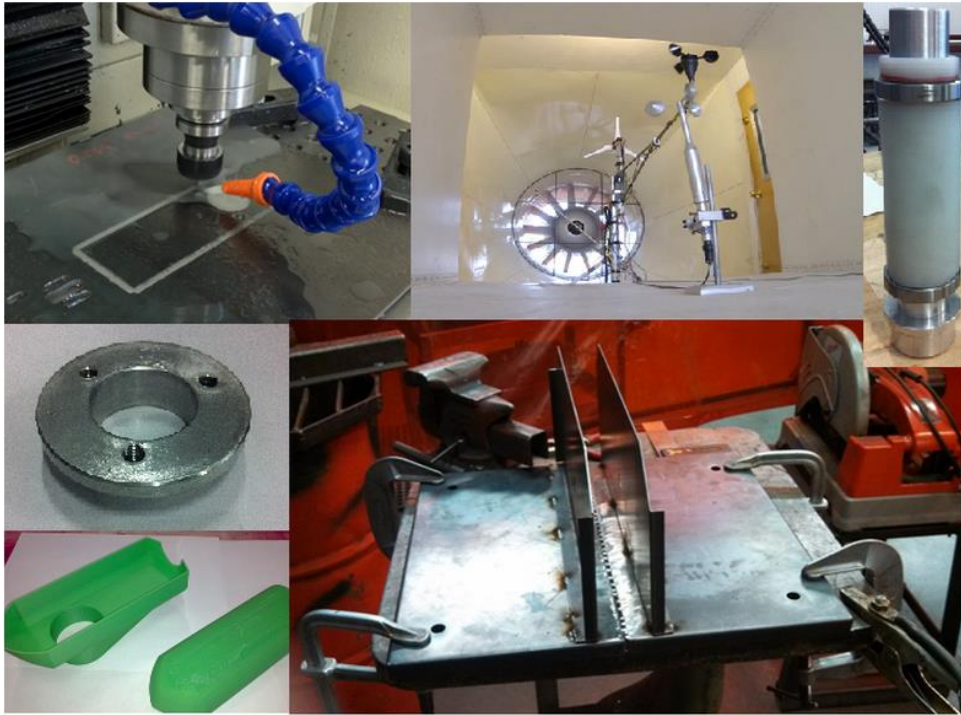


Northern Arizona University



Wind Turbine Technical Design Report

The Collegiate Wind Competition

Sponsored by the Department of Energy

Submitted towards partial fulfillment of the requirements for

The Design Review Subcontest

NORTHERN
ARIZONA
UNIVERSITY



FLAGSTAFF

Table of Contents

1.0 Design Objective	3
2.0 Design Overview	3
2.1 Blades	3
2.2 Hub Design	5
2.3 Nosecone	5
2.4 Yawing System	6
2.5 Integrated Nacelle Design	6
2.6 Mainframe	7
2.7 Base	8
2.8 Tower	8
2.9 Battery.....	9
2.10 Electronic Controls.....	9
3.0 Design Team.....	11
4.0 Modeling and Testing	12
4.1 Rotor/Blade Design Modeling.....	12
4.2 Blade and Hub Design Modeling.....	13
4.3 Tower Design Modeling	14
4.4 Nacelle Flow Modeling.....	15
4.5 Base Design Modeling.....	15
5.0 Engineering Diagrams	15
6.0 Engineering Specifications	16
6.1 Technical Specifications	17
6.3 Turbine Component Dimensions	18
6.4 Power Curve Specifications.....	19
7. 0 References.....	19
8.0 Appendices.....	20
8.1 Appendix A: Team Member Roles	20

List of Tables

Table 1: Tower Analyses Summary 14

Table 2: Technical Specifications 17

Table 3: Major Turbine Component Dimensions..... 18

List of Figures

Figure 1: Blade Profile 4

Figure 2: Manufactured hub 5

Figure 3: Nosecone Design..... 5

Figure 4: Yawing System 6

Figure 5: Rapid Prototyped Nacelle 6

Figure 6: Mainframe and Bracket 7

Figure 7: Base..... 8

Figure 8: Guy Wire Fixture 8

Figure 9: Schottky Three Phase Bridge Rectifier 10

Figure 10: Top Level Algorithm Diagram of the MSP430 code 11

Figure 11: Testbench setup with Motorsolver Dyno Kit equipment 12

Figure 12: Blade Mold Design 13

Figure 13: Turbine Assembly..... 16

Figure 14: Initial Rotor Power Curve..... 19

1.0 Design Objective

The business team has developed a need for a transportable energy source to be used in disaster relief situations. To satisfy this need the project goal is to develop a durable, portable wind turbine to be used in post disaster scenarios. This would allow people to continue using their phones, laptops, and other small electronics after the onset of major disasters and allow people to gather in locations containing disaster relief turbines, enabling them to communicate for emergency aid. In disaster relief situations, the turbines can also be used to power small electrical components such as cell phones.

The design objective of the turbine is to be lightweight and transportable by a maximum of three persons. The turbine base is designed to act as a sturdy base when the turbine is in use and as a platform for which small electronics can be placed while being charged. The base can be fixed into the ground with several different fixtures which allows it to be used on a variety of different terrains. The aerodynamic tower design, discussed later in the report, differentiates the turbine from those currently on the market. The top of the tower utilizes a symmetrical airfoil shape to lessen the turbulence of the airflow around the tower.

2.0 Design Overview

The downwind, horizontal axis wind turbine is designed to fulfill competition requirements. The system makes use of a passive yawing system and three blades which provide a balance between torque production and RPM/power production. This turbine is designed to coincide with the business plan and has been fabricated with lightweight, durable materials to ensure the product's portability. All design analysis can be found in the Rendering Document.

2.1 Blades

Working with such a small rotor diameter, the Reynolds number of a wind turbine blade is extremely low. This made it very hard to model an accurate blade shape because not much data exists for wind turbines with such low Reynolds numbers. This created the challenge of designing a single surface airfoil that would operate at extremely low Reynolds numbers. Testing was completed in an open circuit

subsonic wind tunnel to obtain lift and drag data of a flat plate at low Reynolds numbers and determine the stall characteristics. A flat plate, having a chord length of 0.5 inches and a length of ten inches, was designed with a slight camber for testing. Data is recorded for the normal and axial forces acting on the thin airfoil while wind velocity was steadily increasing. This data is recorded automatically in a LabVIEW program, then the total lift and drag force of the thin airfoil was calculated using the normal and axial forces and the angle of attack.

This information provided the knowledge to be able to run a code utilizing the Blade Element Momentum (BEM) theory to obtain an optimized blade shape [1]. This blade shape contains a certain twist and chord length that was optimized using the BEM code generated. A slight camber is also applied to the airfoil so that the blades will obtain enough torque to get started. The final airfoils are the S834 and CP-080-050-GN (single surface airfoil), which are used in the final design. From these two airfoils, the blade design was optimized using two different software packages and the Blade Elemental Momentum (BEM) theory. Initially two, three, four, and six bladed systems were considered for competition; however, a three bladed system was chosen for the final design because of its ability to cut in at low wind speeds and run at high rpms. The two programs used, BLADED and FAST, determined the forces that are acting on certain blade sections. The final blade profile is shown in Figure 1 and was

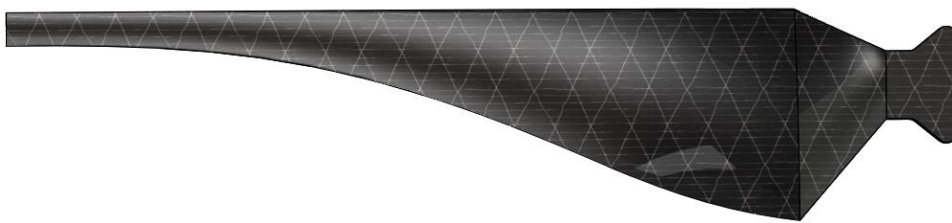


Figure 1: Blade Profile

analyzed using
BEM, FAST, and
BLADED.

The final blade
shape is designed

around the operating Reynolds number from wind speeds varying from 2-17 m/s. In low wind speeds,

the team used a single surface airfoil design to improve the turbine efficiency by having the blades cut-in sooner and produce more power.

2.2 Hub Design



Figure 2: Manufactured hub

The blade root was designed to fit exactly into the hub shown in Figure 2. The three slots in the hub are where each blade root will fit and will be held in place with a hub plate and bolt. The borehole of the hub will be connected to the drivetrain using a collet. The hub design used Aluminum stock, which is cheap, strong, and easy to manufacture.

2.3 Nosecone

To minimize the effects of vortices that shed off of the rotor, a nosecone is included to provide an aerodynamic structure to the design. This nosecone is a simple design which can be clipped onto the hub and is easy to assemble and cheap to manufacture. This design is a simple hemispherical shape that lets the air flow smoothly over the back of the turbine. This design is shown in Figure 3.

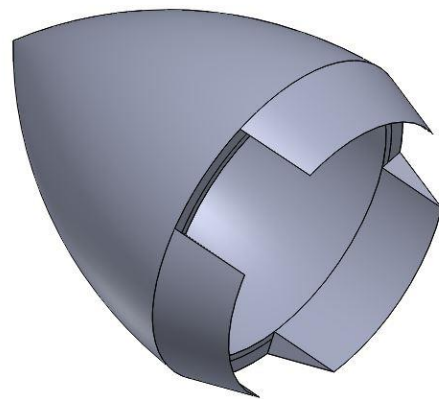


Figure 3: Nosecone Design

2.4 Yawing System

The turbine utilizes a passive yawing system which allows the blades to be directed into the wind. The yawing system design consists of two single row, deep groove ball bearings, a three phase slip ring, a threaded base plug, a yaw sleeve, an upper yaw plug, and a yaw shaft. A sectional view of the yawing system can be seen in Section 1 of the Rendering Document. This image shows how all of the components in this system fit together. The yaw shaft is threaded into a plug at the base of the system. The two bearings and plastic bearing spacers sit on the shaft and an aluminum sleeve fits over the top with a plug press fit into the top. Figure 4 shows the yawing system with the mainframe, slip ring, and generator attached.

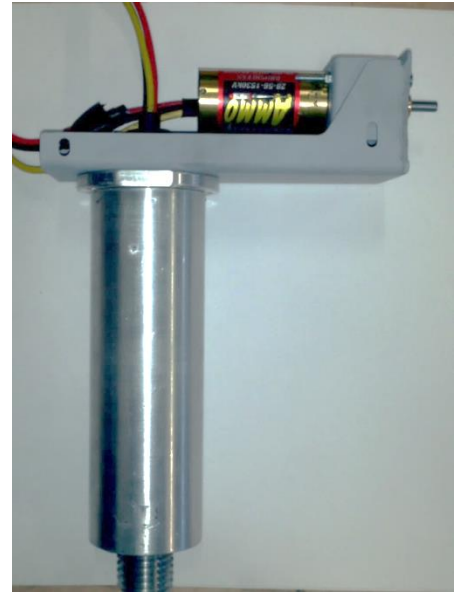


Figure 4: Yawing System

2.5 Integrated Nacelle Design

A fared tower section encases the yawing system and allows for less turbulent wind flow across the turbine tower. This minimizes vortex shedding as wind flows over the trailing edge of the tower,



Figure 5: Rapid Prototyped Nacelle

reducing inefficiencies as the turbine blades pass behind the tower. This aerodynamic casing has been integrated into the nacelle design to create a sleek and aesthetically appealing design.

The nacelle sits above the fared tower section and was designed around the dimensions of the mainframe and the hub. The nacelle is only slightly larger than the hub to lessen inefficiencies as air flows over the nacelle and to the blades. A removable door has been built into the top half of the nacelle to ensure that components can be properly placed and to allow components to

be fully inspectable. The integrated nacelle design has been rapid prototyped using ABS and Ultem plastic. Ultem was used due ease of access of material and will not be used in the market turbine. Figure 5 shows the nacelle just after it was rapid prototyped. The two bottom components were secured together with JB weld and a coat of paint was applied to the whole nacelle (not shown).

2.6 Mainframe

The mainframe is designed to withstand all loading and act as a completely rigid structure while being small enough to fit behind the shadow of the hub. The mainframe has been constructed from 16 gauge sheet metal and cut to shape using a CNC milling machine. FEA proved 16 gauge sheet metal to be sufficient to withstand the necessary loads, this analysis can be seen in Section 2 of the Rendering

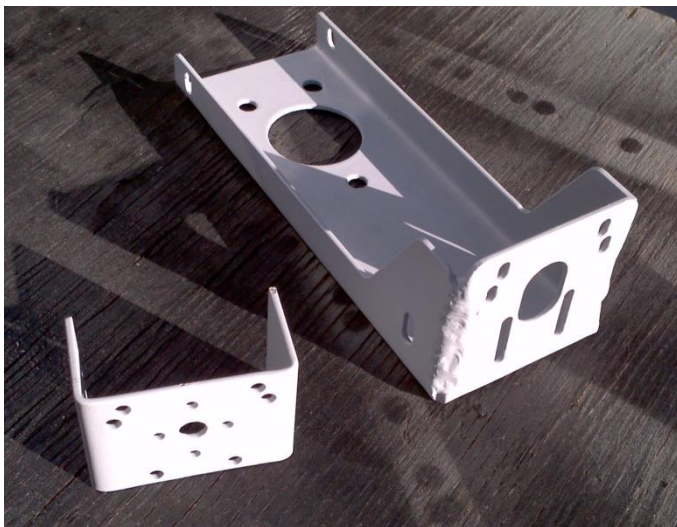


Figure 6: Mainframe and Bracket

Document. The piece was then bent into shape to provide structural rigidity. This component was then painted with a cold-galvanizing compound to prevent corrosion. This design makes use of two components to make accessing the generator simple and to allow the mainframe to be used for a direct drive system and a system which utilizes a gearbox. The generator is first mounted onto

a bracket which can then be mounted onto to the mainframe. These two components can be seen in Figure 6. The mainframe supports the provided Great Planes Ammo GPMG 5225 motor, a three phase slip ring, the nacelle structure, and provides mounting for the passive yaw system. This system is bolted to the yaw plug located at the top of the yawing system and fastened to the nacelle.

2.7 Base

The base has been constructed from 16 gauge sheet metal and has a footprint of roughly 20 inches by 18 inches with a height of 9 inches. There are four holes on the base plates to allow for anchors to be driven into the ground to stabilize the base while the tower is being raised. A hole was placed in the two vertical sections of the base to allow a 3/4"

bolt to be placed through the holes to act as a pivot point when raising the tower.

The base has also been painted with a cold-galvanizing compound to prevent corrosion. The turbine base can be seen in Figure 7. A shelf was placed on the base where a weatherproof enclosure sits and contains the electrical components. This

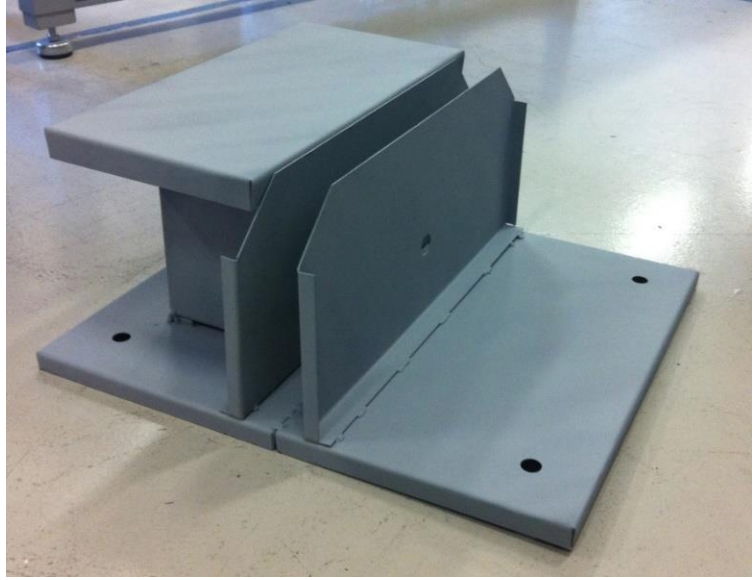


Figure 7: Base

structure also acts as a convenient place for the user to place their electronics while they are being charged.

2.8 Tower

The turbine tower consists of three 6 ft. long threaded 6061 aluminum alloy sections and a single 3 ft.

section at the top of the tower. Each section is held together with a threaded fitting with the exception of the first and final sections. The first section, located at the base of the tower, is held in place with a bolt which securely fixes it to the base and allows the tower to rotate around the bolt. The tower rotation allows for the tower to be erected simply while the base remains fixed. The



Figure 8: Guy Wire Fixture

final section, located at the top of the tower, has a threaded plug press fit into the top where the yaw shaft threads into the tower. A guy wire fixture sits on the final tower couple and can be seen in Figure 8. This fixture is where the guy wires are attached to the tower and is angled at the ideal guy wire angle of 60° with respect to the ground. A cold-galvanizing compound covers the guy wire fixture to prevent corrosion.

2.9 Battery

Although not required for the competition, the battery bank is a key component of the business plan. The UB12120 12 V 10 Ah battery was selected to demonstrate the battery bank application for the competition. This battery was selected based on storage, temperature, humidity, extreme weather conditions and time of the year data. It will be used in Midwest and Coastal areas during hurricane and tornado seasons. From these areas, the turbine system is expected to obtain up to 25 Wh at optimum wind speed with 2 days of autonomy. It is also designed to operate between $30^\circ\text{F} - 75^\circ\text{F}$ with humidity accounted for. It is a 12 V system battery that can be connected to the power output to store unused power for later use.

2.10 Electronic Controls

For the controller design, the team began searching for a rectifier to convert the AC power from the wind turbine into DC to charge electronic devices. Some rectifiers were considered for low forward voltage drop. It was determined that the Schottky three phase bridge rectifier with peak reverse voltage of 45 V and max current output of 45 A provided the best results, shown in Figure 9. The Schottky diodes in this rectifier together have a very low forward voltage drop (less than 0.65 V) and can switch at extremely fast rates.

In order to regulate the output voltage to 5 V into the grid, the team designed a boost converter circuit that could withstand 20 V and 15 A, since previous generator tests results showed that this was an obtainable range. Three iterations of these circuit designs were made as well as revisions of them by implementing them on homemade printed circuit boards. This custom process started with using photo paper and a laser jet printer to print out the basic design. Next, the team cleaned the clad board and cut it to dimensions, which is noted on Table 3. A household iron was used to iron the ink into the clad board. Once the ink was sealed on the board, the team put it into a bath of muriatic acid. This created a reverse of the PCB and left the ink where it was. Finally, it was bathed in acetone to remove the ink, which gave the team their final PCB layout. After that, they were able to drill the mounting holes for the electrical components. This design can be found on the final Printed Circuit Board (PCB) schematic, shown in Section 4 of the Rendering Document.

The final PCB schematic, shown in Section 4 of the Rendering Document, has the MSP430 as the microcontroller. This was determined as best suited for this application due to its interrupt capabilities and extensive low power mode options. A top level diagram of its operation is shown in Figure 10. Several iterations have been made to create a final design that is determined to be capable in handling the electrical brake of the wind turbine. This design has three phase power flow into the PCB from the motor where it is then loaded onto resistors. Brakes are handled by the MSP430 using bipolar junction transistors (BJT's) for each phase of the circuit. These transistors are useful for handling high AC current, which helps to control the motor's desired frequency. The outgoing three phase power will then flow through the slip rings and to the components.

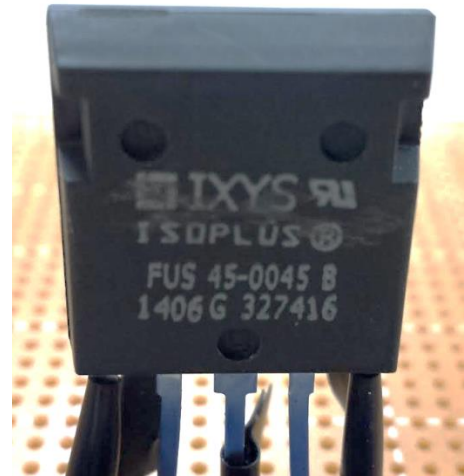


Figure 9: Schottky Three Phase Bridge Rectifier

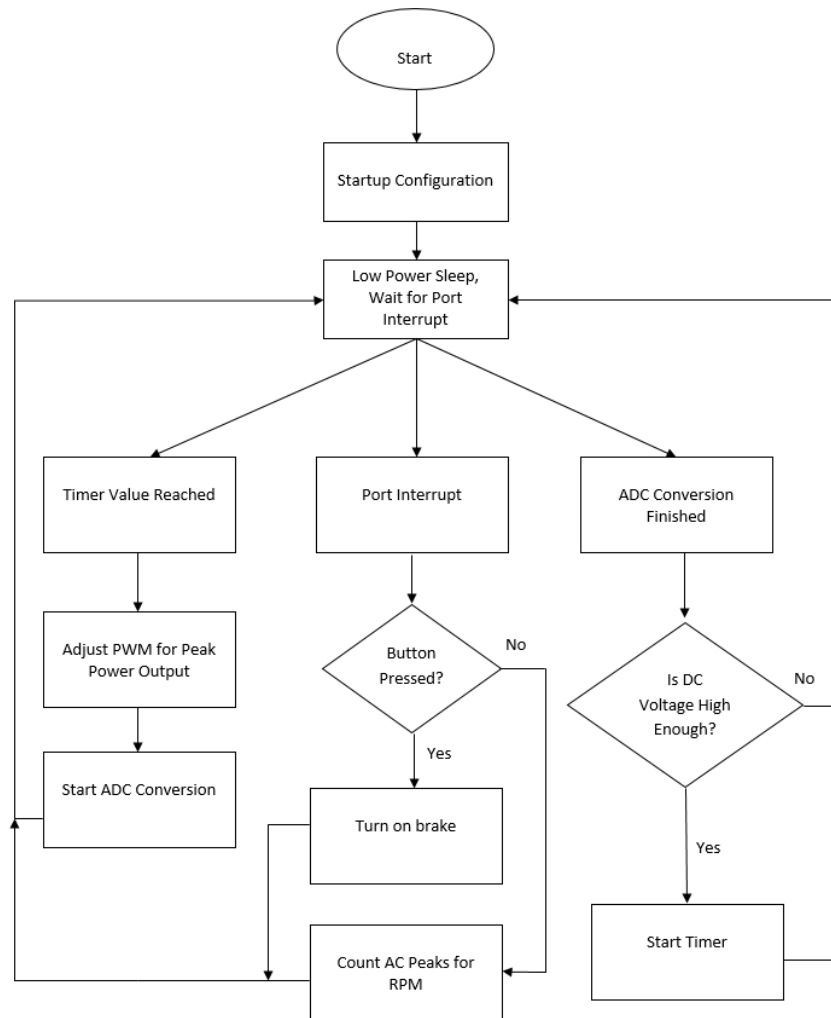


Figure 10: Top Level Algorithm Diagram of the MSP430 code

3.0 Design Team

The NAU team consists of five different sub-teams that all have a wide range of experience and talents.

There are three engineering teams in charge of designing and constructing the overall turbine, a business team dedicated to creating the business plan, and a wind market issues team which collaborates for the Market Issues Presentation. The three engineering teams consist of a blade and hub design team, a balance of system and testing team, and a controls and charging team. The business team is full of business and market plan specialists that have created a business plan and will present the turbine market and company at competition. There is also a market issues team that will work on

completing the Market Issues Presentation. A complete list of all the engineering team members and their project roles is shown in Appendix A.

4.0 Modeling and Testing

Motor testing was completed using testing procedures designed specifically to measure the AC voltage, AC current, DC voltage and DC power waveforms from the motor. A testbench and dSPACE ControlDesk software were used to control the permanent-magnet DC (PMDC) motor and MATLAB software to produce desired plots. Figure 11 shows the equipment used for motor testing. In this set-up, an armature voltage can be applied to the PMDC motor and allow the user to acquire

information. This was used to obtain the motor's rotational speed and carefully regulate the motor in order to maintain a current below 4.5 A, as this is the maximum operating current for this setup.

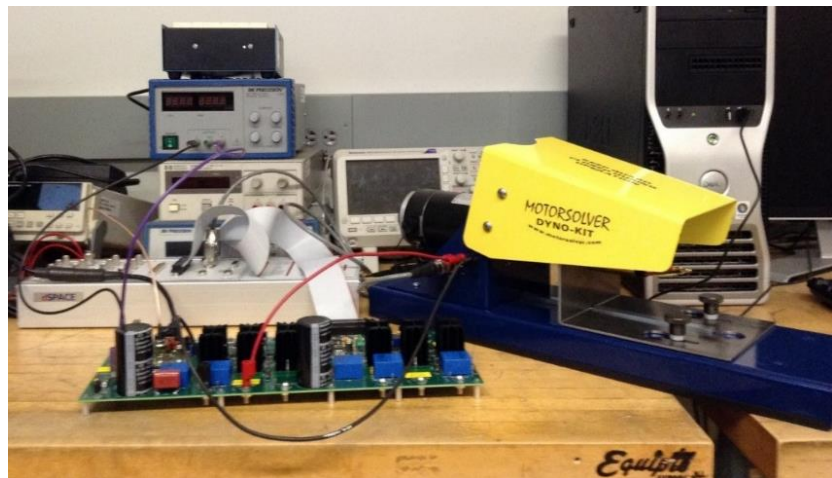


Figure 11: Testbench setup with Motorsolver Dyno Kit equipment

4.1 Rotor/Blade Design Modeling

The blade's Reynolds number was on the order of 10^4 which is extremely low for finding lift and drag on an airfoil. Leading the team to design a 3 bladed design which has a very long chord length and fits perfectly within the constraints of the competition rules and regulations. The chord length and twist of the blade root elements were exaggerated to provide the optimal amount of lift to get the blades to cut-in. The main objective of the blade design was to take up as much rotor plane area as possible to get as much power out of the wind as possible. The stresses on the blades and hub are included in the rendering document which was found using ANSYS Workbench FEA software.

Manufacturing of the blade design incorporated a mold that was completed in SolidWorks. This mold is made up of two sections that have been rapid prototyped to be able to form the very thin shape of the blade profile. These two halves come together to make a single blade. One-half of the mold can be seen in Figure 12.

An extremely thin and strong design was needed to ensure that the blades could be made as thin as possible. Various iterations of the blade design were rapid prototyped to see how the design would look and perform in the wind tunnel. The team sought out the design of carbon fiber blades, over 3D printing, so that the blades could meet the dimensional criteria the team needed. The blade profile could

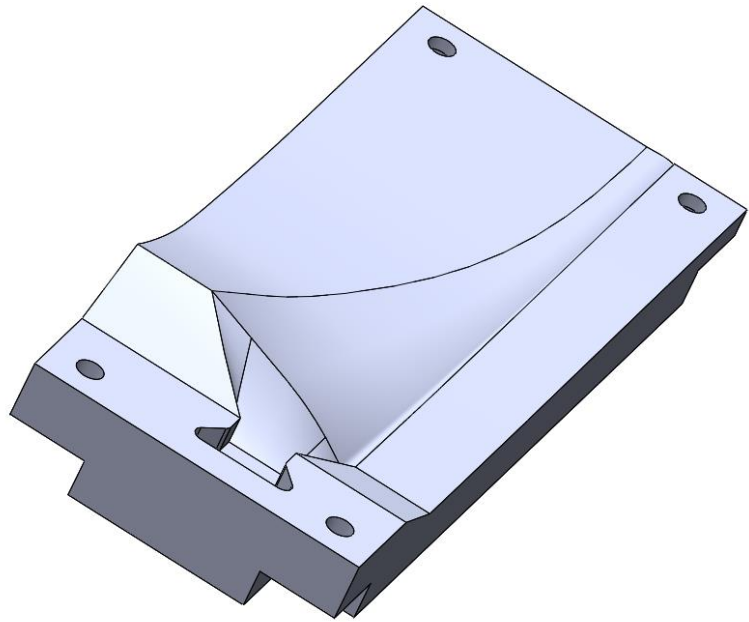


Figure 12: Blade Mold Design

not be rapid prototyped because the blades were so thin and that the machine could not generate the blade tip. A mold was designed in order to create the exact geometry that was needed.

4.2 Blade and Hub Design Modeling

The team iterated through many blade designs which were all modeled through FEA software. The team's FEA expert was able to accurately determine the factors of safety and other stress concentrations that occurred on the blades. Using the ANSYS Workbench, the team applied directions of forces, material properties, and geometry of the designed blade and hub for the rotor. Through this analysis

the team was able to inspect each blade element through a fine mesh that was modeled. For the hub, the highest stress concentrations were located at the edge of the blade root slots. This was because of the radial force that the blades will reach from the maximum RPM. For the blades, the team was concerned about the flapwise bending moment forces acting on the blades. These forces proved to show very slight deflections of 5 millimeters at the tip and factors of safety of 1.5. The described FEA modeling of the blades and hub is shown in Section 2 of the Rendering Document.

4.3 Tower Design Modeling

Analysis initially completed on the tower showed that the tower exhibited fairly large deflections at the desired height and diameter. To minimize deflection, guy wires are used to stabilize the tower. In order to determine the optimal position to reduce buckling deflections, the resultant tension force was placed at a series of heights initially aligning with tower segment, or 6ft (1.83m), increments. This analysis found that the ideal guy wire location was at 14ft (4.27m). Bending analysis was completed assuming the highest stress scenario would be when the tower is raised with a maximum nacelle weight of 60N. Section 2 of the rendering document shows the tower deflection due to a buckling stress from the weight of the components up tower.

Table 1 provides a summary of the results obtained from the analyses done. Using the values for maximum stress, obtained using finite element analysis on the tower design with guy wires, the minimum factor of safety was found to be 4.2, occurring while raising the tower.

Table 1: Tower Analyses Summary

Analyses With Guy Wire Supports for Max Load	
Top Load from Turbine Weight	60 N
Wind Load	100 N
Tower Height	6 m
Maximum Bending Stress	55 MPa
Bending Factor of Safety	4.2
Maximum Buckling Stress	0.4 MPa
Buckling Factor of Safety	180

4.4 Nacelle Flow Modeling

Research conducted on faired tower sections for downwind turbines showed that implementing this design could reduce vortex shedding and decrease loads on the blades. Further analysis was completed using Solidworks Fluid Flow Simulation to determine an ideal taper angle. Several iterations of this analysis was completed with differing taper angles to determine which angle would work best at the rated wind speed of 12 m/s. Based on the results of the velocity flow profile and flow trajectory plots shown in Section 3 of the Rendering Document, a 12 degree taper angle was found to be the best for angle for this application. Flow simulations were also done at the cut in and cut out wind speeds of 4 m/s and 17 m/s for the chosen taper angle in order to verify results.

4.5 Base Design Modeling

To ensure that the material of the base would be sufficient to withstand the forces it was exposed to, analysis was done on the assembled base design in SolidWorks. The individual components of the base were made out of 16 gauge metal in SolidWorks and were assembled as a single assembly using welds. The main force that the base must withstand takes place at the pivot point on the base where the tower bolts to the base. Therefore, the force exerted by the tower under operating conditions was placed there to analyze the Von Mises stress and the displacement. From the FEA analysis seen in Section 2 of the Rendering Document, it can be seen that the greatest Von Mises stress is 2.24MPa and the greatest deflection is 1.82×10^{-2} mm. From this data, it was found that 16 gauge sheet metal was sufficient for the design of the base.

5.0 Engineering Diagrams

An image of the current design configuration is shown in Section 1 of the Rendering Document. This design displays the complete rotor design, nacelle and other major turbine components in Figure 13. The assembled figure shows that all of the turbine components have the proper connections. The hub is connected to the drivetrain through a series of shafts and bolts. The drivetrain and electrical components sit on the mainframe and transmit power down tower via slip rings. The slip ring sits on the

yaw shaft which is enclosed by the integrated nacelle and the yawing system is attached to the tower with a threaded fixture.

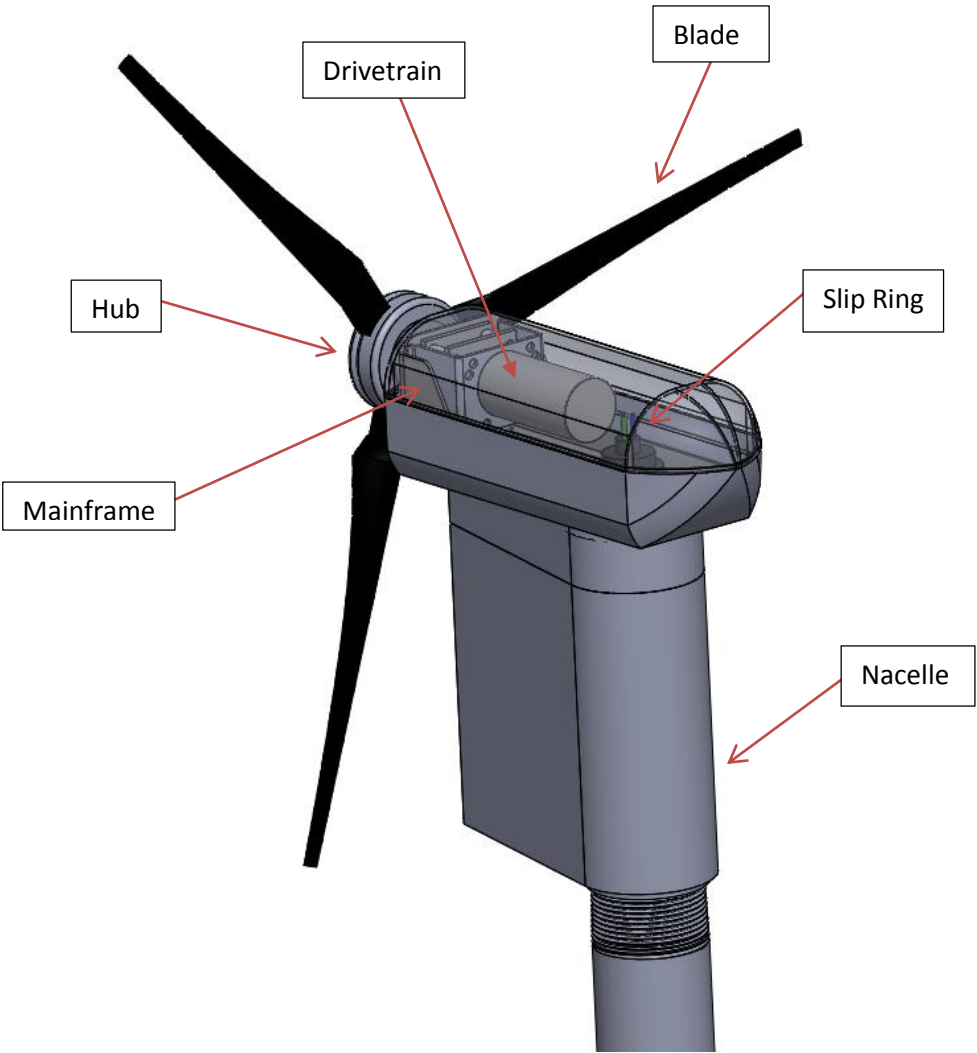


Figure 13: Turbine Assembly

6.0 Engineering Specifications

This section includes the mechanical and electrical engineering specifications of the current turbine design. The technical specifications of the turbine system can be seen in Table 2. Dimensions of major turbine components are detailed in Table 3 of this section.

6.1 Technical Specifications

Table 2 lists the technical specifications of the wind turbine system. Two blade options were considered for design, both of which are listed in the blades row of the technical specifications table.

Table 2: Technical Specifications

Temperature Rating	5 to 122°F (-15 to 50 °C)
Swept Area	962.1 in ² (6221 cm ²)
Rotor Diameter	17.5 in (44.5 cm)
Design Power	14 W at 20 m/s
Weight	35.3 lb (16 kg)
Shipping Dimensions	20"x18"x10"
Tip Speed Ratio	Outboard TSR of 7, Inboard decreases to 5.5
Turbine Controller	MSP430 16-bit microcontroller
Blades	(3) Carbon Fiber Composite (3) Polycarbonate Composite
Motor	Permanent Magnet Brushless In-Runner
Battery	12 V 10 Ah Lead Acid AGM
Airfoil Sections	Single Surface AirfoilS834 and CP-080-050-GN

6.3 Turbine Component Dimensions

Table 3 displays the dimensions of major turbine components.

Table 3: Major Turbine Component Dimensions

	Specifications	Value	Units
Blade Design	Rotor diameter	17.9	in
	Hub diameter	2	in
Yawing System	Yaw Shaft Outer Diameter	2.12	in
Tower	Outer Tower Diameter	1.89	in
	First three tower section lengths	6	ft ea.
	Final tower section length	3	ft
	Assembled tower height	21	ft
Mainframe	Length	6	in
	Width	2.3	in
	Maximum height	2	in
PCB	Length	4.45	in
	Width	5.1	in
	Maximum height	1.5	in
Battery	Length	5.94	in
	Width	3.88	in
	Maximum height	3.78	in

6.4 Power Curve Specifications

The following graph, shown in Figure 14, displays the power curve for the turbine design that was completed using NREL's FAST program to model the turbine design. This data uses the required dimensions of the blade shapes and also the mass of the design, plotting a power curve from a cut-in wind speed of around 5 m/s and a cut-out wind speed of 20 m/s. The calculated rated power is approximately 65 W at a rated wind speed of approximately 12m/s.

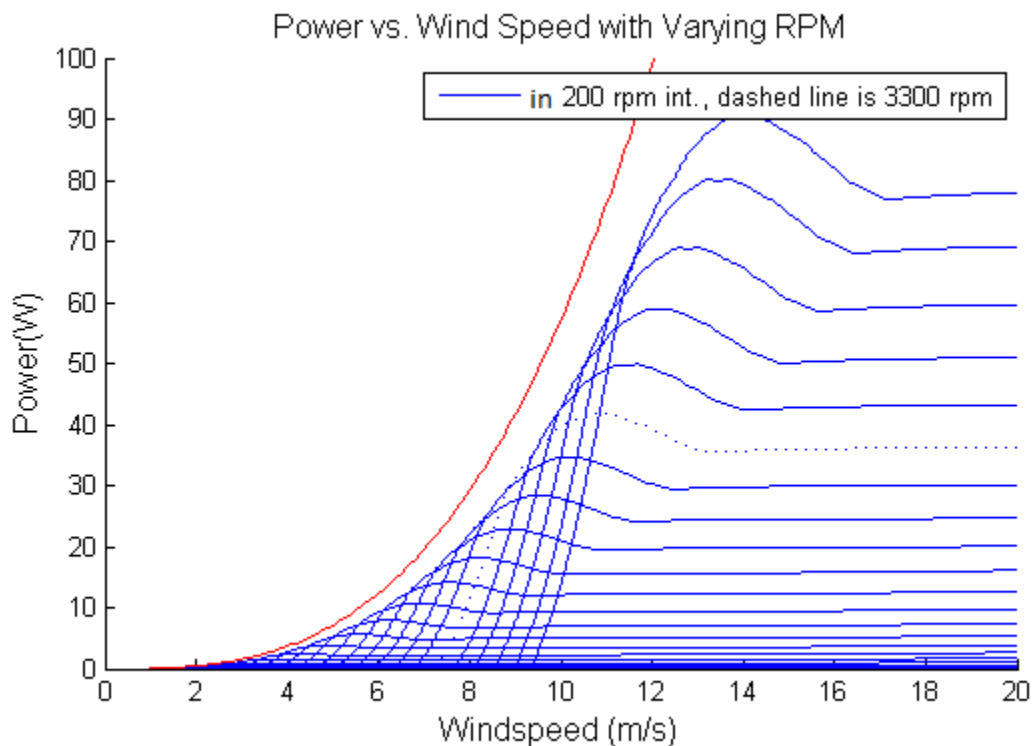


Figure 14: Initial Rotor Power Curve

7.0 References

[1] J.F Manwell, J.G. McGowan, A.L. Rogers, 2009 Wind Energy Explained: Theory, Design and Application 2nd Edition. Wiley Publications. Chapter 3, Section 3.9 pg. 131-13.

8.0 Appendices

8.1 Appendix A: Team Member Roles

Name	Project Role	Responsibilities
Andrew Hoffman	Project Manager	Team leader, MATLAB, Circuit Analysis and Finances
Carlos Tarango	Secretary	Spreadsheets, presentations, and PSpice
Ian Mason	Assistant Technical Lead	Wind Turbine Interface (MSP430 integrated circuit)
Jared Parks	Technical Lead	Wind Turbine Interface, electrical aspects of the wind turbine
Jonathan Pepper	Treasurer	Constructing PCB layouts
Mariflor Caronan	Rules/Regulation Expert	Coordinating info with team members on rules and regulations updates
Nathan Crowell	Technical Lead	Make sure everything is completed. FAST Program Leader
Devon Martindale	Project Manager	Directs team to stay on task. Compile Deliverables. FAST secondary lead
Gabriel O'Reilly	Machine Design Tech	Shaft Design Leader and Machine Design Leader
Norman Khoo	FEA/Stress Analysis Lead	COSMOS, SolidWorks, ANSYS FEA analysis leader
Chris Feyen	Hub Design Lead	Hub Designer and Secondary SolidWorks leader.
Kenneth Saxer	Computer Coding Lead	Software, BEM and SolidWorks Leader
Chris Bozorth	Technical Lead	Ensures technical aspects of the project are completed correctly.
Melissa Head	Project Manager	Facilitates communication between engineering and business students.
Kyle Yates	Inventory Control Lead	Ensures all turbine components fit together and are feasible to manufacture
Anna Manning	Software Lead	Ensures the design and analysis of turbine components in software are correct. SolidWorks leader
Charles Burge	Aerodynamic Specialist	Makes certain turbine components are aerodynamic
Ashley Jerome	Report and Presentation Lead	Edits documents and ensures that all necessary information is included.