on the day of the trial, the average wind speed from the bureau of meteorology was used.

The average wind speed was 6m/s, however there were gusts that exceeded this value and also times where the wind speed approached zero. Therefore an average rotational speed was recorded over the period of 5 minutes. This was measured at an average value of approximately 120 rpm.

Comparing the average wind speed to the average rotational velocity the tip speed ratio was determined to be:

$$\lambda = 2.618$$

The solidity of the rotor is:

$$s = \frac{blade\ area}{swept\ area}$$

$$s = \frac{3*1.25*0.13}{\pi*1.25^2}$$

$$s = 0.099 \quad \text{(high solidity)}$$

The high solidity of the rotor would result in a relatively high torque coefficient. A typical value for a three bladed turbine as taken from (P174, Burton, 2001) is around 0.035. This results in a torque coefficient of around 0.08 at a tip speed ratio of 3, which is within relative proximity to the tip speed ratio achieved during the trial.

Taking the high solidity into account, a theoretical torque coefficient can be approximated.

Assumed torque coefficient $C_Q = 0.1$

Using the equation fort the torque produced by the turbine:

$$T = C_Q * (0.5 * \ \rho * A_1 * u_0^2 * R)$$

$$T = 0.1 * (133.64)$$

$$T = 13.364 \ Nm \quad (@\, 6\frac{m}{s} \ wind)$$

The turbine power can be determined at the tested wind speed can be determined by:

$$P_T = T\omega$$

$$P_T = 13.364 * 12.5664$$

$$P_T = 167.94\, W \quad (@\, 6\frac{m}{s} wind\ )$$

The power contained in the stream tube is calculated using:

$$P_0 = 0.5\rho A_1 u_0^3$$

$$P_0 = 641.47\ W$$

The power coefficient at this speed is then determined by dividing the converted power by the power in the stream tube:

$$C_P = \frac{P_T}{P_0}$$

$$C_P = 0.262$$

The interference factor for the tested operating condition is determined using:

$$C_P = 4a(1-a)^2$$

$$a = 0.08$$

The maximum power coefficient is achieved when the interference factor is equal to 0.5.

Under the testing conditions on the particular day of the trial the turbine operated at a wind speed of 6m/s and achieved a power factor of 0.262. The power produced was 167 W, which is not enough to drive the generator to produce full power however it is expected that when the wind speed reaches 9 m/s, the generator will produce its maximum potential energy.

CHAPTER 7

CONCLUSION

Conclusion

Small scale wind energy conversion systems are an effective, environmentally friendly power source for household and other applications. Although they are subject to climatic behaviour and do not always deliver a constant supply of energy, they can be adapted to energy storage units that allow the selective distribution of the energy once it has been converted.

All modern wind turbines use lift force to create rotational motion in order to drive their gearbox and generator. For electrical energy generation high rotor speeds are favourable as they reduce the gearbox ratio required to achieve the generator's optimum operating speed. Low solidity rotors ensure high rotational speeds are generated, however a rotor must also produce enough torque to overcome the drive train and generator losses. Three bladed turbines are of the most suitable solidity for a broad range of wind speeds and are the most frequently employed as mechanical/electrical converters.

(Burton, Sharpe, Jenkins and Bossanyi 2001) State that on a good site, a wind turbine recovers the energy used in its manufacture and installation within the first year of its operation.

Whilst this is not always the case, it highlights the potential for wind energy converters as a source of sustainable power supply for the future.

The resultant design of the project is a small scale 0.5 – 2 kW electrical energy producing wind turbine. Its design is based on a 3 bladed horizontal axis wind turbine for the application of charging a battery bank in remote or isolated communities and dwellings. The turbine uses and induction generator to produce AC power which then inverted to DC and governed by a shunt regulator.

The rotor has a relatively high torque coefficient and was designed using a cambered aerofoil profile allowing it to produce electricity even at low wind speeds. At low wind speeds the power produced is used to trickle charge a battery bank, the systems energy storage unit. Once the battery bank is fully charged the shunt regulator diverts the supply to a dump load such as a hot water heating unit so no energy is wasted.

The mechanical design incorporates:

- Three bladed rotor system with a cambered aerofoil profile
- 1:6 speed up gear box
- Centrifugal speed governing brake
- 500- 2000 W AC generator (dependant on the area of application, wind speeds etc)
- An aluminium frame
- A fibre glass nacelle cover with air intakes for the convection cooling of the generator and centrifugal breaking unit.
- Vein that allows the rotor to adjust to the direction of oncoming wind (yawing)
- Steel tower (fibre composites are of preference, see future work)
- Reinforced concrete foundation (drilled shaft, bell bottom)

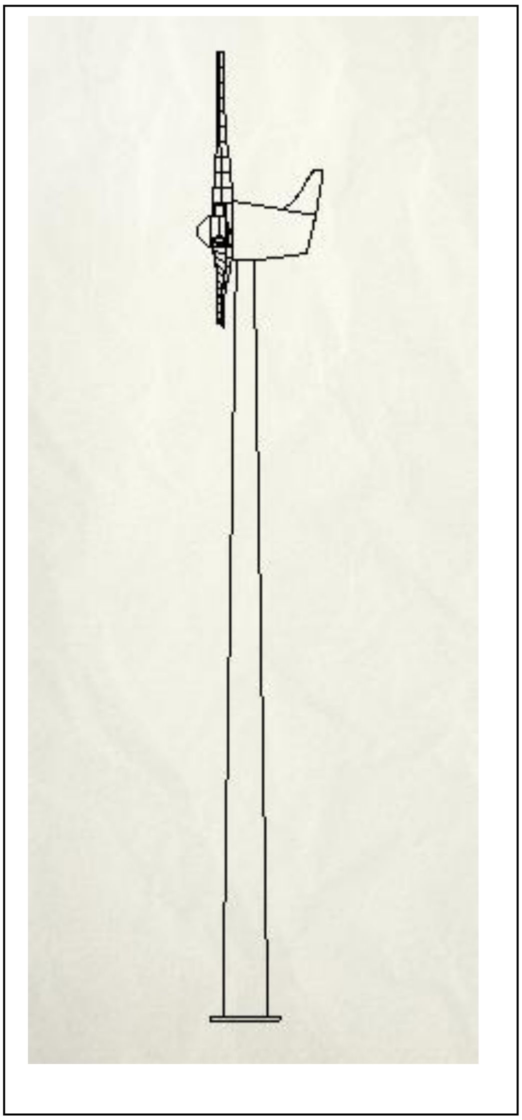


Fig 7.1- Turbine over view, Side view

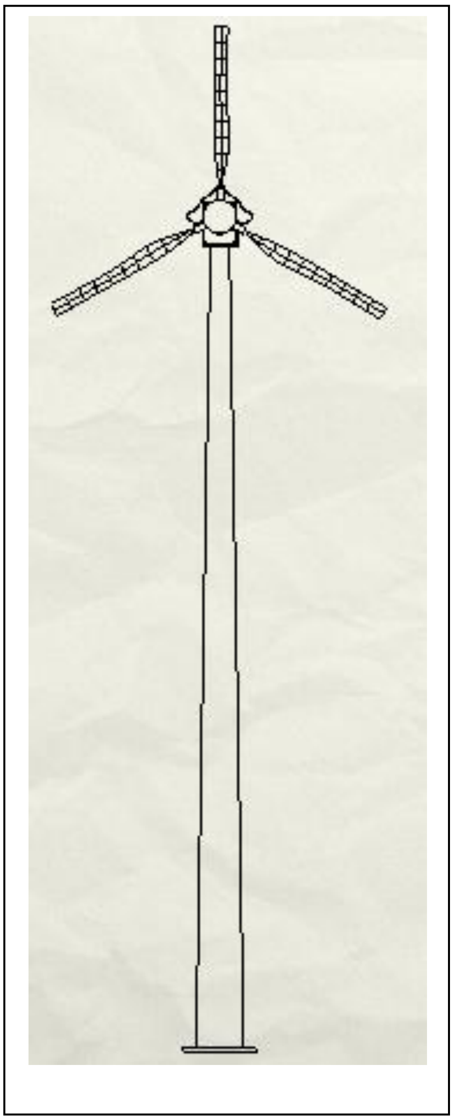


Fig 7.2- Turbine overview, Front view

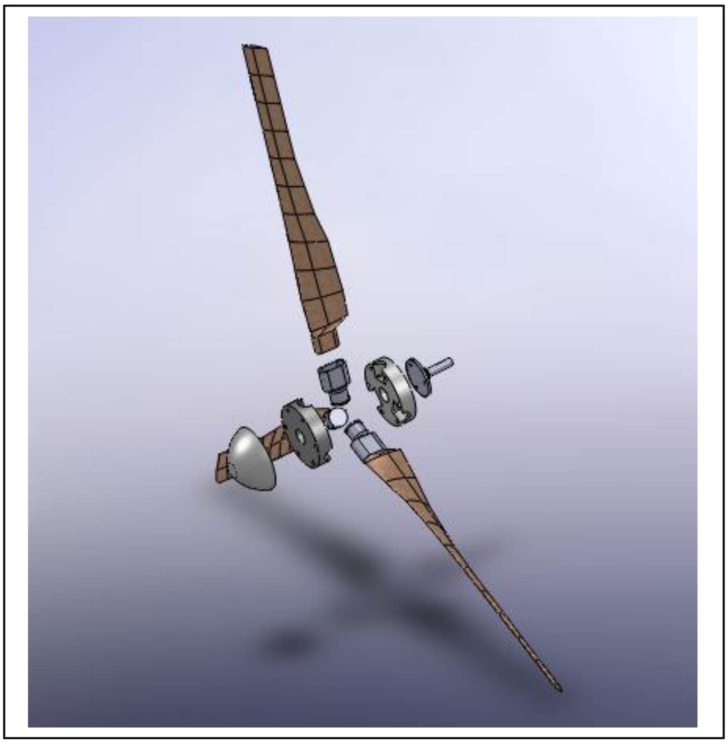


Fig 7.3 - Rotor and hub assembly

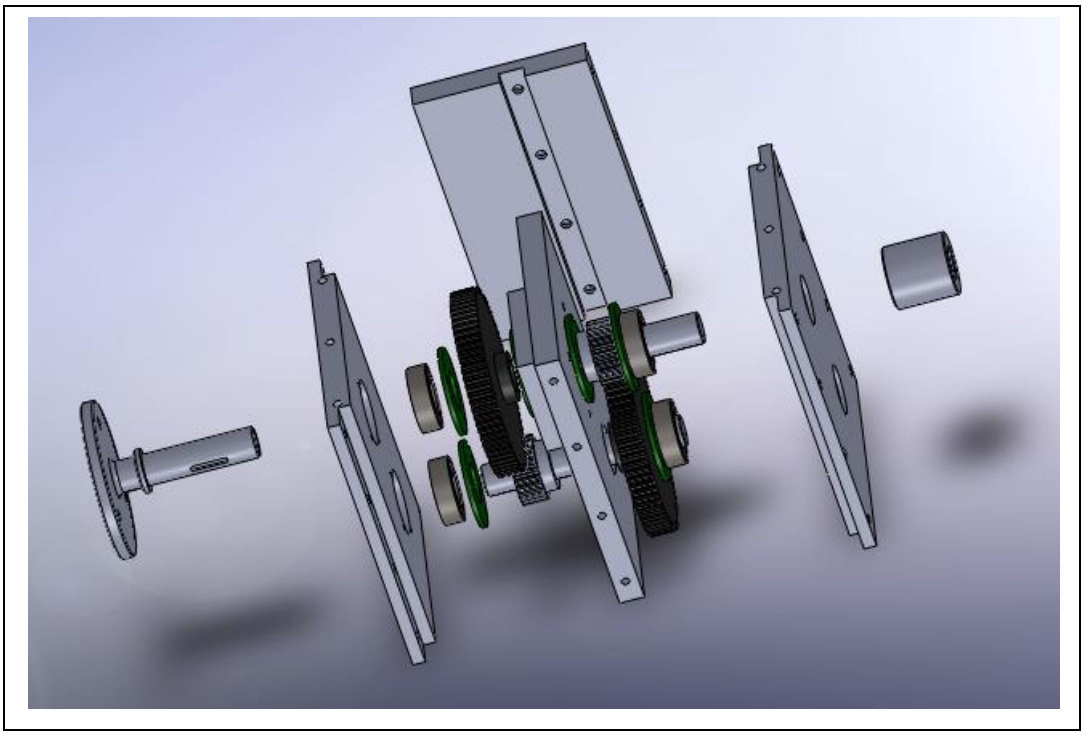


Fig 7.4 - Gear box exploded assembly

The various components of the turbine assembly were designed to be manufactured from materials that are easily recyclable after the turbine reaches its useful life. The gear box housing and nacelle frame work are made from solid rolled plate aluminium due to its high strength to weight ratio and also because aluminium can be easily melted and re-cast. The gears are hardened 4140, a high tensile alloy steel that can be molten and re-cast. The blades were designed to be manufactured from New Guinea rose wood, a short grained, high durability timber, that can be carved, machined and sanded until the desired blade shape is achieved. Using timber as opposed to fibre glass reduces the cost of the blades and also increases the recyclability of the system. A layer of resin is however applied to the outer surface of the blades to water proof the timber.

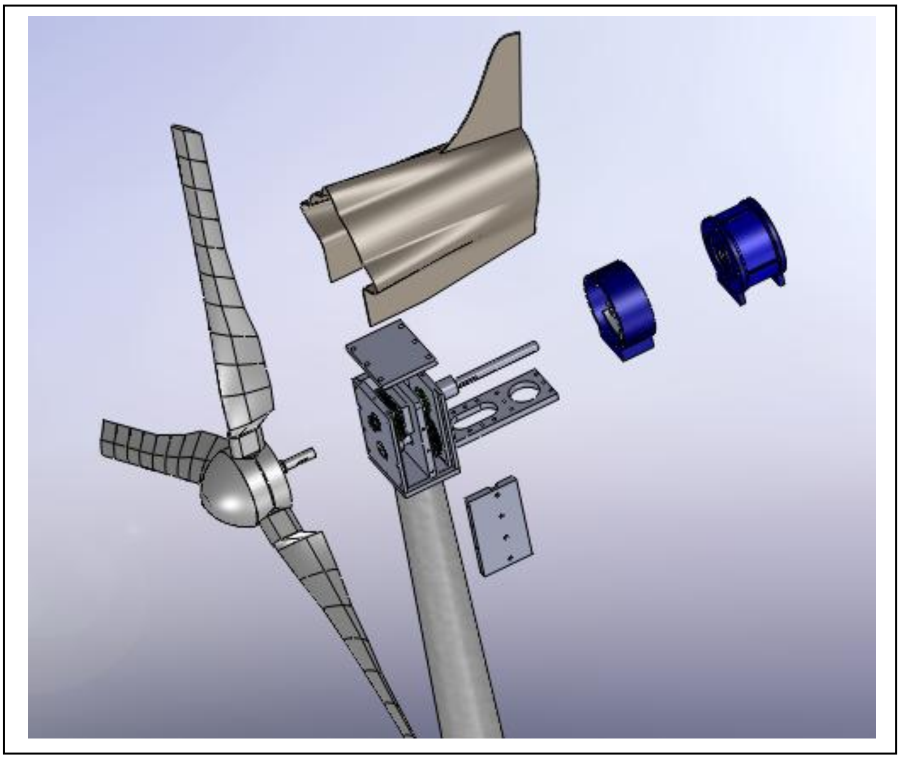


Fig 7.5- Exploded nacelle assembly including rotor

The rotor system is mounted directly to the gearbox input shaft. The input shaft of the gear box is supported radially by two radial roller bearings and axially by a thrust bearing which sits between the gearbox housing and a shoulder on the input shaft. The gearbox uses sealed roller bearings secured by nylon retaining plates to seal the gearbox and constrain the axial position of the gears. The gears are constrained to the shafts using 6mm key ways and grub screws. The speed of the output shaft of the generator is governed by a centrifugal friction brake which is mounted on the shaft prior to the generator. The speed limiter restricts the maximum rotational speed to 1000 rpm ensuring the turbine does not over-speed and cause damage to any internal components or external bodies. The nacelle frame work which acts as a mounting platform for the brake and generator is directly mounted on the gearbox housing. The platform was designed to allow the electrical transmission cables to pass from the generator to the centre of the tower where it is diverted to the inverter and regulator circuit.

The nacelle of the turbine is mounted on a pivoting centre at the tip of the tower. The pivot consist of a sleave with an internal heavy duty thrust bearing which allows the rotor and nacelle to adjust itself to the direction of the oncoming wind.

In its fully assembled state the turbine hub centre stands 5.25 m above ground level with the tip of the blades extending to a maximum height of 6.5m. Wind speed varies with height and its flow becomes more consistent with an increase in height. The 5m tower elevates the turbine to a suitable height above interfering objects such as houses and small trees for its implementation in household applications. However the tower acts only as a base for the turbine and the unit could also easily be mounted to existing platforms such as mechanical wind mill towers, roof tops, water tanks and other suitable platforms.

The turbine is designed to operate at its peak rotational speed at a velocity of 9-10 m/s. However in reality the wind speed will need to be marginally higher to account for the drive train and generator losses as well as the imperfections of the rotor design and tip losses caused by wake rotation.

As only the rotor system of the turbine was manufactured it was not possible accurately test the prototype under realistic loading conditions. Due to the size of the rotor (2.5 m ø) it was not possible to fit the prototype into a controlled wind tunnel for testing. A field test was conducted to attain the rotor’s rotational speed at low wind speeds and to form a basis for further testing.

Future Work

To attain the rotors realistic performance, maximum power coefficient and torque coefficients at different wind speeds, it is envisioned that the turbine be taken to a large controlled flow wind tunnel. The wind speed can then be set to a constant and the rotational speed, interference factor and accurate power coefficients can be gathered at different speeds. Due to a lack of time and equipment torque readings and accurate wind speeds were unattainable during the field trial. A torque measuring device with active feedback control would be a beneficial tool in determining the rotor’s efficiency and mechanical capabilities.

Once the optimum operating conditions are determined, the gear box and generator can be redesigned to a configuration that produces maximum efficiency. This design can then be manufactured and tested to determine the realistic operating performance in an uncontrolled environment.

As the turbine was designed primarily from a mechanical perspective, there is allot of electrical based engineering to do to ensure a safe, effective electrical power regulation and distribution circuit is constructed. Basic electrical theory and circuits were investigated during the course of the project however no specifications were made with respect to the sizing of electrical items and units.

A mechanical to electrical wind energy conversion system is a series of components that require the attention of electrical engineers and technicians as well as mechanical engineers. The tower and foundation design is an area where civil engineers would most likely produce superior designs. The tower designed for this particular turbine was constructed from rolled steel tubing which is very stable and relatively inexpensive. Natural fibre composites are a group of materials that has been receiving allot of attention of late, especially at the University of Southern Queensland. The development of a natural fibre composite tower would be significant accomplishment in terms of future work, not only for the purpose of the project but also for the future of renewable, environmentally friendly materials and energy.

Appendices

Contents

University of Southern Queensland

FACULTY OF ENGINEERING AND SURVEYING

ENG 4111/4112 Research Project

PROJECT SPECIFICATION

FOR: **JOSUA KIRSCH**

TOPIC: DESIGN OF A SMALL WIND TURBINE FOR ELECTRIC POWER GENERATION: 1-5 kW

SUPERVISOR: Dr. Fouad Kamel

ENROLMENT: ENG 4111 – S1,D, 2009 ----- ENG 4112 – S2 ,D, 2009-03-15

PROJECT AIM: This project envisages the design and implementation of a small wind turbine for electric power generation, 1-5 kW. The project encompasses mechanical design of the wind blades, tower, gearbox and an appropriate electricity generator.

SPONSORSHIP:

PROGRAMME: Issue A, 24th March 2009

1. Research the existing background information on wind turbine design for electrical power generation. (Aerodynamics, gearing systems, electrical generation, materials)
2. Research electrical generators and select an appropriately sized generated to achieve the desired electrical output.
3. Test electrical generator and collect data to determine optimum running conditions.(speed, output)
4. Design a gearbox in conjunction with a set of rotors that will supply the required input torque to achieve the desired electrical output.
5. Investigate the different applications for the power produced. (Feed into grid or use directly)
6. Research appropriate component materials to optimise the wind mill structurally and mechanically taking into consideration the disposal method of the turbine after it has exceeded its useful life span.

As time permits:

7. Construct a scaled model of the turbine for testing and demonstration of electrical power production.

AGREED:

____________________(Student) __________________, ____________________(Supervisor)

__/__/__ __/__/__ __/__/__

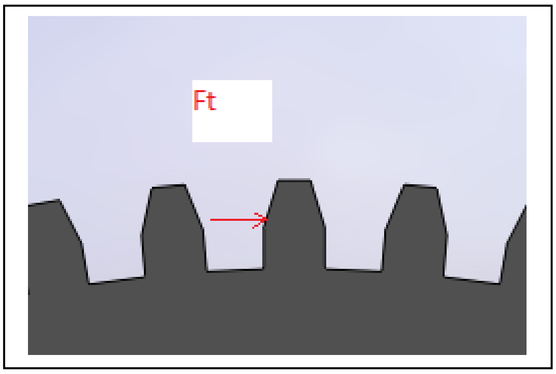
Examiner/Co-examiner:____

Appendix B1

Gear tooth analysis

A gear tooth force and stress analysis was conducted to determine the adequate sizing of the gear tooth form. The size chosen was a module 2 tooth form. The tooth form is imparted on the work piece by a form cutter which cuts the tooth profile on the outer circumference of the blank spur.

Module 2 is a relatively fine tooth form. At its root the width of the tooth is approximately 3.14 mm and the total tooth depth is 4.42 mm. The material chosen was 4140, a high tensile, hardenable alloy.



Cross section of gear tooth.

The force and stress calculations were conducted using material from (Juvinal & Marshek, 2006).

Some values are converted from metric to imperial for the purpose of calculation and then reverted back to metric.

(eq 15.3) $$d_a = \frac{N_a}{P} \qquad d_a = PCD \, ; N_a = Number\ of\ teeth \, ; P = pitch$$

(eq 15.13) $$V = \frac{\pi d_a n_a}{12}$$

$$V = \frac{\pi * 5.67 * 180 rpm}{12} = 267.2 \text{ ft/min}$$

(eq 15.14) $$F_t = \frac{33000\ W}{V}$$

$$F_t = \frac{33000 * 4.26}{267.2} = 526 \text{ lb}$$

Convert to metric

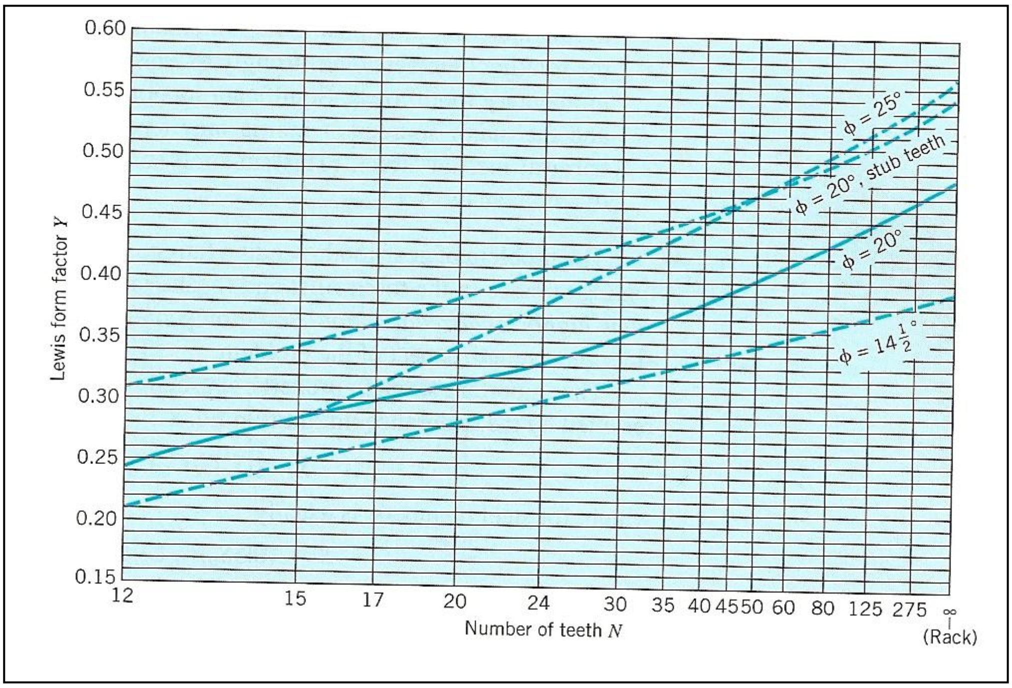
$$F_t = 526 * 4.448 = 2339.6\ N$$

The force imparted on the gear tooth under full breaking (gears not turning), transmitting 3.24 kW of power (at rated speed of 180 rpm) is $F_t = 2339.6\ N$.

Stress calculations.

The gear material is high tensile 4140.

(eq 15.16a) $\sigma = \frac{F_t}{mbY}$ $m = module\ ;\ b = tooth\ width\ ;\ Y = shape\ factor$



FigureA1 -Figure15.21 (Juvinal & Marshek) Lewis factor Y

$$Y = 0.42\ ; \quad m = 2; \quad b = 3.14\ mm$$

$$\sigma = \frac{2339.6}{2*0.00314*0.42}$$

$$\sigma = 887018\ pa$$

$$\sigma = 0.887\ Mpa$$

Referring to appendix C-4a of Juvinal & Marshek

The yield strength of normalised 4140 is 655 Mpa.

The maximum stress in the gear tooth is 0.887 Mpa.

Therefore the tooth is sufficiently sized.

Appendix B2

Spring design for centrifugal breaking system

The centrifugal breaking system relies on the relationship between the centrifugal force created by the rotation of the brake shoes and the relative spring coefficient of the springs in the break assembly. The spring coefficient governs the extension of the springs which controls the breaking applied at high speeds.

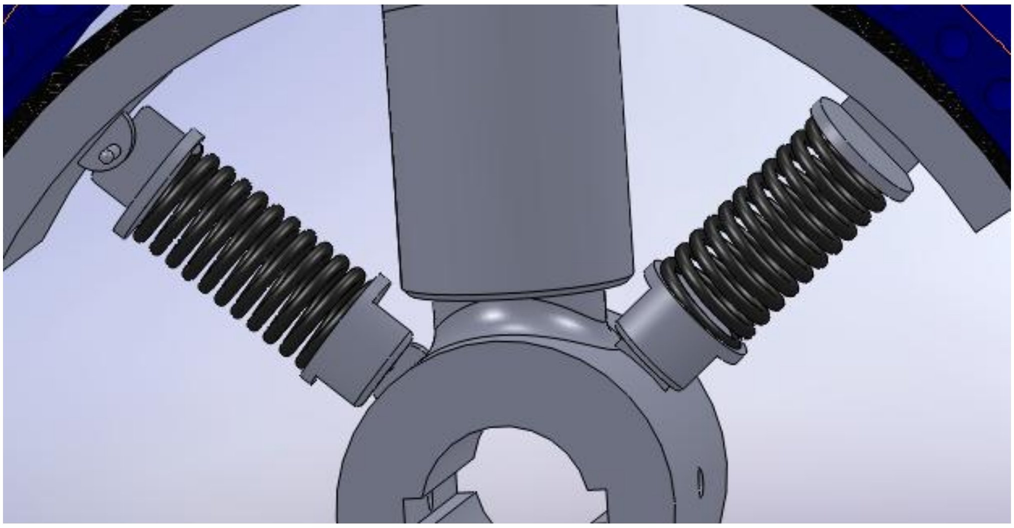
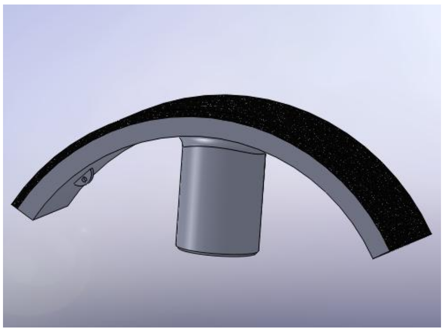


Figure A2 - Centrifugal breaking system- tension springs.

First the amount of centrifugal force is determined for the break shoe rotating at 1000 rpm.



Mass = 0.80 kg

Centre of gravity = y19.82 (from base)

Figure A3 Brake shoe

The centre of gravity of the break shoe rotates at a distance of 49.82 mm from the centre of the hub at low speeds and 54.82 mm at high speeds.

The revolution speed will be 1000 rpm.

The mass of the shoe is 800g.

The radius of rotation is 54.82 mm

Centrifugal force $F = \frac{mv^2}{r}$ $m = mass\,; v = velocity\,; r = radius$

$$v = \frac{rpm}{60 * \pi D}$$

$$v = \left(\frac{1000}{60}\right) * \pi * 2 * 0.0548$$

$$v = 5.738 \text{ m/s}$$

$$F = \frac{0.8 * 5.736^2}{0.0548}$$

$$F = 480.3\ N$$

The centrifugal force experienced by the braking shoe is 480.3 N at 1000 rpm.

Because there are two tension springs governing the movement of each brake shoe, the force is divided equally between the two.

The spring coefficient is therefore:

$$K = \frac{distance}{force}$$

$$K = \frac{0.005}{240}$$

$$K = 0.00002\frac{m}{N}$$

This spring constant is relatively high. A lighter spring can be used if the relative weight of the brake shoe can be decreased. This can be done by machining pockets into the steal sections of the break shoe or even using a high strength fibre composite instead of stainless steal.

Appendix B3

Tower Stress and bending

The turbine tower supports the nacelle containing the gearbox, braking system and electric generator along with the rotor. It experiences both compression and a bending moment about its footing. The compression is due to the weight of the nacelle and rotor whilst the bending moment is induced by the thrust caused by drag forces on the rotor. The tower itself also experiences an unevenly distributed force due to the drag forces created by the oncoming wind. In comparison to the thrust of the rotor, the force experienced by the pole due to drag is quite small.

The tower is 5m tall and at 20m/s winds experiences a thrust force due the drag forces acting on the rotor of 1265 N.

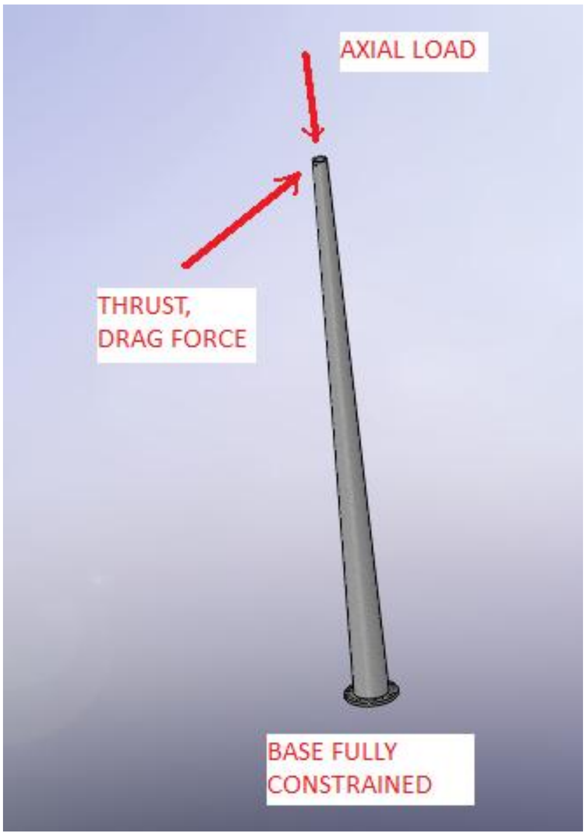


Figure A4 - Loading of tower

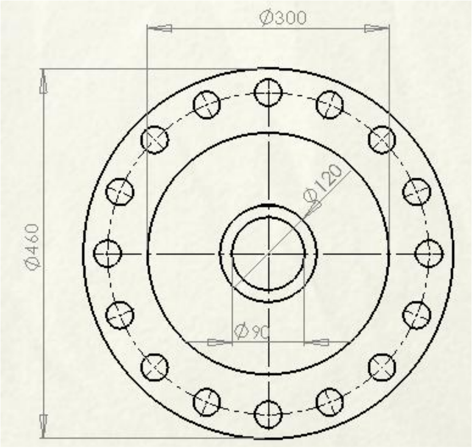


Figure A5 Cross section of pole (top view)

Due to the variance in diameter and wall thickness of the pole, the tower has been modelled and analysed as a 200 mm diameter mild steel tower with a 20 mm wall thickness.

Elastic modulus $E = 210\ Gpa$

Moment of inertia $I = \left(\frac{\pi}{64}\right)\left(d^4 - d_i^4\right)$

$$I = \left(\frac{\pi}{64}\right)(0.25^4 - 0.16^4) \quad = 1.596\, x 10^{-4}$$

Section modulus $Z = \left(\frac{\pi}{32d}\right)\left(d^4 - d_i^4\right)$

$$Z = \left(\frac{\pi}{32\ x\ 0.25}\right)(0.25^4 - 0.16^4) \quad = 1.277 x\ 10^{-3}$$

Thrust experienced at 20m/s = 1265 N

Stress at constrained base $\sigma = \left(\frac{Wl}{Z}\right)$

$$\sigma = \frac{1265 * 5}{1.277\ x\ 10^{-3}}$$

$\sigma = 4.953\ Mpa$ (at flange plate)

Yield strength of mild steel $Y = 320\ Mpa$

Deflection of tower at tip $Def = \frac{Wl^3}{3EI}$

$$Def = \frac{1265 * 5^3}{3 * 210 x 10^9 * 1.596\ x 10^{-4}}$$

$Def =$ 0.00157 m

$Def = 1.57\ mm$

The stress associated with the bending moment being applied at the tip of the tower is not threatening to the towers structural integrity. The deflection caused by thrust loading is not considered to be large enough to cause concern to the operation of the turbine.

Appendix C – Cost estimation / analysis

The prototype of the proposed design will incur a relatively "middle range" manufacture cost. As the design consists of a number of intricate parts that will need to be completely machined in the prototyping stages, the majority of the cost will lie in labour and materials. The generator and electrical distribution system will be a relatively minor cost and initial quotes estimate the generator and electrical circuit components at $600 - $800. There will obviously be a technician's hourly rate to be accounted for as well however it is envisioned that the completion of the circuit take no longer than a day.

The machining of the parts will most likely take place on CNC milling machines which are capable of operating at revolution speeds up to around 12000 rpm which will greatly reduce production time. However the majority of the cost in the prototyping stage lies in the programming time which commonly exceeds the actual machining time. After approaching a prototyping company and enquiring about their standard operating costs an expected machining cost of around $100 an hour can be expected taking into account the setting up time, tooling requirements and other overheads.

COMPONENT	**MATERIAL + COST**	**PRODUCTION + TIME**	**COST**
SECONDARY SHAFT	SS 316 - $ 30	0.5	$ 80
TENSION SPRING	SS 316 – 4 x $15	0.5	$ 110
THRUST BEARING CUP	SS 316 - $ 50	0.5	$ 100
TOWER	MS - $1200	2	$ 1400
TOWER PLUG	SS 316 - $ 50	0.5	$ 100
HUB REAR	NYLON – 2 x $ 200	2	$ 600
INDUCTION GEN	500 W ind. gen	Wiring etc..	$ 800
MIDDLE RETAINING WALL	Al - $ 30	0.5	$ 80
NACELLE COVER	FBG - $ 300	5 - MOULDING	$ 800
NOSE CONE	Al - $ 50	0.5	$ 100
OUTPUT SHAFT	SS 316 - $ 50	0.5	$ 100
24 TOOTH SPUR GEAR	4140 – 2 x $ 50	3	$ 400
72 TOOTH SPUR GEAR	4140 – 2 x $ 20	2	$ 240
BEARING RETAINER	ACETAL – 6 x $ 5	1	$ 130
BLADE PROFILE	NGR – TIMBER – 3 x $ 200	10	$ 1600
BRAKE HOUSING	CAST IRON - $ 100	2	$ 300
BRAKE HUB	SS 316 - $60	1.5	$ 210
BRAKE SHOE	SS 316 – 2 x $ 50	2	$ 300
DRIVE SHAFT	SS 316 - $ 150	3	$ 450
FLOATING BEARING RETAINER	Al - $ 30	0.5	$ 80
GB GEN COUPLING	MS - $ 30	0.5	$ 80
GB END PLATE	Al – 2 x 40	2	$ 280
GB WALL PLATE	Al – 2 x 40	2	$ 280
GEAR BOX BASE LID	AL – 2 x 40	2	$ 280

BEARINGS	Various 2 x thrust	8 total	$ 120
FASTENERS	Various 316		$ 200
HEAT TREATING	Nitriding gears		$ 200
FOUNDATION	Concrete + reo bar	5	$ 600
BLADE ROOT	Al – 3 x $30	5	$ 590
BRAKE PADS	Composite – 2 x $ 30		$ 60
GB PLATFORM	Al - $50	3	$ 350
TOOLING ALLOWANCE			$ 500
PROGRAMMING ALLOWANCE			$ 1000
Total			$ 12 520

The total estimated prototyping cost for the turbine is $ 12 520. This is based on best case scenario quotation without any re-machining or unexpected failures. Because there is always human error involved allowances need to be made to ensure that an accurate scenario is quoted. Therefore the cost estimation should be given an extra 20% funding to account for unexpected losses. New total = $ 15 024

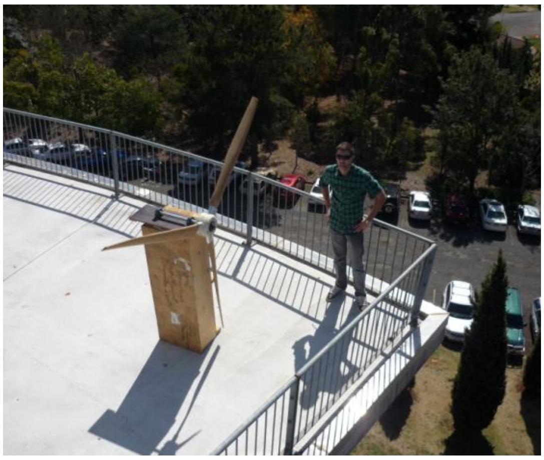
This is a reasonable value for the prototype production cost. Once the operation goes to a production scale it is expected that the turbine can be manufactured and installed for around $ 4000. Although there are cheaper alternatives already on the market this would be of the highest quality and would be almost 100% recyclable.

Appendix D – Photo catalogue

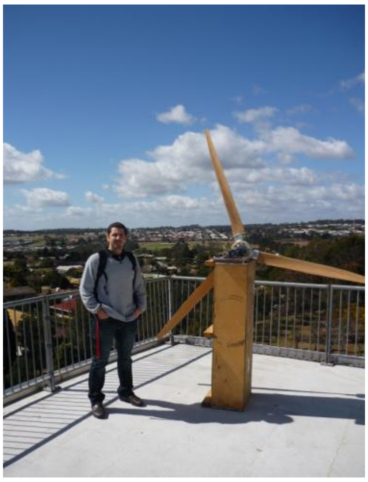
Assembled turbine on Z block roof

Stay clear of rotor

Scaled view



Trusty assistant



Initial shaped blades – caribean pine

Hub and drive shaft in bearing blocks

First assembly of rotor

Hub rear – drive shaft- locking pins

Machined stainless drive shaft

14/07/2009

Blade roots glued into blade bracket

14/07/2009

Timber blades and root brackets

14/07/2009

Rotor assemblyin vice

14/07/2009

Micro hydro turbine generator used for testing

Shaped timber blades –

wood shop Millaa Millaa

Machining drive shaft

Location pin – internal components

Machined nylon hub and unfinished balde root holders


06/07/2009

Hub components in assembly postion


02/07/2009

Hub halves pre machining. Recess machined at 120° intervals


01/07/2009

Mahcined nylon hub


02/07/2009

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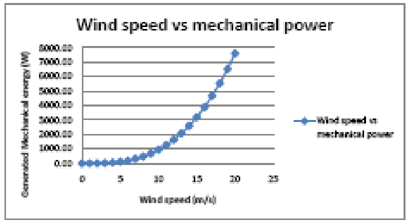
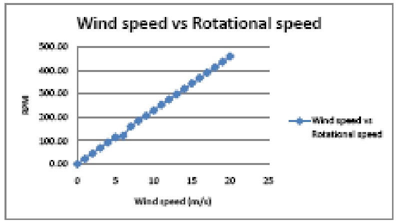
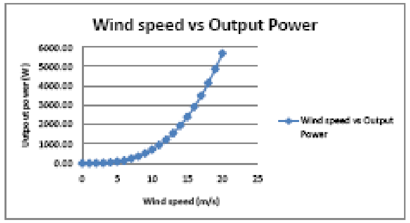
Appendix F – expected rotor performance

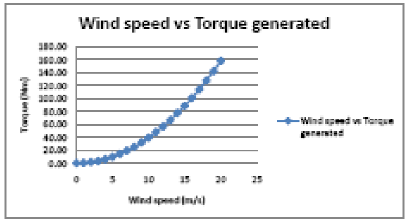
Ct= thrust coefficient maximum = 1
Cp= power coefficient maximum = 0.593
a = fractional wind speed at turbine station maximum = 0.5
u= wind speed at turbine rotor
A= swept area
rho=air density

Density @ 20 C	Rotor radius(m)	Area(m^2)	wind speed (m/s)	Power coefficient	Power mech (W)	Thrust (N)	Maximum Torque (Nm)	omega	RPM	Torque coeff	Power train efficiency	Torque at generator	Output power (W)
1.29	1.25	4.90625	0	0.3	0.00	0.00	0.00	0.00	0.00	0	0	0.00	0.00
1.29	1.25	4.90625	1	0.3	0.95	3.16	0.40	2.40	22.93	0.1	0.75	0.04	0.71
1.29	1.25	4.90625	2	0.3	7.59	12.66	1.58	4.80	45.86	0.1	0.75	0.18	5.70
1.29	1.25	4.90625	3	0.3	25.63	28.48	3.56	7.20	68.79	0.1	0.75	0.40	19.22
1.29	1.25	4.90625	4	0.3	60.76	50.63	6.33	9.60	91.72	0.1	0.75	0.70	45.57
1.29	1.25	4.90625	5	0.3	118.67	79.11	9.89	12.00	114.65	0.1	0.75	1.10	89.00
1.29	1.25	4.90625	6	0.262	179.09	113.92	14.24	12.58	120.15	0.1	0.75	1.58	134.32
1.29	1.25	4.90625	7	0.3	325.63	155.06	19.38	16.80	160.51	0.1	0.75	2.15	244.22
1.29	1.25	4.90625	8	0.3	486.07	202.53	25.32	19.20	183.44	0.1	0.75	2.81	364.55
1.29	1.25	4.90625	9	0.3	692.08	256.33	32.04	21.60	206.37	0.1	0.75	3.56	519.06
1.29	1.25	4.90625	10	0.3	949.36	316.45	39.56	24.00	229.30	0.1	0.75	4.40	712.02
1.29	1.25	4.90625	11	0.3	1263.60	382.91	47.86	26.40	252.23	0.1	0.75	5.32	947.70
1.29	1.25	4.90625	12	0.3	1640.49	455.69	56.96	28.80	275.16	0.1	0.75	6.33	1230.37
1.29	1.25	4.90625	13	0.3	2085.74	534.81	66.85	31.20	298.09	0.1	0.75	7.43	1564.31
1.29	1.25	4.90625	14	0.3	2605.04	620.25	77.53	33.60	321.02	0.1	0.75	8.61	1953.78
1.29	1.25	4.90625	15	0.3	3204.06	712.02	89.00	36.00	343.95	0.1	0.75	9.89	2403.07
1.29	1.25	4.90625	16	0.3	3888.56	810.12	101.27	38.40	366.88	0.1	0.75	11.25	2916.43
1.29	1.25	4.90625	17	0.3	4664.20	914.55	114.32	40.80	389.81	0.1	0.75	12.70	3498.15
1.29	1.25	4.90625	18	0.3	5536.66	1025.31	128.16	43.20	412.74	0.1	0.75	14.24	4152.50
1.29	1.25	4.90625	19	0.3	6511.66	1142.40	142.80	45.60	435.67	0.1	0.75	15.87	4883.74
1.29	1.25	4.90625	20	0.3	7594.88	1265.81	158.21	48.00	458.60	0.1	0.75	17.58	5696.16









Appendix G– Detailed drawings

24 TOOTH SPUR GEAR
72 TOOTH SPUR GEAR
BEARING RETAINER
BLADE PROFILE
BLADE ROOT
BRAKE HOUSING
BRAKE HUB
BRAKE SHOE
DRIVE SHAFT
FLOATING BEARING RETAINER
GB GEN COUPLING
GB END PLATE
GB WALL PLATE
GEAR BOX BASE LID
GENERATOR + BRAKE PLATFORM
GENERATOR + ROTOR SHAHT
HUB REAR
INDUCTION GEN
MIDDLE RETAINING WALL
NACELLE COVER
NOSE CONE
OUTPUT SHAFT
ROTOR ASSEMBLY
SECONDARY SHAFT
TENSION SPRING
THRUST BEARING CUP
TOWER
TOWER PLUG