COLLEGIATE
WIND COMPETITION
U.S. DEPARTMENT OF ENERGY

2018 Collegiate Wind Competition

Final Proposal Report

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2017-2018

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1 BACKGROUND

1.1 Introduction

Wind energy has been a major source of energy in many countries, especially the United States (U.S.). For example, the U.S. built their first wind turbine at the end of 1880's and it was generating about 12kW [1] Today's wind turbines are generating much more power with smaller sizes, which made a case for using wind turbines in the U.S. to meet the growing energy demand seen across the country. Currently, wind energy is providing about 5.6% of the overall energy in the U.S. The U.S. continues to use more wind energy and is actively supporting the growth of this market. One method of meeting the increased demand for technical knowledge of wind turbines is the Collegiate Wind Competition (CWC) that was made by The U.S. Department of Energy's (DOE) and the National Renewable Energy Laboratory (NREL).

The Collegiate Wind Competition was created in 2014 to increase the global clean energy in the U.S. The event has taken place every year since 2014 and involves different universities competing to increase college students' knowledge of wind turbines.

To build the wind turbine, students from different majors work together through multiple teams. There are two main teams: The Testing Team, which is made up of Electrical and Mechanical Engineering students. The Deployment team, which is made up of Business students as well as Mechanical Engineering students. The Testing Team also has two sub-teams, which are responsible for building the turbine. Each team has different components they are responsible for. The two sub-teams are Test Team A and Test Team B; Test Team B (henceforth Team B) is responsible for; the hub, rectifier, nacelle, brakes, yawing, load, and tower design.

1.2 Project Description

Team B was responsible for helping design, build, and test a wind turbine for the CWC taking place in May 2018. Team B derived this objective from the original project description provided by the CWC Rules and Requirements. Following is the original project description:

> *Teams participating in the 2018 Collegiate Wind Competition will be expected to research and design a turbine for a grid scenario with a high contribution of renewables. The turbine should be able to operate in islanded mode.[2]*

From this Rules and Regulations, the turbine must be able to charge a supercapacitor while the turbine experiences no load. After charging, the turbine will experience variable load resistance, thus requiring the power electronics to pull from the supercapacitor during high resistive loads. The ability to utilize an energy storage device during high demand simulates operating in "islanded mode". The turbine will also be tested on power curve output, safety, and durability to ensure the design reflects industry standards.

1.3 Original System

For the 2018 wind turbine, the team was redesigning Northern Arizona University (NAU) 2017 wind turbine. The 2017 design was an iteration of NAU's 2016 design and mainly focuses on the braking, yawing, blade performance, and power electronic topology. For Team B, the focus for redesign, was on 2017's Load, Rectifier, Brakes, Hub, and Nacelle subsystems.

1.3.1 Original System Structure

The 2017 wind turbine subsystems that pertain to Team B were; Hub, Brakes, Nacelle, Tower, Rectifier, and Load. The Hub consists of a main shaft design extended from the hub, where the blades connect, to the generator and brakes. It consisted of two shafts: a stub shaft that connects to the generator, and a drive shaft that operates the brakes. The type of brake system used was a mechanical disk brake. It consisted of a carbon fiber disk and aluminum friction brake pads and is activated by a current controlled solenoid spring. The Nacelle is an open-faced enclosure that contained the hub, generator, main shaft, and brakes. The Tower is a A513 thick-walled mild steel tubing with a A513 mild steel base plate. The rectifier used for the competition was an IXYS FUS45 three phase AC - DC rectifier. It consisted of six total diodes, since two are needed for passive rectification in each phase. Other components that paired with the rectifier were smoothing capacitors, bleed off resistor, and a heat sink. The type of load used was a voltage regulated resistive load for the competition. The team tested the voltage loads at 6V, 9V, and 12V for the competition which simulates the capacity of the storage element. Once the voltage approaches the test load, the regulator diverts power from the storage element to the load to keep the wind turbine stabilized.

1.3.2 Original System Operation

The 2017 turbine team had operational requirements to meet by completion and designed their project accordingly. The blade was designed in Q-blade, an aerodynamic blade modeling program. When tested, the blades produced 17 watts (W) of power at a wind speed of 10 m/s without accounting for electrical and mechanical losses. The blades, generator, and main shaft design were tested to withstand centrifugal, braking force, and thrust forces to simulate high wind speed. The transfer of energy from the generator, through the main shaft, and down the tower was achieved by the strong support of the mainframe and the stability of the tower. The electrical components consisted of a two part, three phase power rectifier, a boost converter, and resistive load. The circuit was designed to have an AC input, coming from the generator, to be converted to DC from the power rectification. After the conversion from AC-DC, the current flows through a DC-DC converter in order to boost voltage if necessary and increase the power to the load. The team tested the voltage loads at 6V, 9V, and 12V for the competition which simulates the capacity of the storage element. Once the voltage approaches the test load, the regulator diverts power from the storage element to the load to keep the wind turbine stabilized [3].

1.3.3 Original System Performance

The blades were supported by a main-frame design that tested its stress and deflection limits. The resulting maximum stress was 9.16 MPa and the maximum deflection was 0.097 mm. The tower's performance was also tested on its ability to withstand stress at its welding points and the deflection at high winds. The maximum stress of the weld is 6.50 MPa and the maximum deflection of the tower is 0.075 mm. These turbine components all operated under a passive yawing system which lets the blades position in the direction of max wind speed by themselves. The electrical components were tested under 6V, 9V, and 12V input in order to receive the response of the output [3].

1.3.4 Original System Deficiencies

There were a few issues with the 2017 wind turbine that affected the overall outcome of the competition. The passive yawing system that the team used does not give the team direct control of the turbine and which direction it faces. This system does not allow the team to reposition the blades when the turbine needs to be immediately shut off. Another issue was the three phase rectifier. A three bridge is a relatively simple in design and only requires a few components, however, there is a significant power loss in diode control rectifiers which can affect the output of the entire system. This can prove to be a problem at low wind speeds because if there is power loss in the rectifier, you cannot draw power from the load because of its low voltage [3].

2 REQUIREMENTS

The CWC rules and regulations outlines many testing specification requirements for competition. This section covered those testing specifications as well as customer requirements given by the client. Those specifications can be outlined as either Customer Requirements or Engineering Requirements. In the following sections, the customer and engineering requirements are described in detail.

2.1 Customer Requirements (CRs)

The CWC guidelines were reviewed to select all appropriate customer requirements. Each CR's description is derived from the details specified in the Rules and Regulations. Each requirement was weighted by the importance specified by the competition. Each CR, weighting, and description can be seen in Table 1.

Customer Requirements	Weighting	Description
Durability	4	The turbine must continue to meet expectations under numerous stressful situations.
Yawing Capability	4	The turbine must yaw to maximize the wind provided.
Limited Size	3	The turbine is confined to a 45cm x 45cm x 45cm total volume.
Electrical Safety	5	The turbine has awareness of safety designed within its electrical & mechanical components (connectors, ventilation, and bleed off resistor).
Mounting System	2	Keep the turbine stationary to the base connection provided by the competition.
Electrical Grounding	2	The grounding is provided by the competition and requires minimal effort to install a connectible ground.
Wiring	1	Safe wiring with sizes appropriate to the competition provided connections.
Purely resistive load	3	Achieve the most stable output from the turbine.
Storage element	2	Electronic circuits must connect to the competition provided storage element.
Braking	5	A braking system is required for turbine safety and regulating power output. Also the system must be connectable to the closed switch provided.
Rotor capacity	4	The power produced in a turbine is directly related to the area for the rotor and blades.

DC signal output	5	The output of the turbine must be DC Voltage

Table 1: Customer Requirements

2.2 Engineering Requirements (ERs)

The Engineering Requirements (ERs) for Team B, seen in Table 2, consist of the components in which the team members oversee. The ERs are based on the customer requirements established by the DOE. Aside from the guidelines that Team B must abide by, Team B has the ability to select materials for manufacturing the test turbine. The following list showcases those ERs and the target or design-to values with tolerances for Team B.

Number	Engineering Requirements	Design Values	Tolerances
1	Tower Modulus of Elasticity (GPa)	200	± 20
2	Hub Modulus of Elasticity (GPa)	200	± 20
3	Nacelle Modulus of Elasticity (GPa)	200	± 20
4	Tail Fin Surface Area (m^2)	0.2025	± 0.05
5	Hub Volume (m^3)	0.091	±0
6	Nacelle Volume (m^3)	0.091	± 0
7	Tower Volume (m^3)	0.091	± 0
8	NEMA Electrical Rating	Type 1	± 0
9	Base Plate Thickness (mm)	16.1	± 2.5
10	Base Plate Fixture Area (m^2)	0.0176	± 0.005
11	Base Plate Modulus of Elasticity (GPa)	200	± 20
12	Base Plate Tensile Strength (GPa)	440	± 40
13	Ground (kΩ)	100	± 10
14	Turbine Wire Length (m)	>1	± 0.5
15	Voltage Limit (V)	<48	± 5
16	Wire Guage (AWG)	10->20	± 2
17	Resitive Network (kΩ)	Unk	± 10
18	Applied Brake Force (N)	12	± 2
19	Brake Current Draw (Vm)	1	± 0.2
20	Manual Switch Cable Length (m)	2	± 0.5
21	Manual Switch Cable Guage (AWG)	22-28	± 2
22	Rectifier phases (#)	3->1	± 0
23	Angular Velocity (°$/sec$)	180	± 0
24	Rotation (°)	360	± 0

Table 2: The Engineering Requirements with their Target Values and Tolerances.

Many of the ERs involve the electrical system due to the several electrical components that Team B designed. The majority of the other ERs involve the structural integrity of the turbines mechanical components. These ERs helped guide Test Team B to create components that satisfied the customer requirements.

2.3 Testing Procedures (TPs)

The engineering requirements have been numbered 1-24 in the section 2.2. From this, a testing procedure has been developed for each subsequent requirement and are presented below.

1-3: The engineering requirement of Modulus of elasticity of the Tower, Nacelle, and hub will be tested under the following procedure; each component will be set up with a force sensor from the materials laboratory and a force will be manually applied to each component material to record the deflection and apply the equation for modulus of elasticity.

4: The yaw fin surface area will be tested by applying a conservation of angular momentum aerodynamic analysis to the system via a MATLAB script. The angular momentum theory along with yaw aerodynamic statistics will determine the geometry that is suitable for the tail fin. Once the tail fin geometry is determined mathematically, it will be modeled tested on a smaller scale within the AeroLab wind tunnel to study the yaw error of the system.

5-7: The volume of each component will be determined by finding the medium of each component having a high modulus of elasticity while being contained within the 45cmx45cmx45cm competition containment box. The blades, hub, and nacelle will take priority spacing, from which the remaining components will be design to fit the requirements.

8: NEMA type 1 electronics enclosure ratings will be verified by purchasing an enclosure from a reputable source that builds to NEMA standards. NEMA type 1 enclosures are constructed for indoor use to provide protection to personnel against access to hazardous parts and to provide a degree of protection of the equipment inside the enclosure against ingress of solid foreign objects (falling dirt).

9-12: The base plate will need to be first measured in order to insure that the thickness is not greater than 16.1 mm. This will be done using calipers from the NAU machine shop. The fixture area will be measured using calipers as well and will be done to insure that the entire test turbine can be attached to the wind tunnel for competition. The modulus of elasticity is known when purchasing through the manufacturer.

13-16: The voltage limit, electrical grounding, wire length and gauge requirements are tested by regulating the electrical components to less than 48V while also being properly grounded. The wire gauge and length is determined by testing connections between Team B's wire gauge size and the competition provided connection sizes.

17: The resistive network will be tested under high and low voltage and current values to determine the proper resistances to regulate the power generation and heat dissipation.

18: The applied brake force is measured by testing the solenoid's function and measuring the axial distance change from the solenoid. Knowing the supplied voltage and current to power the solenoid, the power can be calculated. From which, the force can be calculated and validated for the system.

19: Brake current draw is to be tested under high and low voltage using a multimeter. The multimeter will measure the current values across the brake.

20: Manual switch cable length is to be a minimum of two meters. To verify this length the team will use a tape measure.

21: Manual switch cable gauge is to be a gauge of 22-28AWG. To verify this gauge the team will use a pocket wire gauge, a tool that measures gauges.

22: The rectifier phases is to be tested using an oscilloscope. The oscilloscope will be able to measure the three AC inputs and verify that each line is 120° out of phase from one another. In addition, the DC output will be measured using the oscilloscope to confirm there is only one output line.

23: Angular Velocity necessary to produce power will be tested and verified via QBlade simulation as a part of Test Team A's analysis.

24: The degree of rotation for the system will be tested simply by applying a moment at any location along the nacelle, excluding the axis of rotation, to determine if the system is capable of rotating 180 degrees. The angular velocity will be measured by timing the amount of time is required for the nacelle to rotate about the towers axis.

2.4 House of Quality (HoQ)

The House of Quality which is fully detailed within appendix A, is a tool that connects the customer needs with the engineering requirements. The rules and regulations that Team B abided by include both the Customer and Engineering requirements. Setting up the HoQ allowed the team to see which components of the turbine are critically important to doing well in the competition. Table 3 shows a few of the ER's related to our customer requirements and the importance of those requirements in relation to our overall project. Generating the HoQ revealed that the most important ER for Team B is the voltage limit that is generated by the wind turbine. This corresponds with meeting the limitations of the rules and regulations.

Table 3: A sectional view of the overall HoQ.

		Units	GPa	GPa	GPa		
Customer Requirement	**Weight**	**Engineering Requirement**	Tower Modulus of Elasticity	Hub Modulus of Elasticity	Nacelle Modulus of Elasticity	Tail Fin Surface Area	Hub Volume
Durabilty	4		9	9	9	1	1
Yawing Capability	4					9	1
Limited Size	3					9	9
Electrical Safety	5						
Mounting System	2						1
Electrical Grounding	2						
Wiring	1						
Electrical Output	4						
Purely Resitive Load	3						
Storage Elements	2						
Ventilation	3						
Lead Off Resistors	4						
Electrical Connectors	4						
Braking	5						
Close Switch	3						
Rotor Capacity	4						
DC signal Output	5						
Absolute Technical Importance (ATI)			36	36	36	67	37
Relative Technical Importance (RTI)			14	14	14	2	13
Target ER values			200	200	60	0.2025	0.091
Tolerances of Ers			± 20	± 20	± 10	± 0.05	±0
Testing Procedure (TP#)			1	2	3	4	5

The ER, Tail Fin Surface Area, is determined to be the second most important factor in meeting the customer requirements according to the Relative Technical Importance (RTI). Therefore Team B spent more time finding the correct tail fin area to be successful in the competition.

3 EXISTING DESIGNS

This chapter will cover the research done by Team B and shows the organizational breakdown that has been created to help with the designing efforts. Team B used different means of research to help understand a wind turbine and be aware of how sub-systems work together to achieve a functioning small wind turbine for competition.

3.1 Design Research

Existing designs were analyzed by benchmarking previous CWC wind turbines. These turbines were all developed by previous NAU engineering students and have allowed the team to analyze previous approaches taken. As a team, each test turbine was taken apart and examined to see how each subsystem was constructed. Frequent communication with NAU faculty member David Willy has taken place to ensure a full understanding of each previous year's turbines and areas in which this year's team improved. Individual turbine subsystems were researched to further analyze wind turbine options that meet the competition's ERs. This process consisted of web searches and meetings with NAU faculty members from relevant fields to see what is most commonly used in existing designs.

3.2 System Level

The team has looked into similar designs that Team B's turbine is modeled after. Professor David Willy has instructed Team B to reverse engineer each of the previous NAU Collegiate Wind Competition turbines to determine their strengths and faults. These system level designs are used as templates for the new 2018 CWC turbine to be based off of. These systems are useful templates because they are designed around similar engineering requirements. [4] All similar system-level designs must be a horizontal axis wind turbine, generate electricity (DC output signal), rotate along the vertical axis for yawing, and have a braking system. Some of the systems design these sub-level components more effectively than others and are helpful for determining the direction of Team B's design.

3.2.1 Existing Design #1: 2013 Competition Turbine

Figure 1: 2013 Competition Turbine

This system-level design, shown in Figure 1, is a rough template for redesign. Many of the engineering requirements were not met on the 2013 competition turbine. The 2013 turbine was designed to operate downwind which seems unpractical for Team B's redesign. During the competition a major design flaw was discovered: the nacelle is too large and blocks the flow of wind from contacting the lower section of the blades. This flaw made it difficult for the turbine to begin rotating, however the blades were designed to maintain rotation. As a result, once the system overcame the cogging torque it operated well. The 2013 turbine's tower was threaded in two places unlike similar designs that attempt to minimize tower components. Having the tower threaded in two locations is a poor design option when considering the competition endurance test that rotates the turbine 180 degrees per second. The spinning nacelle could cause the tower to unthread and fall into pieces. By reverse engineering this system, Team B was able to gather information on important design considerations.

3.2.2 Existing Design #2: 2014 Competition Turbine

Figure 2: 2014 Competition Turbine

This system-level design, shown in Figure 2, is the most basic template for our 2018 redesign. It is comprised of very few components in comparison to other designs. The 2014 turbine has a yaw tail attached to it but operates in a fixed position due to poor bearing design. Similar to the 2013 competition turbine, the 2014 turbine utilizes the generator, operating as the load, as a braking mechanism. This brake system design was not successful because it slows the turbine slightly rather than stopping it completely. This turbine gave Team B a good idea of what to avoid when making design selections.

3.2.3 Existing Design #3: 2017 Turbine

Figure 3: 2017 Competition Turbine

This system-level design shown in Figure 3 is the best template for Team B's 2018 redesign. This system contains dramatic differences in sub-system designs. There are significant increases in the quality of the components. One of the new sub-system designs is the braking mechanism. The brake for this system is mechanical and utilizes a disk brake activated via a solenoid when voltage levels become too high. The team initially had a smaller tail for yawing but this design did not take into the account of the thrust force of the blades and a new tail was successfully improvised for the competition. Overall, this system is a useful guide as Team B moves forward with designing the 2018 turbine.

3.3 Functional Decomposition

Illustrated in Appendix B is a breakdown of a wind turbine into each component that both Test Teams A & B were responsible for designing and building for the CWC. Team B is responsible for the rectifier, load, hub, tower, brakes, nacelle, and yawing. Team B's Black Box and Functional Model only consider the subsystems that they are responsible for.

3.3.1 Black Box Model

The Black Box model in Figure 4 helped Team B understand what inputs the wind turbine have provided and what the outputs of the system. It is important to know that the wind turbine is reliant purely on wind both as a material and as energy in order to generate electrical energy. This requires the design of the hub, tower, and nacelle to be built in a way that optimizes the amount of energy the blades produce from the wind. The power electronics heat up as the generator sends current through the rectifier, chopper, and load. This thermal heat can change the electrical components' characteristics and, if not properly ventilated, can cause components to malfunction. The other energy output for the wind turbine is electrical energy. Team B wants to maximize the electrical energy output by designing a rectifier and load with minimal power losses.

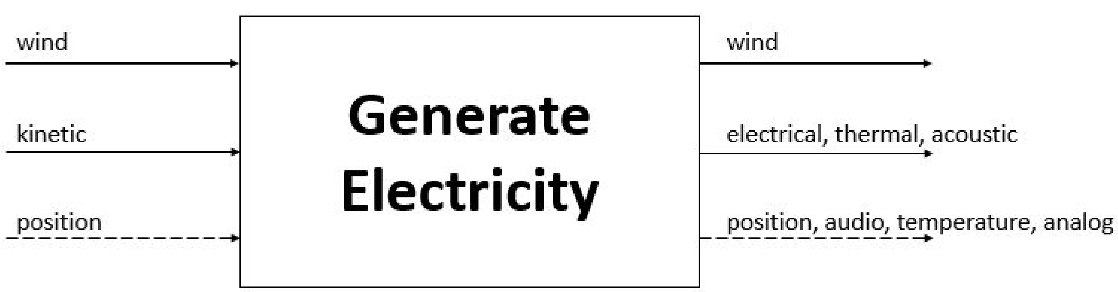


Figure 4: Black Box Model

3.3.2 Functional Model/Work-Process Diagram/Hierarchical Task Analysis

Illustrated in Figure 5 is the functional model that breakdowns how the wind interacts with parts of the turbine and creates mechanical energy. This mechanical energy goes into the generator and emits electrical energy that flows through the rest of the power electronics and load. These components produce thermal energy as well as output electrical energy. This Functional Model helped break down the Black Box model more thoroughly and allows the team a more in depth analysis. The model also helps with understanding wind power and how a wind turbine system works.

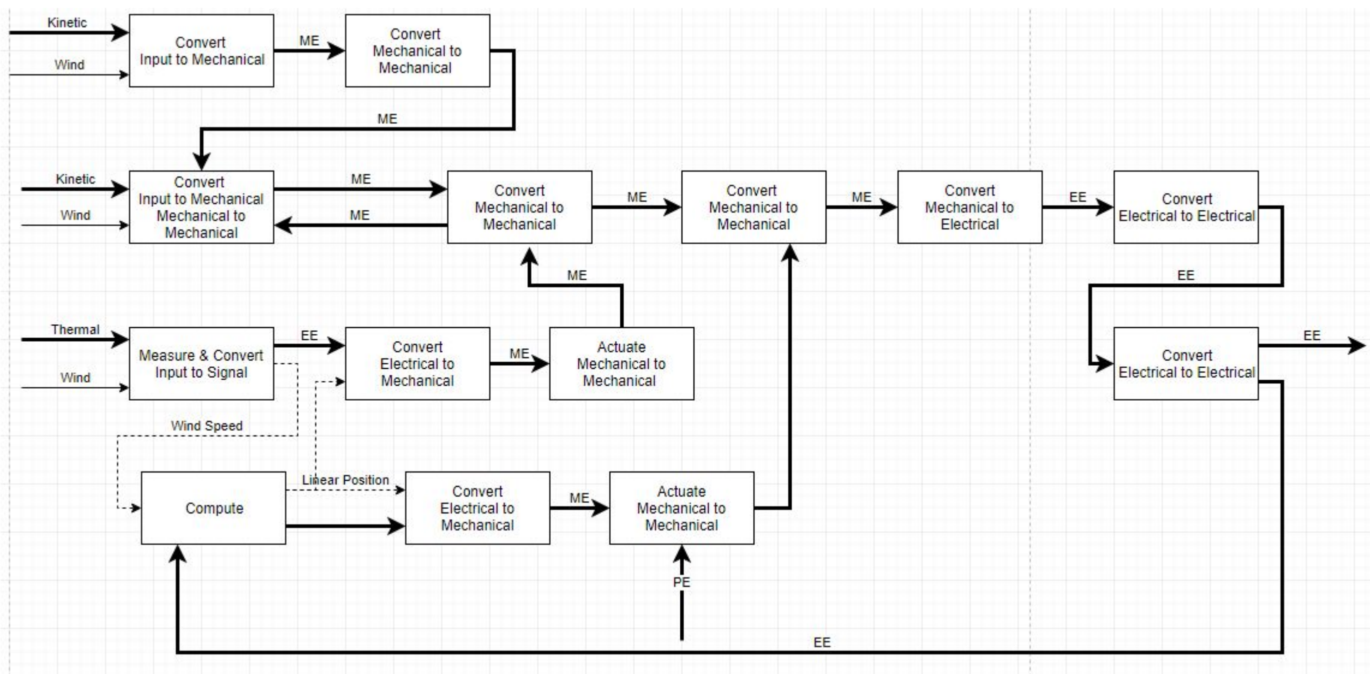


Figure 5: Functional Model

3.4 Subsystem Level

The overall wind turbine requires a number of different subsystems which need to be designed and optimized by meeting the customer requirements. Team B has the following subsystems that were analyzed: the system load, hub design, voltage rectifier, tower, nacelle, brakes, and yaw.

3.4.1 Subsystem #1: Voltage Regulator

The importance of the voltage regulator is to keep the voltage output steady with no voltage drop. There are different types of voltage regulators and there are some types of diodes that do the same work as the voltage regulator does for instance the linear voltage regulator, switching voltage regulator, and Zener diode.

3.4.1.1 Existing Design #1: Linear Voltage Regulator

The linear voltage regulator, shown in Figure 6, is a basic way to have the constant voltage the circuit needs. The voltage regulator has three pins one for input, the second is connected to the ground, and the last one is for providing a stable voltage output. [5]

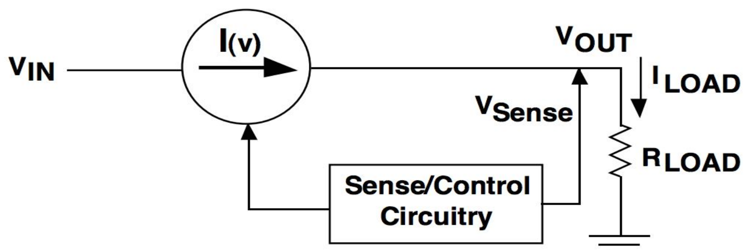


Figure 6: Linear voltage regulator [6]

3.4.1.2 Existing Design #2: Switching Voltage Regulators

The switch voltage regulator is one of the most efficient voltage regulators due to the series elements, which are either off or conducting. The regulator switches the input signal on and off at a very fast pace time essentially creating a pulse input. The circuit is then able to use a combination of MOSFETS, capacitors, and resistors to keep the voltage at a consistent value [7]

3.4.1.3 Existing Design #3: Zener Diodes

Zener Diodes, like the one shown below in Figure 7, work in different way than the other Diodes because it can be used as a voltage regulator. Zener diodes are different from other Diodes because the current can flow in both directions. [7]

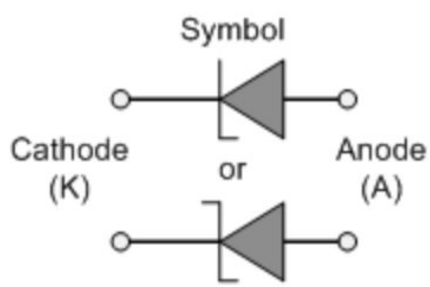


Figure 7: Zener Diodes [8]

3.4.2 Subsystem #2: Hub Design

The hub of the turbine is important because the hub connects the shaft to the blades of the turbine. The stresses from the thrust produced by the blades is concentrated at the hub. The connection between the hub and the blades are important because it converts the rotational energy of the blades to the rotational energy of the shaft in order to produce power.

3.4.2.1 Existing Design #1: Passive Pitching Spring Hub

This subsystem would involve springs mounted inside of the hub that would attach to the blades and cause them to turn depending on the wind speed. This system uses rotational inertia to cause the blades to pitch more and more depending on how fast the blades are spinning.

3.4.2.2 Existing Design #2: Active Pitching Hub

This subsystem would be either an electronic or mechanical actuator that would actuate depending on the wind speed. This design would allow the braking system to break faster and would decrease the cut in speed of the blades.

3.4.2.3 Existing Design #3: Flat Fixed Pitch Hub

This subsystem design would mimic previous designs by using a mechanical system to clamp the blade in order to hold them in place. This design would cost the least and still provide the needed mounting points for the blades.

3.4.3 Subsystem #3: Rectifier

The rectifier of the turbine is very important because it changes the current from AC to DC, allowing energy to be stored to the load. It is also crucial to the CWC because a failure to convert to DC results in a zero for the testing section of the competition. This component could be removed if test team A decides to go with a DC generator instead of an AC generator.

3.4.3.1 Existing Design #1: Full Wave Rectifier, Three Phase

The diode rectifier (uncontrolled rectifier) based converter system transfers power in a single direction, e.g. from generator to the grid. This type of power converter is normally used in a wound rotor synchronous generator (WRSG) or a permanent magnet synchronous generator (PMSG) based wind power generation system instead of an induction generator. This design uses six diodes to transfer power into a single direction. Illustrated in Figure 8 is a schematic of a full wave rectifier discussed in this section. A full wave rectifier would fulfill the testing requirements outlined in CWC rules and regulations stating that the turbine must emit a DC value in order to qualify for scoring.

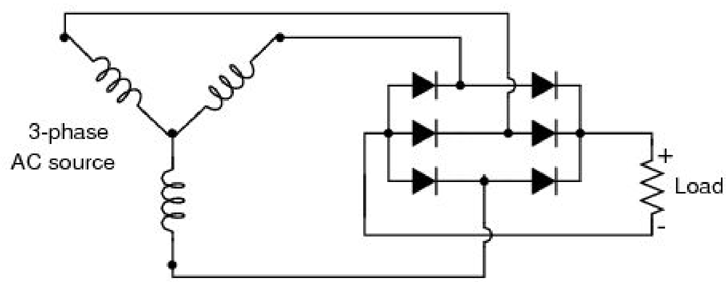


Figure 8: Three Phase Full Wave Bridge Rectifier [9]

3.4.3.2 Existing Design #2: Three Bridge Rectifier

A three bridge rectifier provides a slightly better current capacity and better heat dissipation than the full wave rectifier. This design uses twelve diodes to transfer power into a DC signal. This design has the potential to create a bigger voltage drop because of the increase in diodes, however the results create a DC output with less voltage ripple[9].

3.4.3.3 Existing Design #3: Ideal Rectifier

An Ideal rectifier utilizes MOSFETs or other transistors to control the DC output with minimal loss[9]. This system utilizes a comparison to allow current flow when the voltage is above the reference voltage of zero volts, allowing for a fluid movement of the DC output.

3.4.4 Subsystem #4: Tower

The tower is one of the most crucial components of the wind turbine. Many of the stress concentrators occur along the tower. The design of the tower must be able to withstand the weight of the other components of the turbine as well as the forces applied to the wind turbine along the blades, nacelle, and tower [10]. There is no one way to design a tower, so several design variables are considered. Towers are almost exclusively manufactured with steel [11].

3.4.4.1 Existing Design #1: Freestanding Tower

A freestanding tower consists of one or more pipes beginning from the base of the turbine up to the nacelle. This is the simplest of tower designs and is the most widely used design for large-scale wind turbines. The tower structures are hollow as the size increases but a larger foundation is needed at the bottom to support the turbines components [11].

3.4.4.2 Existing Design #2: Tilt-up Tower

A Tilt-up tower design incorporates a pivot point at the base of the tower. The Tilt-up design allows the turbine to be raised or lowered in case of inclement weather. This style of tower prolongs the life of the turbine increasing its durability. The Tilt-up tower is primarily used for smaller wind turbines ranging from one to five kilowatts in energy output [12]. Therefore these towers are mainly seen providing additional power to homes and small businesses rather than industrial areas.

3.4.4.3 Existing Design #3: Guyed Tower

A Guyed Tower consists of a freestanding tower with tie down cables attached to the Nacelle to help resist much of the force applied to the tower by the wind. The tower usually consists of a lighter tower material which lowers overall cost [13]. Guyed towers can be seen in small to medium scale providing power to homes and for research purposes.

3.4.5 Subsystem #5: Nacelle

The Nacelle is the component which houses the shaft, generator, gearbox, and yawing systems of the wind turbine. Without a Nacelle, a wind turbine would not be able to easily turn into the direction of the wind. To capture the largest amount of energy, a wind turbine must be pointed in the direction in which the wind is coming from. An efficient turbine must have a working Nacelle in place.

3.4.5.1 Existing Design #1: Open Frame

All the components within the Nacelle are visible. Having visibility of our components would allow us to see if our turbine is working properly. If anything was to malfunction while under testing, the system could be shut off for safety purposes. Open Frames allow for easier access to each component inside of and attached to the Nacelle for quick replacement or improvement [14].

3.4.5.2 Existing Design #2: Closed Frame

A closed frame Nacelle allows for different types of blade designs such as an upwind or downwind blade type [11]. Aside from different blade designs, the closed frame nacelle looks better aesthetically compared to an open frame design. Issues with a closed frame are more prevalent in downwind systems as the airflow passes around the nacelle along a larger area, preventing flow to the base of the blades.

3.4.6 Subsystem # 6: Brakes

This subsystem is included within the design to either slow the turbine down, or stop it completely during moments of high current, as well as the competition actuated brake test and loss of power test. The brake is a necessary subsystem that maintains control over the blades rotation and prevents the turbine from destructing if rotating too fast. Two of the most popular designs for small wind application where taken into consideration for the turbine, dynamic and mechanical braking.

3.4.6.1 Existing Design #1: Dynamic Brake

This subsystem design variation utilizes the generator as the load during a moment of current overload and creates a reverse in the flux of the magnets in the generator. This magnetic resistance makes it difficult for the blades to rotate and slows down the turbine. Throughout previous competition years, this method of braking has not been successful because it cannot completely stop the blades if there are high wind speeds. A positive aspect of this braking mechanism is that it requires very few components by repurposing existing systems.

3.4.6.2 Existing Design # 2: Mechanical Disc Brake

This subsystem design variation is a current actuated, spring loaded arm with rubber stoppers. A voltage meter is connected to a solenoid that actuates the spring when current is too high. When actuated, the arm clenches a rubber disk attached to the shaft to stop the rotation of the blades during a moments of current overload, loss of power, and actuated braking. A positive aspect of this design variation is its effectiveness for completely stopping the brakes. This braking method was very successful for the 2017 CWC team. A downside to this design is that it is very technical and requires additional components. The additional components add weight and reduce available space in the nacelle.

3.4.7 Subsystem # 7: Yaw

This subsystem is included within the design to orientate the turbine such that the blades are constantly positioned in the direction of the wind. This method of variable orientation allows for the blades to capture the wind more efficiently, thus producing greater power.

3.4.7.1 Existing Design #1: Active Yawing

Active yawing turbines utilize an electric motor that rotates the turbine blades into the direction of the wind based on automatic signals, either from wind direction sensors or manual actuation. A positive aspect to an active yawing turbine, if implemented successfully, is continuously remaining in the direction of the wind and generate greater amounts of power. Oppositely, one of the major downsides of an active yaw turbine is that it requires many mechanical and electrical components for it to operate effectively. All active yaw systems include a rotatable connection between nacelle and tower known as a yaw bearings. This type of yaw system also contains a yaw drive to actively variate the rotor orientation. For the turbine to stop rotating a yaw brake is required to restrict the rotation of the nacelle. For the yawing system to operate in such a way that the blades remain facing the direction of the wind, a control system is necessary. A control system processes the signals from wind direction sensors such as wind vanes or an anemometer. [15] Although active yawing gives the user control of the turbine orientation, the additional components have potential to increase error. These components increase the weight of the turbine and decrease valuable space.

3.4.7.2 Existing Design #2: Passive Yawing

Passive yawing systems analyze aerodynamics on a flat plate of flexible geometry to orientate the turbine blades into the direction of the wind by summing forces of thrust, lift, and drag. In their simplest form a passive system comprises of two components. A simple roller bearing connection between the tower and the nacelle, and a tail fin mounted on the nacelle. Although simple, passive yaw systems have been very successful in small wind application when designed appropriately. The tail fin is designed in such a way that it turns the wind turbine rotor into the wind by exerting a corrective torque to the nacelle. By analyzing the aerodynamics on the tail fin, the corrective torque is equal and opposite of the torque being applied by the wind. This allows for the turbine to constantly remain facing into the direction of the wind. It is easier for the fin to exert a torque on the nacelle when it is placed further away from the axis of rotation. However, competition requires the turbine to fit within specified dimensions. Therefore, the tail fin is close to the nacelle and has to be much larger for it to operate effectively.

3.4.8 Subsystem #8: Load

The load carries the power output from the turbine. It is necessary to stabilize the circuit and prevent overvoltage and overcurrent fed back into the circuit.

3.4.8.1 Existing Design #1: Resistive Load

A resistive load is a power absorbing system, meaning that all the power generated from the circuit is dissipated at the load rather than fed back into the system. The DC resistor, seen in Figure 9, stabilizes the wind turbine by *resisting* electrical flow of the generator, slowing the blades and not allowing them to spin out of control. The voltage regulator dictates where the power is going after it is generated. There are two places: the storage element and the load for the power divert. The voltage regulator determines that by the amount of voltage stored in the storage element.

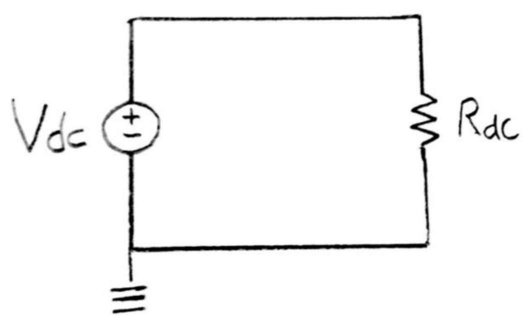


Figure 9: Resistive Load

3.4.8.2 Existing Design #2: Resistive - Inductive Load

A resistive and inductive load is half active and half reactive. A reactive load feeds power that is produced back into the circuit by an inductor see Figure 10. The inductor experiences a high inrush current when it is turned on, meaning the current spikes to a high value before settling down to a lower value (steady-state). This means that the other electrical components can experience the effects of the inrush current, potentially damaging them [10]. However, an inductance can also provide a short source of power if the production from the wind turbine falls at low winds. The inductance can also be used to step up the voltage, with the coupling of a few other electrical components, if the turbine first needs to pull power from the load in islanded mode.

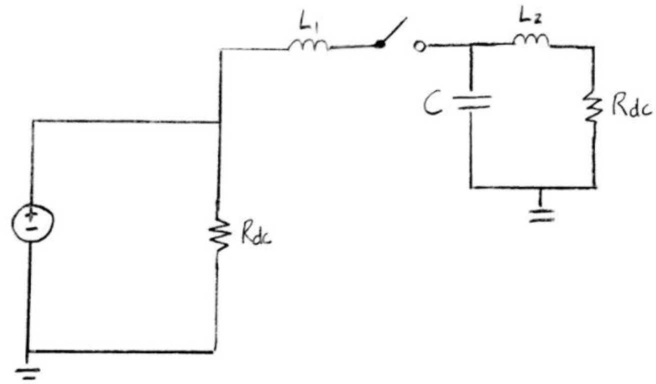


Figure 10: Resistive Inductive Load

4 DESIGNS CONSIDERED

Each of the existing subsystem designs mentioned throughout section 3 were taken into account while iterating full scale designs. Through these iterations, Team B created three full designs that would incorporate each subsystem into a functioning turbine. Through rigorous discussion and research on existing subsystems, the team selected the subsystems to further study and begin implementing. The considered designs for the team's subsystems are illustrated throughout this chapter in sections 4.1 to 4.6. The remaining designs considered can be found in Appendix C.

4.1 Design #1: Full Build #1

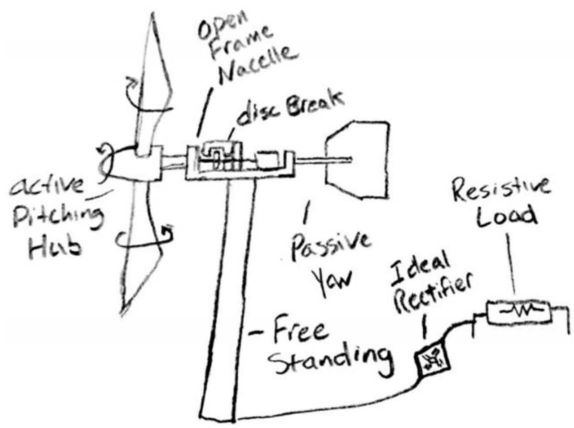


Figure 11: Full Build #1

For this wind turbine design, seen in Figure 11, Team B implemented all seven of the components they are responsible for. This system's design assumes that the wind turbine would have an AC generator. For this design the system would have; an ideal rectifier, voltage regulated resistive load, active hub, freestanding tower, open frame nacelle, mechanical disk brake, and passive yaw. The goal of this design is to maximize the power output for the small wind turbine. Many of the components utilize active systems, meaning that this system has higher efficiency. This efficiency means more complex components that will require more development efforts.

4.2 Design #2: Full Build #2

For this wind turbine design, Team B incorporated all seven of the subsystems that we are responsible for. This system's design also assumes that the wind turbine would have an AC generator. For this design the system would have a three bridge rectifier, resistive/inductive load, flat tip hub, freestanding tower, closed frame nacelle, dynamic brake, and passive yaw. The goal of this system design is simplicity. Test team B believes that a simpler system allows for a more reliable design during testing at competition. However, this approach would result in less efficiency and lower scoring at competition.

4.3 Design #3: Full Build #3

For this wind turbine design, Team B incorporated five of the subsystems that they are responsible for. This system's design assumes that the wind turbine utilizes a DC generator. For this design, the system would have a resistive/capacitive load, active hub, freestanding tower, open frame nacelle, and active yaw. The goal of this system design was to consider what components could be eliminated from test team B components. A switch to a DC generator eliminates the need for a rectifier. An electrically loaded active hub acts as a pitching mechanism for the blades and braking system for the turbine. As a result, the test team would have two fewer components to design and allows the team to have assistance developing other subsystems. This system design means a lower voltage output because of the DC generator and a complex hub/braking design.

4.4 Design #4: Active Pitching Hub

This design has a fixed hub mounting plate that will have an actuating plate that would be used to change the pitch of the blades by the use of linear actuators. This system allows the braking system to be more effective by pitching blades to maximize the drag on blades. The linear actuators would be connected to an Arduino that would have a sensor connected to it that would be used to indicate when to actuate the pitching. The active pitching design, seen in Figure 12 would also decrease the cut in speed of the turbine by increasing the amount of thrust the blades produce during the cut in process. Overall this design would increase the efficiency of the turbine. The main issues surrounding this type of design includes drawing electricity from the generator in order to actuate the hub thus decreasing from the power produced by the turbine. The active hub would also cost more to manufacture. [16]

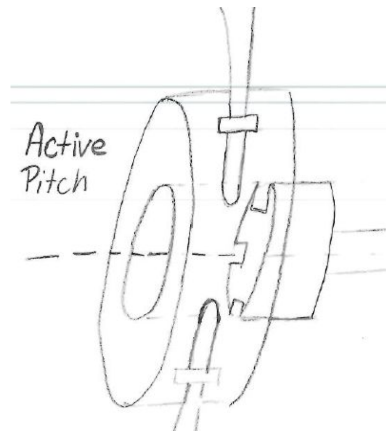


Figure 12: Active pitching hub

4.5 Design #5: Freestanding Tower

There are several benefits to utilizing a freestanding tower design like the one imaged in Figure 13. The first is the simplicity for manufacturing the tower. Because it has a base plate attached to the bottom of the tower, the setup for testing is minimal. Due to its simplicity, the freestanding tower is versatile compared to the other designs that were researched. There are some issues that follow the freestanding tower design. Primarily, the design has a higher overall cost due to increased material. The freestanding tower design is the most iconic design however it is the most plain. The guyed wire and lattice tower designs are not used as frequently are more aesthetically pleasing than the average freestanding tower. Although the freestanding tower is not as creative as the other design options that were considered, it is the most practical design option for Team B to use for the competition.

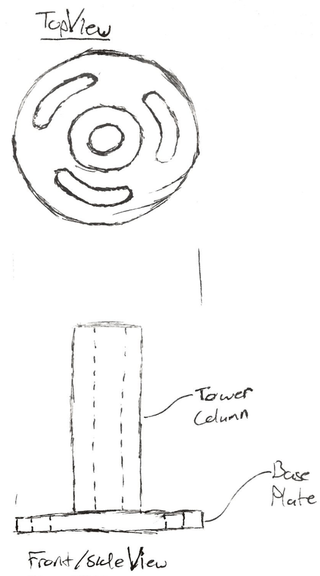


Figure 13: Preliminary sketch of Free Standing Tower Design

4.6 Design #6: Open Nacelle

An open nacelle design allows for easier access to components contained within the framework seen in Figure 14. This nacelle design also creates more freedom to design better generators, brakes, shafts, and hubs. Having an open frame design allows Team B to design for a rotor/shaft/generator placement at the front of the nacelle or above the nacelle. Placing the rotor/shaft/generator assembly above the nacelle removes torques about the towers axis, which increase our yawing capability. Issues surrounding an open frame design include larger forces due to air passing around components. The placement of the rotor/shaft/generator assembly creates either a large torque or a larger bending moment about the towers axis. Both the increased torque and moment would negatively affect the turbine regardless of which placement option is selected. Another downside to an open nacelle is that the design does not look as good as the closed nacelle. While utilizing an open frame design does allow for more drag forces on the various components on the nacelle, Team B would be designing to minimize the overall aerodynamic impact of drag on our turbine.

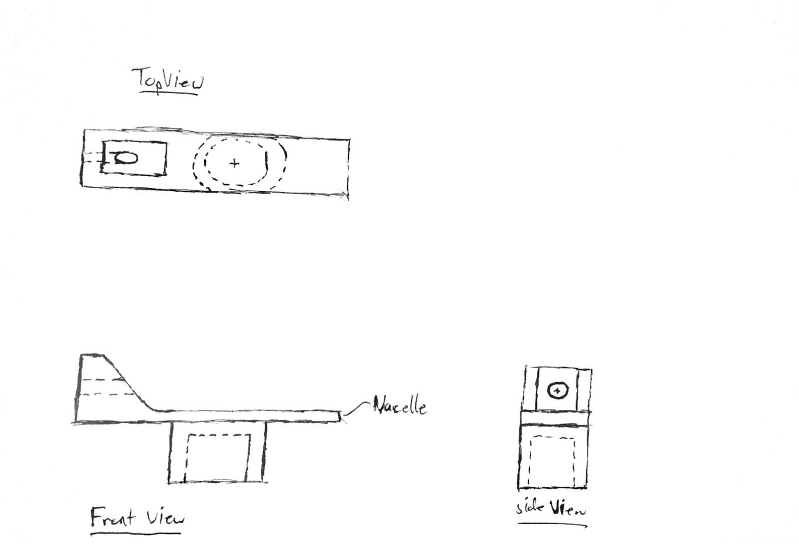


Figure 14: Preliminary sketch of the Open Frame Nacelle

4.7 Design #7: Three Bridge Rectifier

A three bridge rectifier design would allow for a DC signal output with minimal voltage ripple, while still being a passive design. By using power diodes to convert the AC signal, the three bridge rectifier eliminates the need for a timing control system that an ideal rectifier would require. The downside to this approach is the voltage drop from the diodes in the circuit. The increase in the voltage drop would be doubled from a full bridge rectifier. This increase in voltage drop is negligible when generating a high AC voltage output. A three bridge rectifier would work with an AC or DC generator and should not impact any of the other electrical components. See Figure 15 and section 3.4.3.2.

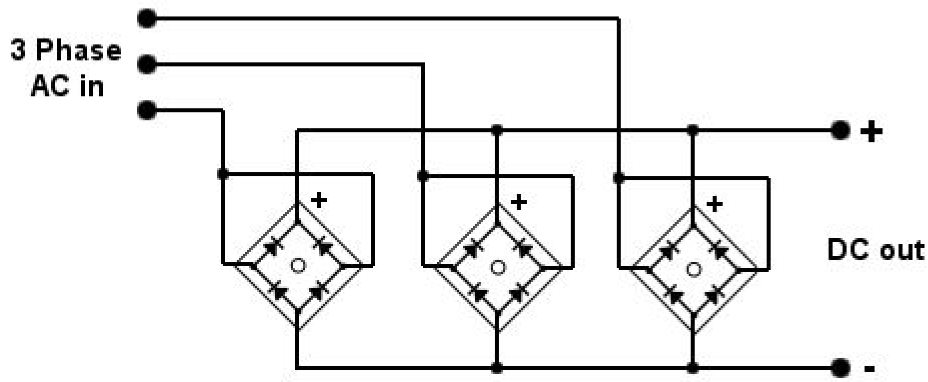


Figure 15: Three Bridge Rectifier [17]

4.8 Design # 8: Disc Brake

Shown below in Figure 16 is a sketch of a considered braking mechanism. The disc brake mechanism is a current actuated, spring loaded arm with rubber stoppers. A voltage meter is connected to a solenoid that actuates the spring when current is too high. When actuated, the arm clenches a rubber disk attached to the shaft to stop the rotation of the blades during a moments of current overload, loss of power, and actuated braking. This brake design has a much higher reliability for stopping the blades from spinning in comparison to other brake designs like the generator dynamic brake. This design requires additional moving parts added to the system, creating more weight and reducing available space within the nacelle. This braking mechanism would also require a great amount of electrical control theory to actuate the brake effectively. The Braking system would be connected to some electrical components that would help the system to work in the most efficient way. The electrical circuit would be connected to the Arduino, the Arduino would determine the output voltage from the load. If the voltage is too high, the Arduino will output the current to the solenoid. When the solenoid is provided with power, the system would be activated and would help to stop the rotation. Team B acknowledges the potential difficulties associated with the disc brake design, from which, efforts to increase reliability and perfect control theory are ongoing.

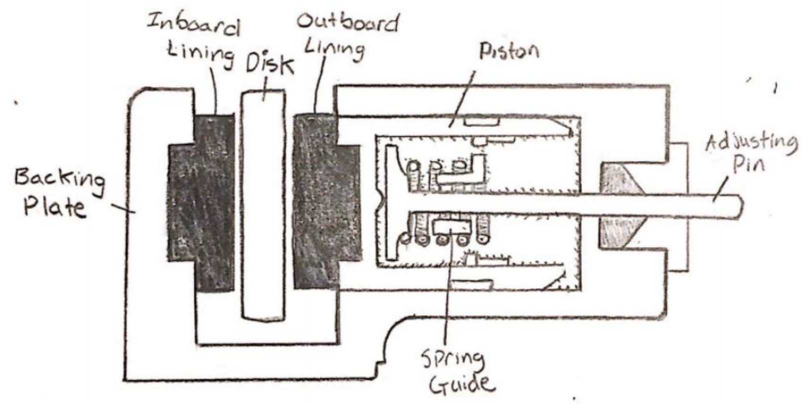


Figure 16: Disc Brake Mechanism Sketch

4.9 Design #9: Passive Yaw

This yawing design method, illustrated in Figure 17, is much simpler and requires less electrical components in comparison to an active yaw system. Although simpler, when dealing with a small wind turbine application, passive yawing can be much more reliable and cost effective. Passive yawing systems analyze aerodynamics on a flat plate of flexible geometry to orientate the turbine blades into the direction of the wind. This is achieved by summing forces of thrust, lift, and drag. The downside to a passive yaw system is that there is no control over the direction of the turbine. The direction in which the blades face is purely dependent on the direction of the wind.

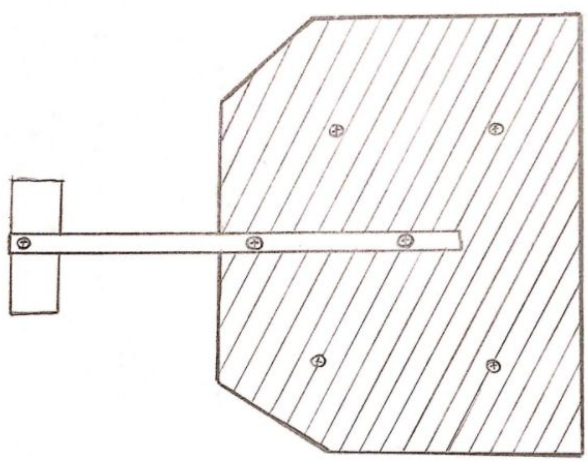


Figure 17: Passive Yaw System Sketch

4.10 Design #10: Resistive Load

The purely resistive load consist of one DC voltage resistor. The resistor would need to have a high resistance in order to handle voltage ratings of 48V, which is the limit that the turbine can produce from the described competition requirements. With a high resistance, the current would be relatively low allowing sensitive components of the circuit to operate without producing excessive heat. A purely resistive load also allows the rest of the turbine to draw power from the load without running the risk of inrush current or voltage spikes that capacitors and inductors have potential to cause.

4.11 Design #11: Switching Voltage Regulator

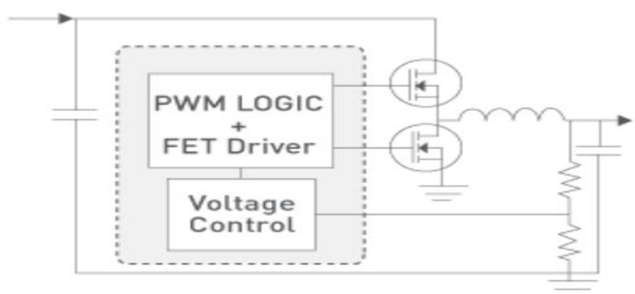


Figure 18: Switching voltage regulator [18]

The voltage regulator, seen in Figure 18, is needed for the circuit to keep the voltage steady and the design protected. It would have a positive impact on the design, especially the load. The switching voltage regulator has a high efficiency compared to the other voltage regulators and diodes because it protects any voltage loss from occurring. The regulator output is constant voltage that protects the design from any damage that could happen due to the unsteady voltage that going into the load and the other components with the turbine. The switching voltage regulator accepts high input voltage and results in a higher voltage output. The switching voltage aspect of the regulator implies that a voltage output of opposite sign is applied to the circuit when desired. However, switching voltage regulator has an electrical noise and it is complicated to be designed.

5 DESIGN SELECTED – First Semester

In this section the selection process for which design the team has selected based off of the criteria and requirements set by the customer is discussed. The design selected is stated in Section 5.1 and includes justification of how the design meets all of the important criteria that have been discussed with the customer and advisors. In Section 5.2, the analysis behind each component is described to provide justification for the designs chosen.

5.1 Rationale for Design Selection

Team B had researched all possible design concepts and identified the system we wanted to implement. The final design selection, which is shown in section 4.1, is the results of Team B's evaluation of all three full build designs through a decision matrix shown in Table 4.

Table 4: Decision Matrix for Design Selection

Requirements	Weight	Design 1	Weighted Score	Design 2	Weighted Score	Design 3	Weighted Score
Durability	0.15	2	0.3	3	0.45	1	0.15
Manufacturability	0.2	2	0.4	3	0.6	1	0.2
Efficiency	0.2	3	0.6	2	0.4	1	0.2
Competition Scoring	0.35	3	1.05	2	0.7	1	0.35
Cost	0.1	2	0.2	3	0.3	1	0.1
Total:	1	**12**	**2.55**	13	2.45	5	1

The final design was a voltage regulated resistive load with an electrically loaded active hub, passive rectifier, freestanding tower, open frame nacelle, mechanical disk brake, and passive yaw. An open frame nacelle allows ease of access to components contained within the framework and further manipulation of the additional subsystems. A passive yaw system is a simple system that requires less electrical components in comparison to an active yaw system. This method of yawing has been successful in previous competition years and increases available space while reducing weight compared to an active yaw. Competition testing will require the nacelle to rotate at rates up to 180 degrees per second and a passive yaw system provides the freedom for the incoming wind to rotate accurately and quickly. The braking mechanism Team B has selected to implement is a mechanical disc brake. This brake design has a higher reliability for stopping the shaft from rotating and will be beneficial during the competition required actuated brake testing. A freestanding tower is the most practical method of elevating Team B's turbine and can be easily attached and manipulated if necessary. Having a freestanding tower allows the turbine to fit within the competition specific sizing requirements. An active pitching hub is a new design concept for NAU's CWC team and has potential to greatly decrease the necessary cut in speed and provide more consistent power output. The voltage regulated load will allow for the system to pull power from the grid to operate the active hub and braking system using a DC signal.

5.2 Design Description

The prototype was created by both Test Team B and Test Team A and encompasses the mechanical subsystems of the entire turbine. Figure 19 shows the prototype that was created out of PVC tubing and cardboard. The purpose creating this prototype was to get a sense of scale for our test turbine. Rough dimensions were used to create the subsystem components and therefore created a visual that would be similar to the scale of the final test turbine.

Figure 19: Prototype for the Test Wind Turbine. Includes Test Team A components.

5.2.1 Rectifier:

The team is was using a 19TQ015S, an off the shelf (OTS) Schottky diode used to build a bridge rectifier. The decision to implement a passive rectification system was derived from researching what is industry standard for small wind turbine applications. In addition, a passive rectifier is a simple, low cost, and reliable wind energy conversion system (WECS) [19] .

Below in Figure 20 and Figure 21, the Simulink simulation the team used to simulate the characteristics of the 19TQ015S bridge rectifier in parallel with a capacitor being used to smooth the output voltage ripple from the rectifier. The team selected a 100uF OTS capacitor to optimize the smoothing of voltage ripple. This simulation allowed the team to iterate and converge on the capacitance value chosen.

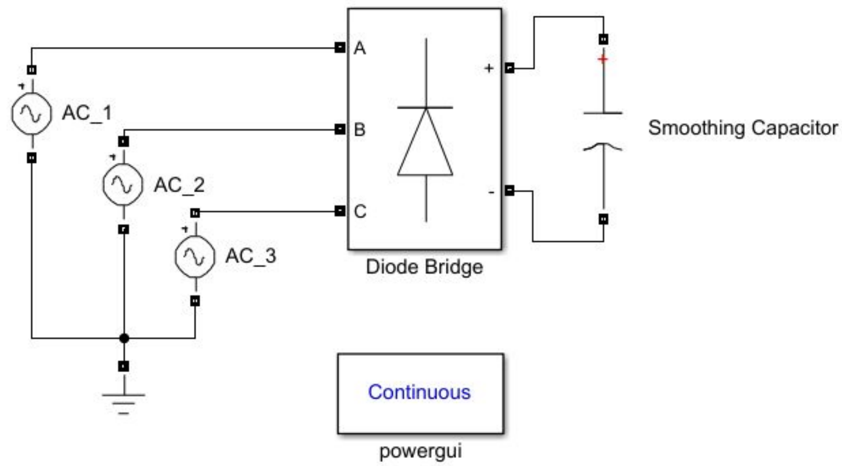


Figure 20: Rectifier Simulink Simulation

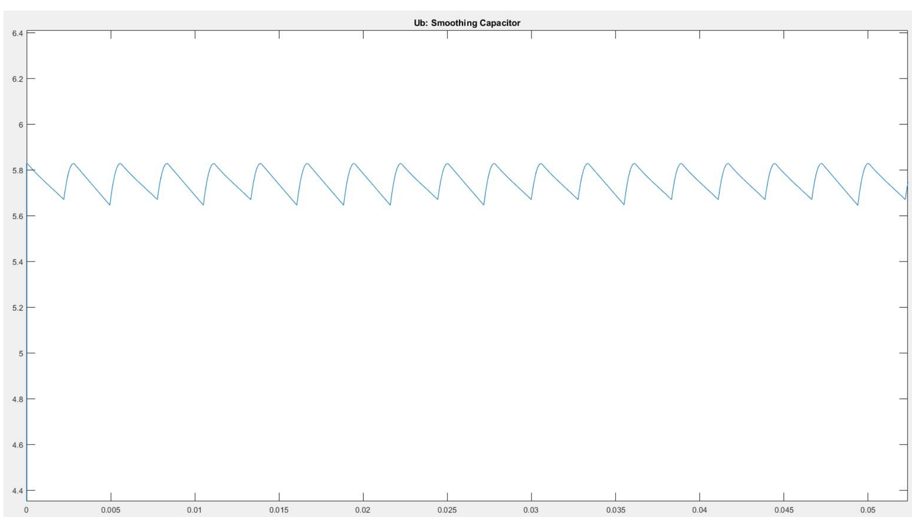


Figure 21: Rectifier Simulink Output (V/s)

5.2.2 Active Pitching Hub:

The team used an active pitching hub system. This system has a base plate that mounted directly to the shaft. The plate used to mount the hub to the shaft is also used as a base plate that has the pitching system mounted on the face, this is shown Figure 22 below. The material that is used for this plate will be 6061

T6 Aluminum. This plate has 6061 T6 Aluminum and Ultra High Molecular Weight Poly Urethane (UHMW) components mounted to it. These components is used for attaching the blades to the hub. The structural components are made out of the aluminum and all non-structural components are made out of UHMW. This material selection was made because the density of UHMW is roughly ⅓ the density of 6061 T6 Aluminum. By reducing the weight inside the hub the initial torque that is needed to rotate the hub will decrease thus lowering the initial cut in speed. At the competition the lower the cut in speed achieved, the higher the amount of points the team will be awarded. The pitching system, located on the face of the mounting plate, includes a linear actuator that is mounted on the Nacelle. This design decision was made to eliminate the need for a slip ring on the hub, thus also reducing the weight of the hub. The linear actuator is mounted to an actuator plate that is connected to a rotating actuator plate. This allows the linear actuator to be statically mounted to the Nacelle. The rotating actuator plate has three actuating rods that connect the actuating plate to the blades. This connection is done by converting the linear motion of the actuator to the rotational motion needed to pitch the blades shown in Figure 22. As shown in the drawing below there is three rotational mounting points in this system, one for each of the blades. These rotational mounting points are mounted to the hub base plate by two M5 bolts per mounting point.

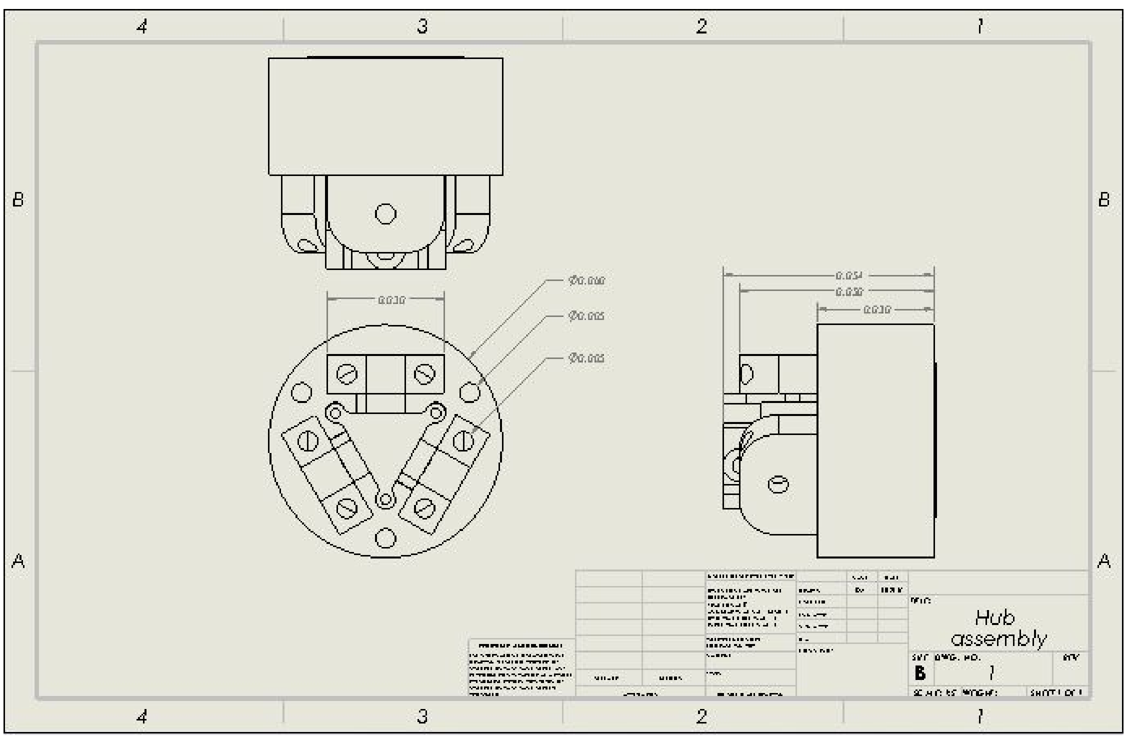


Figure 22: CAD Drawing for the Hub

5.2.3 Brakes:

An electric disc brake is implemented on the team's turbine to stop the shaft from rotating. To justify this decision, a dynamic analysis was conducted on the disc-shaft system to determine the applied force necessary to stop the shaft from rotating. In this analysis a MATLAB algorithm was generated such that the values of unknown factors determining the necessary force are easy to change. The material is titanium with a density of 4507 kg/m^3 because it is strong and commonly used in disc brake application. It was also assumed that the disc has a radius of 3 inches and a thickness of 0.087 inches. The final assumption made was the required time to stop the disk is 0.005 seconds. The results of the analysis yielded a relatively low force of 5.14 N. The full analysis can be found in Appendix C. With these results, the team looked into potential latching solenoid actuators to determine one appropriate for our system. The right solenoid for our system would ideally apply a large force while drawing little power.

5.2.4 Load:

Team B utilized a resistive load that is coupled with bulk energy storage components. The load carries the power that the turbine produces and regulates the power fed back into the system. The objective of the circuit, seen in Figure 23, is it must be capable of regulating voltage to the storage element provided by the competition. The circuit is built with a 20Ω wire wound resistor, a 0.4Ω drop resistor, along with a 58F storage capacitor coupled with a 100kΩ resistor, and controlled with two power MOSFETS. The conditions of the load was as follows; if the source voltage from the Boost Converter is above 12V and the turbine is operating in steady-state, the capacitor is charging and remain charged. To simulate the progression of the durability test, which involves the storage element, the capacitor must charge completely before one minute. The voltage source charging the capacitor was a continuous increasing DC voltage to simulate the power generation of the turbine from start, to steady-state. When both MOSFETs shut off the circuit reroutes to the bulk energy storage with very high resistance in order to hold the charge of the capacitor, the charging and charge held by the capacitor can be seen in Figure 24. MOS2 is a regulatory component that optimizes the current through the bulk energy storage and will operate strictly on current demands from the Arduino if necessary. If components of the turbine need to charge from the capacitor, the MOSFETs will close allowing the capacitor to discharge where needed.

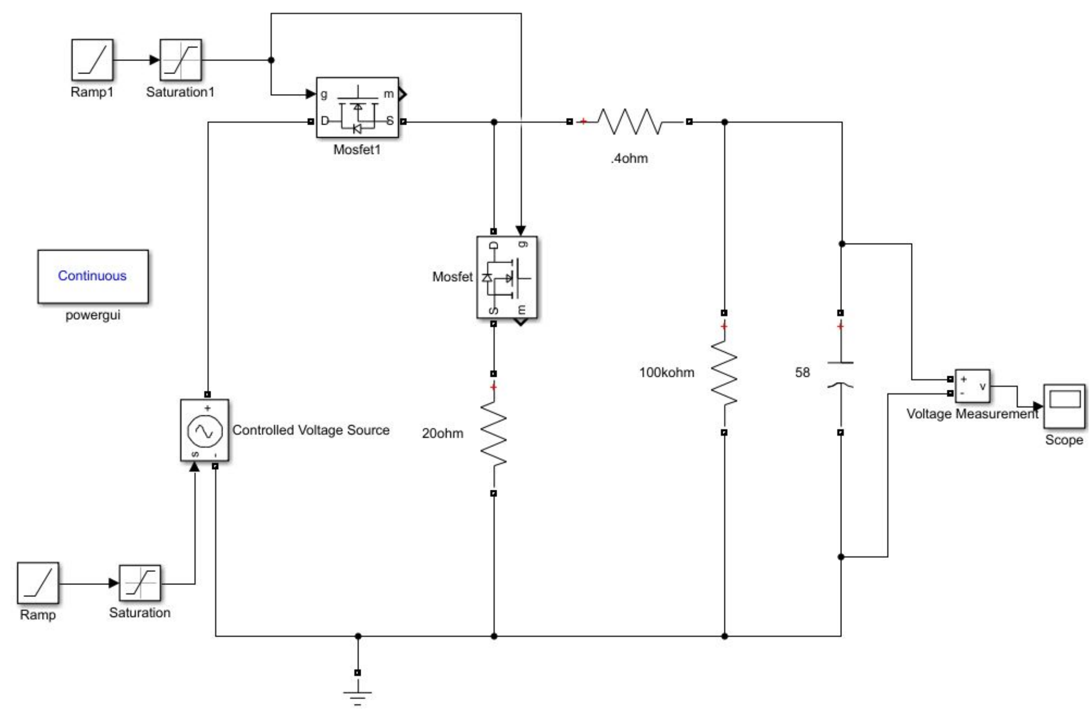


Figure 23: Storage Element and Load Circuit

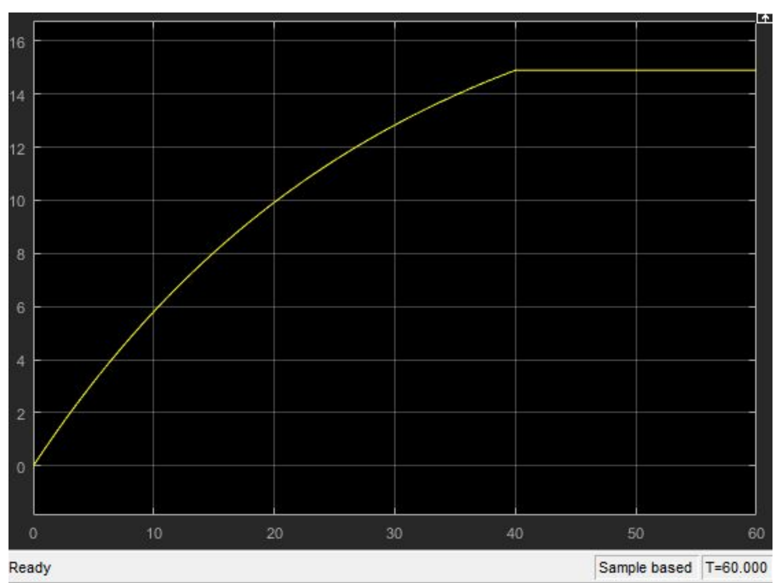


Figure 24: Storage Element and Load Circuit Voltage Response

5.2.5 Controls:

Team B was using an Arduino for controlling some components in the turbine and the main ones are the braking system and the Active pitching Hub. Arduino is a controlling board that can be programmed to do some specific work depending on the way it was coded. So, the Arduino was connected to a wind speed sensor, which named Rev. C, to determine the velocity of the wind speed. In addition, it was connected to some resistors that are placed in series to create a voltage divider circuit. The voltage divider is needed because there is a high voltage input that was more than 5V. The Arduino has a maximum input of 5V, so to keep the device safe and to protect it from any damage the voltage divider decreased the voltage that goes into the Arduino. The voltage divider will be connected to the rectifier, so the output from the rectifier going to the Arduino can be less than 5V. However, a voltage divider was not used because the generator is outputting 10V. Which made the rectifier have a maximum output of 5V which allowed it to connect to the Arduino without connecting it to any resistors. After the voltage and wind speed is determined by the Arduino either of braking system or the active hub are activated when they are needed. To place the braking system on the disk it was connected to a solenoid, which will help to move the spring that is plugged into the brake. The spring is connected from the solenoid to the brake. So, when the Arduino determine a high wind speed it provides power to the solenoid to move the spring that made the brake system activate. Furthermore, the Arduino was connected to a linear actuator that plugged into the active pitching hub. Active pitching hub was activated when the wind speed is medium high, to help the system work in more efficient way by rotation the blades that are connecting to the hub system.

```
const int switchh = 12 ; //
const int led = 8;

void setup() {

pinMode(7,OUTPUT);

pinMode(switchh, INPUT);
pinMode(led,INPUT);
Serial.begin(9600);
}

void loop() {
/*digitalWrite(7,LOW);
delay(1800);
digitalWrite(7,HIGH);
delay(1800);
  */
 int  x = digitalRead(switchh); // Find out if the switch is pressed or not.

  if ( x == LOW) {      // if the switch is not pressed
    digitalWrite(7,HIGH); // Relay is off
    digitalWrite(led,HIGH); // led is on
  }
  else  // If pressed.
  {
    digitalWrite(7,LOW); // relay is high ( off)
    digitalWrite(led,LOW ); // led is low ( on)
  }
}
```

Figure 25: Arduino Codes

5.2.7 Voltage Regulator

The controls of the turbine were controlled by an Arduino within the turbine side of the design. Figure 26 shows the layout of the circuit that supplied power to the Arduino during start-up and steady-state instances. The Arduino requires at least 6V and 300mA in order to operate every MOSFET transistor along with the braking and active hub system. MOS1 supply's roughly 2V to resistor 1, which was the input to the Arduino, at initial startup of the turbine and was accompanied with a differential amplifier in order to boost the voltage. A high power diode directs the voltage to MOS2 to regulate a steady state input to the Arduino. After the current is directed to MOS2, the Arduino created a pulse width modulated voltage to the gate of MOS2 to rapidly switch it on and off while also turning off the connection to MOS1. The resultant output was 6.1V and 248mA and can be seen in Figure 27.

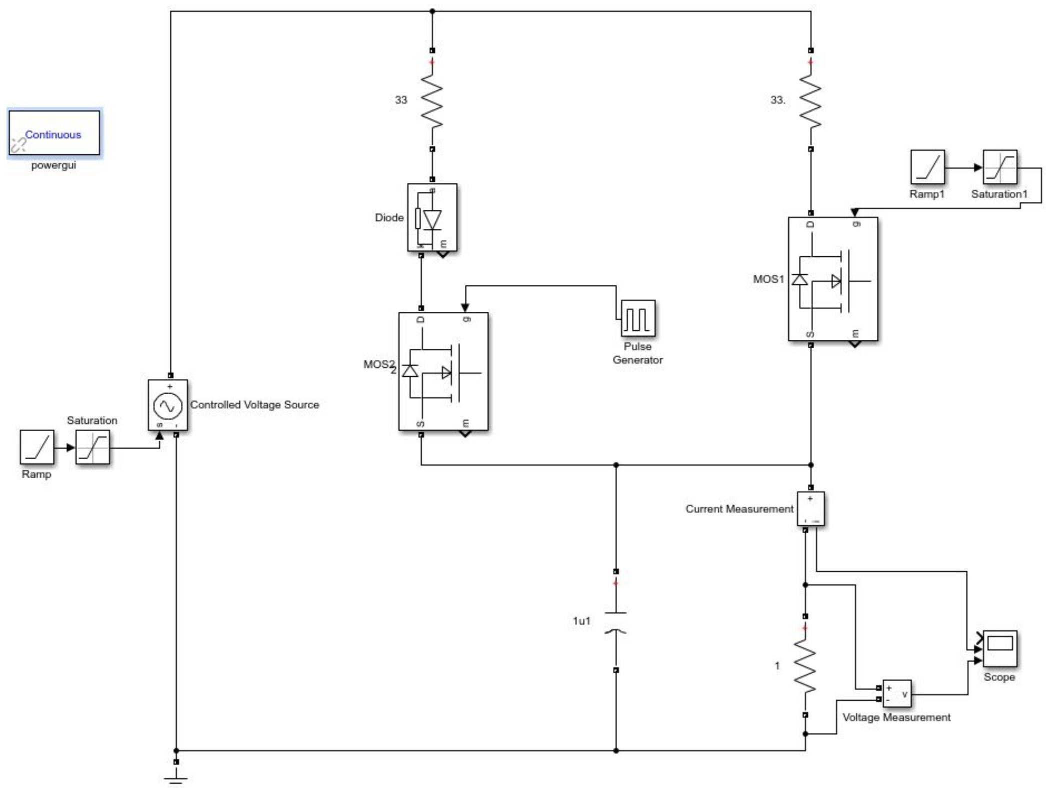


Figure 26: Voltage Regulator to Power Arduino

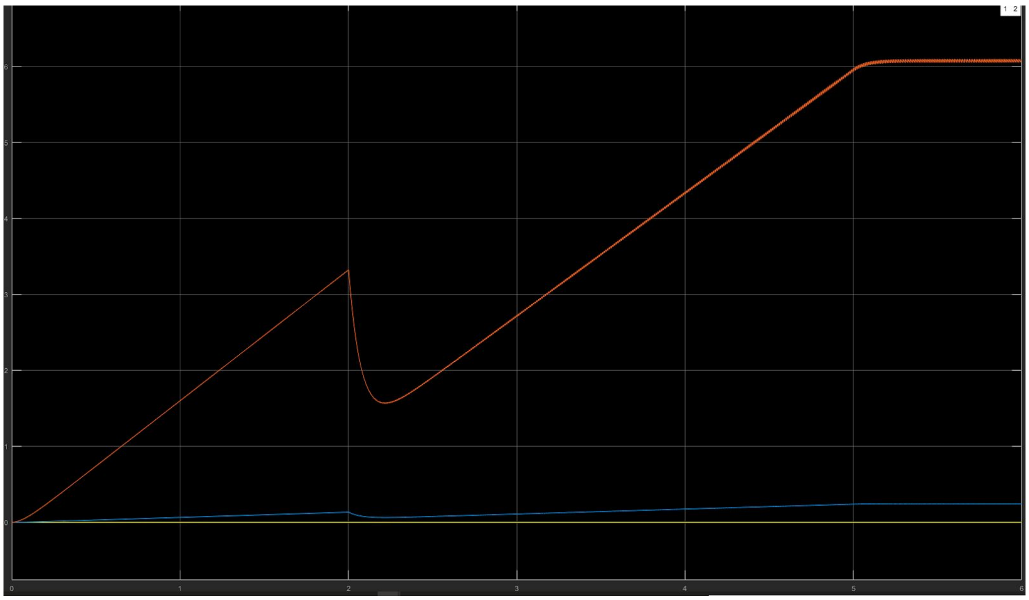


Figure 27: Voltage Regulator Response; *Orange = Voltage, Blue = Current*

5.2.6 Yaw:

A passive yaw system with a delta wing yaw fin was implemented on the team's turbine. This system was designed such that the tail stabilizes the turbine and maintains the orientation of the blades in line with that of the wind. This design of the component was decided due to the availability of statistics for lift, drag, and centers of pressure for delta wings. This made iterating and converging on a design solution easier. The passive yaw system was selected due to its simplicity and reliability for small wind turbine application. Knowing this, an angular momentum analysis was conducted on blade the system to determine the thrust force imparted from the wind. The primary assumption made when calculating the thrust force from the blades was through one-dimensional momentum theory with Betz limit optimization. This analysis was for an ideal situation giving the maximum theoretical thrust force. From the one-dimensional momentum theory with Betz limit optimization applied over an actuator disk along a streamline, the equation for the thrust force is given below as Eq(1). [20]

$$T = U_1(\rho AU)_1 - U_4(\rho AU)_4 \tag{1}$$

Here, ρ is the air density (with Chicago as the datum), A is the cross-sectional area of the wind tunnel, U is the air velocity, and the subscript 1 indicates the upstream position and the subscript 4 indicates the downstream position. For the max possible thrust it was assumed that the incoming velocity, U1, was the max velocity of wind produced by the wind tunnel. From the Collegiate Wind Competition rules and regulations, the max wind speed is 20m/s. The full analysis can be found in Appendix C. The results of which were used for an ongoing aerodynamic analysis to determine the optimum tail fin geometry.

5.2.7 Tower:

A freestanding tower design was implemented for the final design for the test turbine. An iterative solution using a MATLAB code shown in Figure 28, was created to determine the minimum outer diameter that is needed in order to withstand the forces created in the wind tunnel. The Forces that were acting on the tower include the drag force imparted by the wind on the tower and the thrust force due the wind against the blades. Maximum values for the forces were assumed for the calculation of the outer diameter while the Modulus of Elasticity specific to which material that is chosen was variable. The controlled variables were the length of the tower at 76 cm, inner diameter at 2.22 cm, and density of air in the Chicago area at 1.204, and a factor of safety of 20. The output found from this calculation was an outer diameter of 5.11 cm. The resulting solidworks part file can be seen in figure 29.

```matlab

clear; close all; clc;


OD = .1; % m
Ft = 40; % N
l = .76; % m
ID = .0222; % m
E = 220*10^9; % Pa
TS = 435*10^6; % Pa
FS = 20;
ymax = (TS*l)/(FS*E); % m
Vmax = 20; % m/s
density = 1.204; % kg/m^3
v = 1.52*10^-5;
Cd = 1.2;

error = 1;
tolerance = .001;
relax = .01;
iterations = 0;


while (error > tolerance)
    iterations = iterations +1;

    Re = Vmax*OD/v; % Reynolds Number

    Fd = Cd*OD*l*.5*density*Vmax^2; % Drag Force along the Tower

    num = 64*((Fd*((l/2)^2)*(l/2-3*l)) + 2*Ft*(l^3)); % Numerator for resolved max deflection of a beam for the Outer Diameter
    den = 6*pi*(E)*ymax; % Denomenator for resolved  max deflection of a beam for outer diameter

    D4 = num/den + ID^4; % Solving for the Outer Dimeter^4

    ODnew = sqrt(sqrt(D4)); %Solving for Outer Diameter

    error = abs(ODnew-OD);
    diff = abs(ODnew-OD);

    OD = OD - diff*relax;


end
OD = ODnew;

```

Figure 28: Iterative Solution for Outer Diameter of the Tower

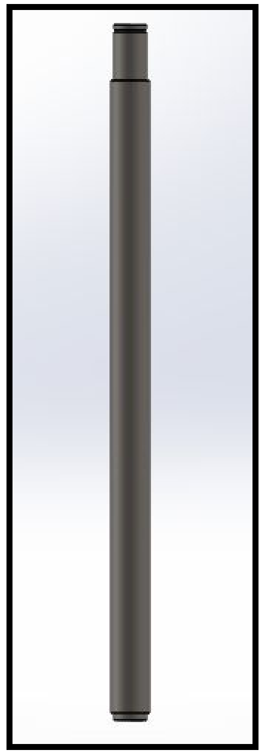
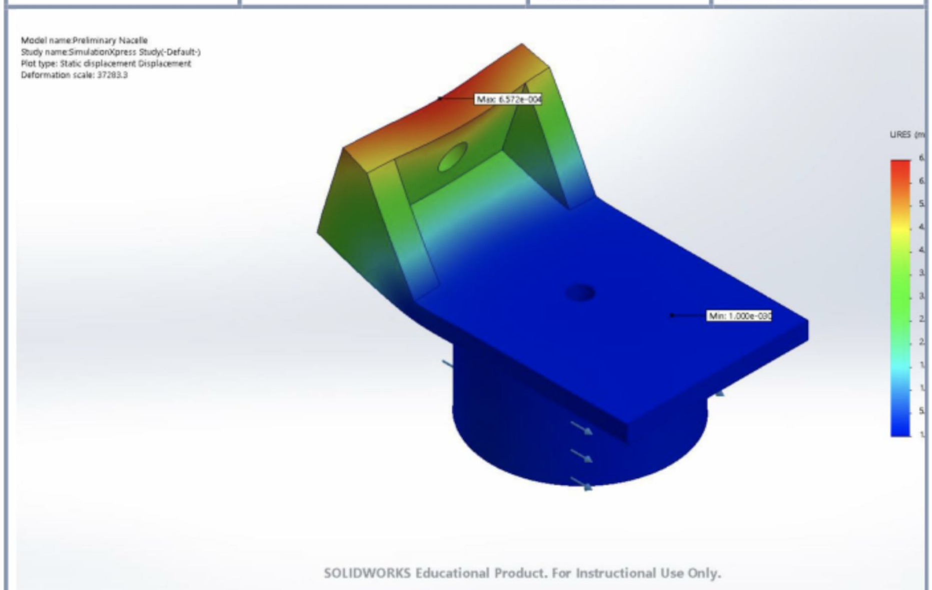


Figure 29: Solidworks Part of Tower.

5.2.8 Nacelle:

The nacelle subsystem was established as an open frame. This allowed open access to the other subsystem components. The Nacelle was primarily used to mount all other subsystems and therefore required a more extensive analysis when the subsystems were attached. The state of analysis included an FEA of the material and shape of the nacelle itself shown in Figure 30. Forces are applied on the front face of the nacelle and the torsional loading around the whole mount for the shaft. A force of 40 N was applied as the thrust force onto the front face and a torsional load was 2 N/m on the shaft mount. This analysis provided a maximum deflection of 6x10^-4 mm. The length and width of the nacelle were 20cmx10cm and was designed to fit each of the subsystems.

Displacement	URES: Resultant Displacement	0 mm Node: 25	0.000657218 mm Node: 1239



Preliminary Nacelle-SimulationXpress Study-Displacement-Displacement

Figure 30: Nacelle FEA Analysis with max deflection.

6 PROPOSED DESIGN - First Semester

The electrical components were initially simulated using Simulink software to determine the component values and power requirements. After sufficient programming and simulating, the proper components were purchased and compiled into a printed circuit board (PCB). The PCB board was designed using Altium DXP 17, a software that allowed the team to lay out how the board was printed. The mechanical components, shown in Figure 31, were analyzed with simulations to determine material strength and forces applied. The final components were collected and manufactured in NAU's machine shop room. The following chapter was broken by each component into their own individual implementation including; software programs, electrical tools, and external resources to build and test their designs. Following the implementation explanations is a list of Test Team B's Bill of Materials.

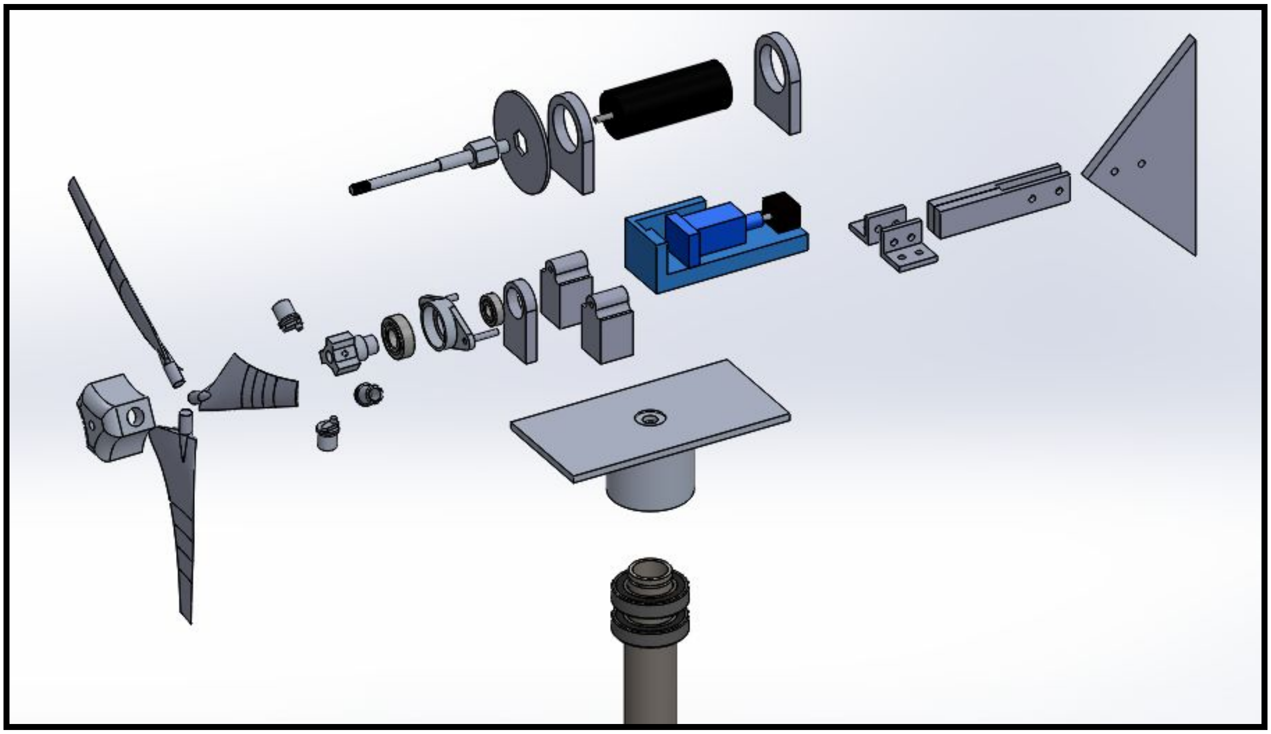


Figure 31: Exploded View CAD

6.1 Rectifier

The circuit analysis for the rectifier was conducted using Simulink software to evaluate the circuit and how it would perform under different conditions without burning out any of the power electronics. Once the power electronics were purchased and assembled by the team, then physical testing of the circuit was needed to verify that the voltage, current, and power outputs from the rectifier matched the Simulink simulation. Equipment needed for this testing included: AC generator, multimeter, circuit tester, and an oscilloscope. All of the equipment needed was provided in the Engineering Building or School of Informatics, Computing, and Cyber Systems (SICCS) located on NAU Mountain Campus. Team B needed the AC generator to simulate the three phase power produced by the wind turbine, which is the input to the rectifier circuit. The oscilloscope was used to verify the AC signal going into the circuit and the DC signal coming out. The multimeter was used to confirm current and voltage output that the oscilloscope measured. To ensure a robust system the rectifier was tested a minimum of 10 times at 5V, 10V, 15V, and 20V. The wind turbine is expected to produce 0-10V depending on wind speeds and by building and testing a rectifier that works at 20V it ensure a durable system. The rectifier circuit was then built on a printed circuit board with the other electrical components and tested at the same voltages. Once the board was tested successfully the team will have additional boards made so there are replacement circuits if a component fails.

6.2 Active Pitching Hub

The active pitching system used SolidWorks to model and simulate the motion. The compiled assembly was analyzed through an FEA analysis on SolidWorks. This analysis included all the maximum forces that the hub will be subjected to during normal operation. The final FEA analysis was a final validation of all the sizing of the components to ensure that there was a factor of safety in all dimensions. The hub was made from 6061 T6 Aluminum and UHMW. These materials were purchased through the internet and shipped to NAU. These materials were then manufactured in the machine shop on campus in building 98C. The machines that were used to manufacture this system are the CNC mill, manual mill and lathe. The lathe was used to manufacture the housing for the actuating components. This actuating housing was made out of UHMW since it is a non structural component of the hub. The hub base plate and the actuating components of the hub was manufactured on the CNC mill and manual mill. These components were made out of 6061 T6 Aluminum. The components were then assembled and mounted to the shaft. The shaft was manufactured with a threaded end that allowed the hub to be mounted by threads and a set screw to the shaft. This completes the design for the hub.

6.3 Brake

The braking system used SolidWorks to model and simulate the dynamics of the assembly. The assembly was analyzed through the FEA application within SolidWorks. The forces applied within the program were equal to that of the force applied by the solenoid linear actuator. This analysis and testing determined if polylactic acid plastic filament is suitable for the final design. If so, the SolidWorks designed assembly was going to be 3D printed using the Cline Library Makerbot 3D printer. Further force application testing was conducted on the physical model to determine if it is durable enough to withstand the force of the solenoid. This was an iterative process to create the perfect geometry for our system. Once this backing plate of the brake mechanism was finalized, the team ordered ceramic brake pads, as well as the stopping disc that is attached to the shaft. The brake component was tested to determine if it is powerful enough to stop the rotating shaft by activating the brake while the shaft is rotating at a high rpm.

6.4 Load and Voltage Regulator

The circuit analysis for the load and voltage regulator was conducted using Simulink software to determine proper component values and power transfer. The load circuit is capable of providing power to components of the turbine if necessary, and to charge the capacitor slightly under its rated voltage. The model turns on the power MOSFET to simulate the charging of the capacitors during turbine steady-state operation, then simulate the discharging the capacitor to components where needed. The voltage regulator circuit was designed to provide a steady power source to the Arduino during both startup and turbine operation. After simulations in Simulink were completed, the testing required the use of a voltmeter and the physical components, with proper values, to be bread boarded to experience reactions of the circuit. To record the reactions, an oscilloscope was utilized to determine if the outputs of the circuit were accurate and correct. The circuit was tested under both high and low voltage and current values to specify an estimated range of operation to conclude the reliability of the circuit. Finally, after the testing phase was completed, both circuits were connected to the turbine and tested again under various conditions that the turbine itself experiences.

6.5 Controls

The circuit analysis for the control was conducted using the Arduino software to find the best components needed to help both braking and active hub systems. The Arduino Nano was chosen to control the other components by programming it. The Nano was selected due to less current and voltage it needs to be supplied with. The Arduino could have been supplied with a maximum power of 12V and it must be constant, to get a constant voltage in this range a voltage regulator is needed. The voltage regulator chosen is the switching voltage regulator, because of the efficiency and low voltage loss. A solenoid actuator was used because it works by extending forward and claps backwards, which was needed for the brake to be placed on the disk and to be removed. The solenoid could have been either medium or small sized. It was not selected yet due to the brake and pitching hub weights. If they had high weights it would need more force, which would need the medium sized, and for less weight the small sized would have been used. The solenoid was provided with 250mA from the load and the Arduino was just to make the brake activate or deactivate. Furthermore, the Arduino was connected to another solenoid that was used for pitching the hub, to help the hub system move forward and backwards. The solenoid was similar to the one is being used for the brake system, but it was the medium sized due to the force needed to move the active pitching hub.

6.6 Yaw

The yaw system was designed with a delta wing yaw fin configuration. The delta wing yaw fin geometry was analyzed within a MATLAB code. The MATLAB script was based around an aerodynamic moment analysis about the yaw axis. This analysis took into consideration the moment of inertia about the yaw axis and would require measuring the weights of components throughout the system. The result of the code analysis was the geometry of the fin that produced the least yaw error. The delta wing configuration was analyzed and tested because lift, drag, and center of pressure statistics are well known and available, making it easier to iterate and converge on an appropriate geometric solution. Once a geometry was determined, a scaled model was replicated to test in the NAU AeroLab wind tunnel located in the machine shop building 98C. The wind tunnel testing of the yaw model identified yaw error and give insight into potential improvements within the design. The model was an exact scaled replica of the larger system, this implied that it was made from aluminum similar to that from which the full scale design was constructed from.

6.7 Tower

The tower was established by first implementing the outer diameter iterative solution shown in Figure 28. Once an outer diameter was selected, a SolidWorks part file was created with appropriate sizing, dimensioning, and applying tolerances as in figure 29. This part file underwent an FEA analysis which set an initial confirmation that the material and sizing can withstand the forces that are applied during testing and competition. With a successful FEA analysis, purchases were made for material OTS for the tubing. This tubing required some machining by lathe which was done in the machine shop at NAU in Building 98C. The Tower also needed to be welded to the baseplate which also took place in the machine shop. Once the tower and base plate were attached the subsystem underwent testing procedures to determine if they meet various engineering requirements. Testing requirements included a deflection analysis using a controlled force to determine the modulus of elasticity.

6.8 Nacelle

The nacelle was created as an open frame design. The nacelle was designed to provide sufficient space for each of the subsystem components to attach. Once the spacing for the nacelle was designed, an FEA analysis was done to insure that the nacelle could withstand the forces created while competing. The remainder of the FEA analysis was done utilizing the attachments that connects each of the subsystems to the nacelle. This included shear forces on bolts with washers and nuts holding the bolts in place. With a successful FEA analysis a purchase for the nacelle materials such as plating and tubing. Once the materials were received, the nacelle frame was built and then tested. The nacelle needed to be placed in the same way that the tower was tested to determine the modulus of elasticity. With successful testing the wind turbine was built using the nacelle.

6.9 Budget

Below in Table 5, was a current breakdown of CWC Team's budget and anticipated expenses for Test Team B.

Table 5: CWC Team Budget

CWC Test Team B Budget			
			Cost ($)
DOE Fund			2400
Fundraising			0
Gore Fund			3000
Market Team			400
Test Team A			1300
Test Team B			1300
Test Team B			
Anticipated Expenses			
Yaw			-70
Brake			-50
Rectifier			-30
Hub			-315
Nacelle			-75
Bearings			-50
Base Plate			-150
Tower			-471
Load			-12
Travel Expenses			(TBD)
Total			-1242
Current Available Dollars			1300
Expenses to Date			0
Expected Balance			58
Current Balance			1300

The cost of the electrical subsystems are based on the prices of components from Digikey, an online electronics supplier. The mechanical subsystems are based on the price of material from multiple online suppliers. Manufacturing of the mechanical systems will be done in the machine shop to minimize costs.

6.10 Schedule

Team B was scheduled to have a final design approved by technical advisors by the end of the first semester, so building could take place at the start of second semester. The team tried to have all parts selected and purchased by the end of this semester, any parts that needed to be ordered next semester was supposed to happen by January, 15th, 2018. Second semester the team wanted to begin constructing subsystems and integrating them into the whole test turbine. The initial build was supposed to happen between January 23rd, 2018 and February 16th, 2018, once the wind turbine is fully constructed Team B will work with Team A to test the system in a wind tunnel. If any subsystems fail, teams would determine the problem and test until the turbine worked successfully. Team B wanted to have final tests done by April 14th, 2018. This would allow the team sufficient time to ship components prior to the competition taking place May 8th, 2018.

7 IMPLEMENTATION - Second Semester

From first semester, our turbine design had undergone multiple iterations to ensure a quality product before manufacturing and testing. Many components and the material for the turbine could have been expensive therefore it was important to design for manufacturing and to finalize the design. Iterative processes included tolerances, spacing, weight distribution, heat dissipation, and their effect on the efficiency of the overall system. This iterative process of perfecting the turbine design for manufacturing had set our team back a month in hope of creating a better and improved turbine. The latest iteration of the turbine is shown below in figure 32.

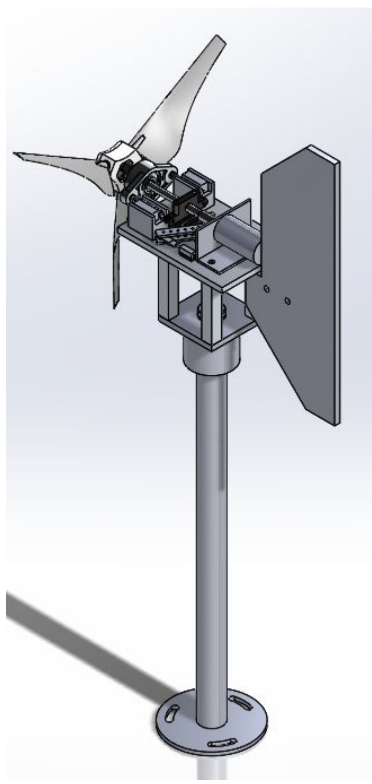


Figure 32: Latest Turbine Design

7.1 Manufacturing

Overall manufacturing was achieved both in house and from outside sources for building the turbine. Mechanical manufacturing of the turbine was done almost completely in-house. This included: milling, lathing, CNCing variously sized sheets of aluminum, welding the baseplate and tower, and assembling components with bolts.The electrical system's hardware was almost entirely outsourced and was assembled in-house. The manufacturing processes for the electrical and mechanical systems are explained in detail within this section.

7.1.1 Electrical System

The manufacturing process for the electrical subsystems consisted of sending a PCB design to Advanced Circuits, a company that manufactures PCBs. After the board had been printed and shipped to NAU, electrical engineering students soldered the individual components onto the PCB. This process was done using soldering paste, a heat gun, magnifying lense, and small forceps. The forceps allowed for components to be placed with precision. The heat gun was used to heat the soldering paste, which solidified when it cooled.

7.1.2 Mechanical System

The manufacturing process for the mechanical subsystems consisted of manual and automated machinery. The manual lathe was utilized in order to manufacture the tower and a few small components of the ative pitching hub. A manual mill was used to manufacture the down tower plate. The blades were printed using the Fortus 400 mc. The blades were printed using ULTEM 9085. The brake system was manufactured with ⅛" aluminum plating and was completely constructed within the NAU fabrication shop. The yaw tail was cut from a ⅛" thick sheet of aluminum in the fabrication shop and was attached to the nacelle using an angle iron with M6 hex bolts.

7.2 Design Changes

Throughout the course of the second semester of this project, many design changes had occurred through iteration towards a competition ready turbine. These design changes from the first semester were explained throughout this section.

7.2.1 Active Pitching Hub

The major changes that were made to the design of the active pitching hub had been the the length of the actuation arm, added an extrusion to the hub body, and changed the material type of the hub body. The length of the actuation arms had been changed multiple times because the blades were able to rotate more than 90°. Once the blade rotate more than 90° that actuation arms would bind up and the systems would not move. Thus the arms were shortened to allow the blades to rotate a maximum of 90°. The blades are to be fixed to the blade mounts once the mounts were installed in the hub body. Since all three of the blades were oriented in the same direction an extrusion had been added to the hub body in order to align the blades all at the right angle. By ensuring that all of the blades were at the right angle the turbine would operate at the optimum efficiency. The last major change that had been made before testing was the material and manufacturing process for the hub body. The hub body was now made out of a PLA filament and was 3D printed with a 40% infill. This change was made to reduce the friction between the hub body and the blade mounts. By changing the material to a plastic the friction coefficient between the plastic and the 6061 aluminum decreased. This subsequently allowed the linear actuators to have a higher factor of safety for actuating the blades.

7.2.2 H-Bridge

Previously the electrical system had not account for the need of a circuit that allowed bidirectional power flow for charging and discharging a supercapacitor. As a result, a h-bridge was put in parallel with the boost converter. This h-bridge required four additional MOSFETs than the electrical system required before this change, meaning that the PCB had to accommodate these additional MOSFETs. This resulted in a larger PCB schematic, but no significant changes to the physical size of the board. This h-bridge circuit was suppose to make a more reliable electrical system when the generator was not producing enough power because it would pull from the supercapacitor when needed and would charge the supercapacitor when excess power was being produced.

7.2.3 Nacelle

The design from the previous semester had changed drastically. The original nacelle design limited the amount of space available for other subsystems to be mounted and therefore required design changes. The largest change was caused by the size and orientation of the slip ring.In order for the slip ring to function properly in relation to the motion of the wind turbine while it was rotating, the slip ring was inverted above the tower. If the slip ring was to be placed on the previous nacelle, the generator, shaft and brake mechanism would no longer function. To solve this issue, the nacelle was raised to a higher platform. The resulting design, shown in Appendix E, created a down tower plate and an up tower plate. The plates were separated by four aluminum spacers which created a volume in which the slip ring could be placed and avoid interference with the other subcomponents. The up tower plate also was enlarged to create more opportunities for subsystems to be attached to the nacelle and to one another.

7.2.4 Tower

The tower design from the previous semester remained the same apart from a few minor changes due to other subsystem changes. The largest change was the height of the tower, which was reduced by 8 cm setting the tower height at 68.1 cm. The outer diameter of the tower was also changed to reduce overall weight and is now 4.13 cm.

7.2.5 Rectifier

The rectifier design from the previous semester had remained the same apart from choosing different diodes. The purpose for this change was to reduce the forward voltage drop and allow for the PCB to be entirely surface mount. Since the previous semester a smoothing capacitor with a value of 100µF was selected to reduce the ripple voltage.

7.2.6 Dump Load

A new design consideration for this semester was the implementation of a dump load. The function of this was to control the output of the system in the event of a voltage spike or a larger than expected system voltage. It functions with two transistors, one acting as a diode, and a low value resistor (0.27 **Ω**). Using control theory, we could activate the dump load forcing a majority of the power to be dissipated from the resistor as heat and kept the system safe.

7.2.7 Power Distribution

The distribution of power was the configuration of providing power to the Arduino microprocessor, brake actuators, and hub linear actuators. Previously, these components were configured to draw power from the resistive load of the design. After the team received an answer from the DOE about the nature of the load, we realized that we could not draw power from the load at all times during testing. For this reason, we decided to transfer all power distribution electronics to the turbine side. The Arduino had to be turned on before the turbine could operate properly and produce a steady power output. Since the generator would produce about 0.5V at cut-in wind speed, we were placing two boost converters, 0.5V - 5V converter and 5V - 11V converter, in series to power the Arduino. Following, the actuators were receiving power from the three channel 5V boost converter, which was the regulated output of the turbine. Both the converters and relays were placed off the PCB to avoid increasing the size of the board. These design changes had forced us to buy off the shelf boost converters to power the Arduino at such low input voltages and utilize relays to control the actuators.

7.2.8 Braking Mechanism

The braking mechanism had changed significantly from last semester. Initially, the brake operated such that a solenoid directly pushed the brake pad onto the rotating disk. However, with changes in the electrical design, only 5VDC was being sent uptower to power electronics. The result of this meant that a direct push from a 5V latching solenoid would not be sufficient. To account for the decrease in force applied by the solenoid a lever arm had been designed to increase the force applied to the brake. Creating a lever arm that would push onto the brake meant selecting a new solenoid that would pull rather than push. Shown in Appendix E, is the new braking system design.

7.2.9 Yaw System

The yaw system design was very similar to last semester's design as it was still a passive yawing system attached via angle irons. However, some changes were made so that the generator fits better and the hub could be moved closer to the axis of rotation. This was accomplished by adding two tails, one on each side of the nacelle such that the generator fits in-between. Moving the generator back between the tails allowed for a larger tail fin and for the entire hub/shaft/brake assembly to be moved back allowing for better yawing capability overall.

7.2.10 Control

The control for the brake and hub systems experienced some changes in equipment and code. The changes were in the type of linear actuators due to the forces needed to be supplied and their operating mechanism. For the brake connection to the Arduino, the team decided to use one solenoid instead of two. So, there was a relay connected to a solenoid to supply it with the power when it needed to be activated. The relay would be used because it operated like a switch, when the Arduino provided a signal the switch would turn on, so the circuit was closed. There was one relay and one solenoid for the brake system and it would operate at the same two conditions, which were the cutoff power in the PCC, and when the button was high. To sense cutoff of power, the team added a current sensor which required peripheral components like resistors, and capacitors. The linear actuator for the hub system was changed from a latching solenoid to a signal operated servo actuator. The linear actuator had three wires, two wires connected to the ground and VCC, and a third wire that wrote a signal from the Arduino to the linear actuator. So, there was no need to use a relay for the hub linear actuators because they were controlled from the signal wire. The voltage sensor was also changed from the original design. The earlier plan was to use a wind speed sensor to read the changes in the wind speed to the Arduino. However, the sensor was not operating efficiently and it was reading the changes in temperature, not changes in speed. Instead the team decided on a voltage sensor that utilizes two resistors in series and had an analog pin connected between them. This allowed coding to be simplified and any errors in the readings were easily optimized.

8 TESTING

[Discuss your testing plan. Referencing the Chapter 1 design requirements, listed specifically and exactly, explain how you independently and scientifically tested each. Provide complete test results and discuss problems encountered. **Clearly show which of the design requirements are satisfied, which are not, and which are ambiguous.** For every failed test, (i) provide a compelling technical argument of why success was expected, (ii) provide a detailed and technically justified redesign to address the problem including supporting engineering calculations, part drawings, and other documentation as necessary
[**Note**: This section documents design / prototype changes made **after testing begins** (i.e., changes made due to test results). Changes due to fabrication issues should be described in the previous Chapter.]
[Include in Final Report only.]

Test team B was responsible for meeting the following design requirements: yawing capability, meeting limited size, providing a mounting system, ensuring electrical safety, braking, supplying DC voltage output, providing electrical grounding, implementing a storage element, and ensuring durability. All of these design requirements have been met within our team's final product. Most of these requirements were tested in the wind tunnel to prove they were accomplished. Yawing capability was tested by offsetting the turbine in the wind tunnel, and was proven by the turbine's ability to face in the direction of the wind when the tunnel was turned on. This was not accomplished the first try, yawing capability took some time to perfect due to resistance within the tower and nacelle connection. Yawing was improved by adding spacers and bearings within the tower, as well as greasing the components such that the turbine yawed more smoothly. Meeting the limited size requirement was straight forward and only required taking measurements to ensure it was accomplished. The turbine was modeled in SolidWorks in order to assure that the size requirement was met. However, when creating the turbine in reality, final measurement had to be taken to make sure it met the requirements and the team succeeded. Providing a mounting system was also straightforward, the turbine was designed with a base plate such that it would mountable to the competition's rotatay system. This was tested by mounting the turbine to a similar but stationary system in the wind tunnel and observing how it stands up to high wind speeds. After testing at high wind speeds the mounting base plate was proven successful. Electrical safety has been an ongoing process to ensure that the turbine passes safety inspection. Unfortunately, there is no way to completely test this requirement and will only be completely determined based on the competitions judges. Our team has stored our electrical components down tower in a NEMA Type-1 storage container recommended by competition and our uptower electrical components have been encased in 3D-printed cases to ease the mind of competition judges. Also the wiring of the system has been replaced with high temperature wires near the load. Next, braking has been one of the requirements with the most testing and changes. The brake was once a simple lever arm mechanism that worked at low wind speeds but failed at higher wind speeds. After testing, an additional rotation point was added near the brake pad to allow more linear translation and provide a greater contact surface on the disc rotor. This new addition to the braking mechanism did not seem to influence the brakes ability to stop rotation. One of the reasons that the brake was still experiencing failure was potentially because of the magnetic latching solenoid's strength on the lever arm. Based on the static analysis conducted on the lever arm, the solenoid was theoretically capable of stopping the turbine at its highest torque but was not experiencing the same results in reality. From this the team decided to scrap the solenoid and apply one of the linear actuators that was previously used on the pitching hub system. This actuator applies greater force and is more easily adjustable because of its vast 2cm arm. This was tested in the wind tunnel and was proven to work at higher wind speeds but is still under construction for competition. The requirement of DC voltage output was very easily tested in the wind tunnel. The team purchased an AC to DC rectifier that converts AC electricity to DC electricity, this was tested using a DC voltage reader and was proven successful. Electrical grounding was also easily tested using a voltage reader, when the system was connected to power the voltage reader was able to ensure that the components were grounded to the tower. Providing an electrical storage system for the competition judges to use was tested by using an ultra-capacitor for our system during wind tunnel testing and was proven successful. Rotor capacity was tested by determining the power output comparative to rotor size during tunnel testing, but was unable to be altered due to sizing requirements. This is an arbitrary requirement that has been proven successful. Durability was also tested in the wind tunnel by testing the turbine to failure. The tunnel was ramped up to 15m/s and the blades sheared from the hub. This failure was a result of poor shaft design and a poor connection between the blades and the hub. This was fixed by shortening the shaft and adhering the blades earlier to allow the steel welding to cure. The control testing was focusing on two systems, which are the active hub and brake system. Testing the active hub was done successfully where the team was using two linear actuators and a voltage sensor. The voltage sensor needed to be located on the PCB board, so using a voltage sensor out of the shelf would require big amount of size or space on the board, so instead of buying one the team built a voltage divider which was to have two resistors in series and read an analog value between them. Depending the voltage the linear actuators were actuating and the blades were having different angles when it increase the length of actuating. Furthermore, the other system need to be controlled was the brake system, and it was successfully braking on the tunnel test until 7 m/s. However, the mechanical team did some edits to the system and it supposed to be braking for higher speed rating. The brake system had a solenoid, four-channel relay, button, and a current sensor. The current sensor was used to check if there is a cut off in power, and it is braking when the current is less than 0.3 A. The team chose the value of 0.3 A, because there is an error with the current sensor within 0.84 A, so instead of going to 0.15 A the team increased the range to be in the safe side. The Solenoid was used to proved force to the brake when it is latching the brake is activated when it is unlatching the brake are deactivated. In addition, the button will send a signal to activate the brake when it is pressed and deactivate it when the button is released. The relay is used as a H-bridge and switch at the same time, where two channel had VCC and GND, and the other two channels were GND and VCC, meaning the relay will switch the polarity of the VCC and GND to make the solenoid latch and unlatch regarding the previous conditions. Overall, both system were able to be controlled and were tested in the tunnel test, but the active bitching hub is no longer used regarding some conditions that was explained in the active hub test section.

Power Distribution:
The distribution of power to the electrical system along with the Arduino Due was executed by bridging a boost converter between the output of the full bridge rectifier and the arduino. Testing of this configuration consisted of determining the voltage across the rectifier that will ultimately turn on the Arduino. Cut-in speed resulted in a 3.06V rectification voltage which

9 CONCLUSIONS

The following chapter will discuss the project over the past two semesters. In Particular, the chapter will analyze where the team was successful and areas for improving as a team. This allows for valuable reflection and success in future projects.

9.1 Contributors to Project Success

During both semesters of Capstone, there were a few aspects of project performance that had contributed to the team's success. Organization was the aspect that had benefited the Collegiate Wind Competition team the most throughout the two semesters. One of the first tasks that the team accomplished was organizing the team into three different sub-teams and gave each team different responsibilities. Two of these sub-teams were given the task of designing and testing a small-scale wind turbine that would compete against other universities. These two sub-teams divided the subsystems of a wind turbine and assigned each team member as a lead for at least one of the subsystems. This breakdown of the workload had allowed for individuals to be held more accountable for their efforts over the course of the year, which resulted in higher quality work being produced by the team. This initial effort to organize the team of 19 multidisciplinary engineers into smaller sub-teams had also helped negate individuals from not contributing since there were fewer people for each sub-team lead to manage. Similarly, time management had been crucial to the success of the team. Each sub-team had a lead who attended an hour-long weekly meeting with Professor David Willy. Each sub-team had an hour-long weekly meeting. Electrical engineering students had an additional six hours a week that they met. Lastly, the two sub-teams responsible for designing and testing the turbine were to meet bi-weekly during the first semester and once a week second semester. All of these meeting times in addition to the other coursework team members had required good time management to ensure deadlines were being hit for Capstone. Capstone was very time demanding, so trying to organize and schedule meetings that all team members could attend was difficult and required team members to be flexible. As a whole, the team was excellent with scheduling and willing to make time for meetings. This flexibility allowed for the team to produce higher quality deliverables and be better prepared for presenting the content in class. However, despite all of the meetings scheduled it was not enough time dedicated to ensuring deliverables were of a high quality. As a result, individuals often spent many additional hours working on the project. Other tools that contributed positively to both semesters performance were the utilization of Google Drive, email, and group texts. Google Drive allowed all 19 students to see relevant documents and edit them in real time instead of having to assign someone to be responsible for drafting word documents. This was important when the project report was over 70 pages and small edits that someone wanted to be made could be missed if only one individual was responsible for implementing edits team members provided. Email and group texts both allowed for communication between members of the team. Communication was important to such a large team, so any tool that helped make communicating easier was very beneficial. As a team, we knew that communication could hurt us, so in our coping strategies, we committed ourselves to using these different tools. An email was best used for event invites or communicating with university faculty, while texts worked best for quick responses from team members. Without these tools, the team would not have been able to meet the goals that were set at the beginning of the first semester. The goals set at the beginning of the first semester were stated in the team charter to hold the whole team accountable. These goals consisted of an equal effort by all team members, high-quality deliverables, continual communication, and team members being willing to work extended hours to fulfill our team purpose of building a functional wind turbine for the Collegiate Wind Competition. The team had accomplished the purpose of creating a functional wind turbine and are currently working on further improving the turbine for the competition. Throughout last semester the team was able to meet most of the goals that were stated. The deliverables the team submitted were always of a high quality that we felt confident in submitting throughout both semesters. The team often had to work extended hours to produce high-quality deliverables and that meant communication was essential to know the status of different aspects for the project. The only goal that was not accomplished was the equal effort from all team members, however, peer evaluations and conversations with individuals not putting in as much effort helped to improve this issue as the semesters progressed.

9.2 Opportunities/areas for improvement

In any team, there are always areas for improvement that would result in higher efficiency as well as a sustainable working environment. Our team is not an exception to this. There were opportunities for the team to improve on and by reflecting on these missed opportunities it would allow for the team to implement changes for future projects to ensure everyone meets the goals stated and have a more productive team. The ground rules set in the team charter were all based on actively communicating with each other and making sure that everyone was contributing to the project. There were isolated incidences where individuals were not responding to any form of communication before high-value deliverables were due. This resulted in other team members having to do the work expected of that absent team member. These sort of situations meant that both of the main ground rules were not being followed because a person was not putting in the effort that the rest of the team was and failed to communicate with the team to let them know that the work was not going to be done. A strategy to accomplish this goal of motivating members on the team needed to be developed with the input from other team members to ensure it was agreed upon. Our coping strategies consisted of ways to deal with communicating with such a large team, however, they failed to address how we would handle individuals not putting in an equal amount of effort. This oversight of a common issue that occurs on a team hindered our ability to properly handle situations that occurred throughout the project. As a result, an update to the team charter with a response to these situations would be valuable. The most negative aspect of the team's performance would have to be not meeting deadlines that were set for ourselves as a team. Our capstone project was a competition project so we had a tighter deadline than a noncompeting project. This difference meant that our team had to have self-imposed deadlines outside of the capstone class if we were to have a functional wind turbine for the competition. Both semesters we set milestones but failed to set deadlines for tasks to accomplish those milestones. This poor planning and not having a detailed enough Gantt chart that team members were held to result in the team being further behind than was wanted as we approached the competition. Another negative aspect was the lack of communication between the two test teams. Both teams had components that were dependent on one another, so the two teams needed to be communicating from the start of the project. There was an individual who was elected as test teams lead to be the individual responsible for making sure the two test teams were working together and meeting deadlines. Test team meetings did not start occurring until the second half of the first semester. The whole Collegiate Wind Competition team has encountered a few setbacks due to confusion from the rules and regulations provided by the United States Department of Energy (DOE). The team had sent in multiple emails to the DOE for clarification and had received vague responses that stated certain rules are up to the team's interpretation. This confusion had slowed down our design time because the team wanted to maximize the number of points that the wind turbine could get during the competition. However, as a team, we needed to reevaluate the rules and consider where we could lose points to simplify the design or accommodate for design failures that we did not know about until the turbine was built. With a lot depending on the team getting our turbine built and into a wind tunnel to test by the beginning of March we needed to have good organization. This would have required critical paths to be determined and the first six weeks of the second semester to have deadlines set. Having all of these deadlines set would have improved our team's performance and ensured that we had a functional turbine built for the Competition earlier in the second semester and would have allowed for more testing to occur. Also, having leadership positions up for reelection would have benefited the team since some test team leads did not contribute enough and as a result tasks took longer than they needed to. With the team on a tight schedule, our leadership and organization as a team needed to be exceptional the second semester. Electrical engineering students on the team have been able to learn a substantial amount about mechanical problems and methods of engineering. The different perspectives has helped team members when approaching problems because we now consider the mechanical impacts of design changes or electrical impacts of design changes.

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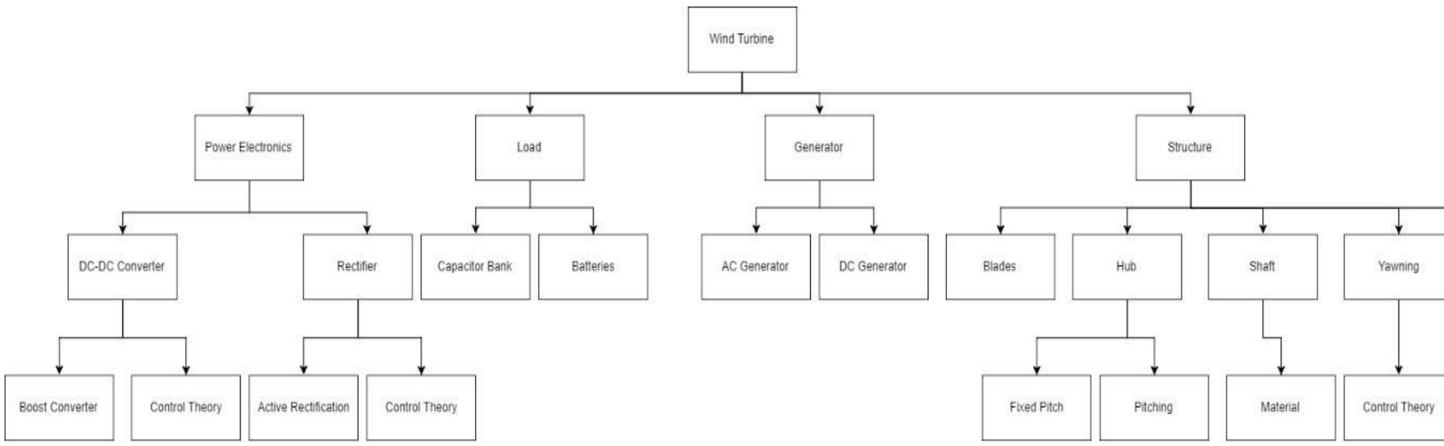
11 APPENDICES

11.1 Appendix A: House of Quality

		Units	GPa	GPa	GPa	m^2	m^3	m^3	m^3	Type	mm	m^2	GPa	GPa	kΩ	m	V	AWG	kΩ	N/m
Customer Requirement	**Weight**	**Engineering Requirement**	Tower Modulus of Elasticity	Hub Modulus of Elasticity	Nacelle Modulus of Elasticity	Tail Fin Surface Area	Hub Volume	Nacelle Volume	Tower Volume	NEMA Electrical Rating	Base Plate Thickness	Base Plate Fixture Area	Base Plate Modulus of Elasticity	Base Plate Tensile Strength	Ground	Turbine Wire Length	Voltage Limit	Wire Guage	Resitive Network	Applied Brake Force
Durabilty	4		9	9	9	1	1	1	1		3	1	9	9				1		3
Yawing Capability	4					9	1	3												
Limited Size	3					9	9	9	9		9	1				1				
Electrical Safety	5									9					9		9	1		
Mounting System	2						1	1	1		9	9	9	9						
Electrical Grounding	2														9			1		
Wiring	1									9					1	3		1	3	
Electrical Output	4									1							9	1	3	
Purely Resitive Load	3									1					1		1	1	3	
Storage Elements	2									1							3			
Ventilation	3																			
Lead Off Resistors	4																1	1	1	
Electrical Connectors	4																	1		
Braking	5							1												9
Close Switch	3																3	1		
Rotor Capacity	4																			
DC signal Output	5																			
Absolute Technical Importance (ATI)			36	36	36	67	37	50	33	63	57	25	54	54	67	6	103	30	28	57
Relative Technical Importance (RTI)			14	14	14	2	13	10	17	4	5	21	7	7	2	30	1	18	19	5
Target ER values			200	200	60	0.2025	0.091	0.091	0.091	Type 1	16.1<	0.0176	200	440	100	>1	<48	10->20	10->150	1290
Tolerances of Ers			± 20	± 20	± 10	± 0.05	±0	± 0	± 0	± 0	± 2.5	± 0.005	± 20	± 40	± 10	± 0.5	± 5	± 2	± 10	± 100
Testing Procedure (TP#)			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18

11.2 Appendix B: Wind Turbine Component Breakdown



11.3 Appendix C: Analysis

<u>Yaw system analysis</u>

When analyzing the tail, there are three primary forces that act on the tail that will dictate the necessary geometry. The three forces that act on the tail are thrust, lift, and drag forces. Each force calculation has its own assumptions that drive the calculations as well as assumptions for applying the forces onto the tail. The primary assumption made when calculating the thrust force from the blades is though one dimensional momentum theory with Betz limit optimization. This analysis is for an ideal situation giving the maximum theoretical thrust force. The following assumptions are used when applying this analysis:[20]

- Homogeneous, incompressible, steady state flow;
- No frictional drag;
- infinite number of blades;
- uniform thrust over the disc or rotor area;
- a non-rotating wake;
- the static pressure far upstream and far downstream of the rotor is equal to the undisturbed ambient static pressure

The process for calculating the thrust force is given through Eq(1-3). From the one-dimensional momentum theory with Betz limit optimization applied over an actuator disk along a streamline, the equation for the thrust force is given below as Eq(1). [20]

$$T = U_1(\rho AU)_1 - U_4(\rho AU)_4 \tag{1}$$

Here, ρ is the air density (with Chicago as the datum), A is the cross-sectional area of the wind tunnel, U is the air velocity, and the subscript 1 indicates the upstream position and the subscript 4 indicates the downstream position. For the max possible thrust it is assumed that the incoming velocity, U1, the max velocity of wind produced by the wind tunnel. From the Collegiate Wind Competition rules and regulations, the max wind speed is 20m/s. For a steady flow $(\rho AU)_1=(\rho AU)_4 = \dot{m}$, where $\dot{m}$ is the mass flow rate. From this the thrust equation simplifies to eq(2) [20]

$$T = \dot{m}\,(U_1 - U_4) \tag{2}$$

U_4 can be found by applying Betz optimum values for the axial induction factor, a. The Betz optimization gives a=1/3. From this, the equation for U_4 is given below as eq(3) with a=1/3: [20]

$$U_4 = U_1(1-2a) \tag{3}$$

Brake System Spring Force Analysis

Assumptions that drive the calculations:

When designing the brake system, one of the most important components is the spring. This spring is designed to apply a great enough force onto a spinning disc to stop the rotating shaft. For this project the blades have not yet been completely designed, therefore there are a multitude of unknowns when determining the angular velocity of the spinning disc and its rpms. In this analysis a MATLAB algorithm is presented such that the values of unknown factors determining the necessary force are easy to change. The current assumed material is titanium with a density of 4507 kg/m^3 because it is strong and commonly used in disc brake application. It is also assumed that the disc has a radius of 3 inches and a thickness of 0.087 inches. The final assumption made is that the required time to stop the disk is 0.005seconds.

Equations:

To find the necessary force to stop the brake it is first necessary to consider the disc's kinetic energy. The kinetic energy is a function of the disc's mass (m), radius(r), and angular velocity (ω). The angular velocity is found using Eq. (4) below:[21]

$$. \omega = (2*\pi)/R \tag{4}$$

Next the volume of the disk can be calculated using Eq. (5), from which the mass of the disk can be found by dividing by the known density. Here h is the thickness and r is the radius.

$$V = \pi*r^2*h \tag{5}$$

Now knowing the mass, radius, and angular velocity, the kinetic energy is calculated using Eq. (6)below:[21]

$$K = .5*(.5*m*r^2)*\omega^2 \tag{6}$$

For the disc to rotate from a speed ω to zero in a given time, t, there is a resulting acceleration α. The angular acceleration is found from the rate of change of angular velocity with respect to time. This is given as Eq. (7).

$$\alpha = d\omega/dt \tag{7}$$

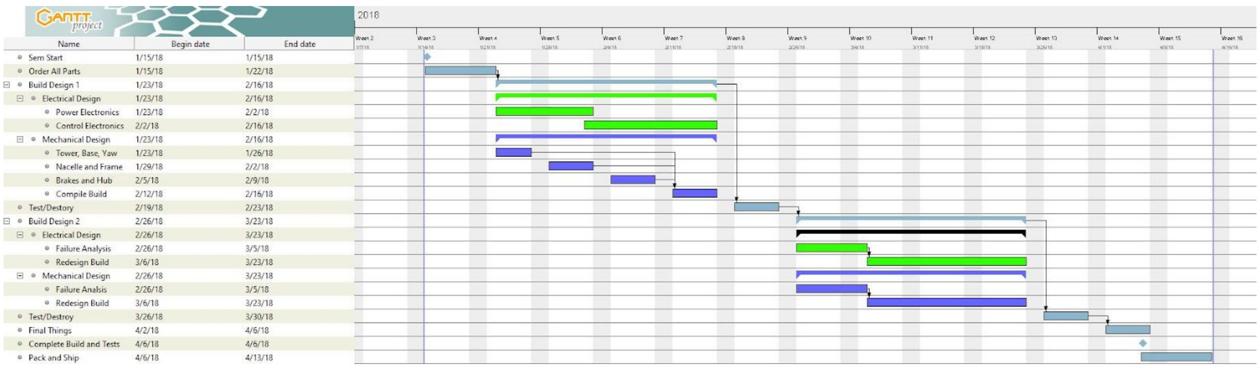
Finally, the torque is calculated by multiplying the angular acceleration by the moment of inertia. From which the torque is set equal to the force multiplied by the radius and the force can be found using Eq.(8).

$$F = T / r \tag{8}$$

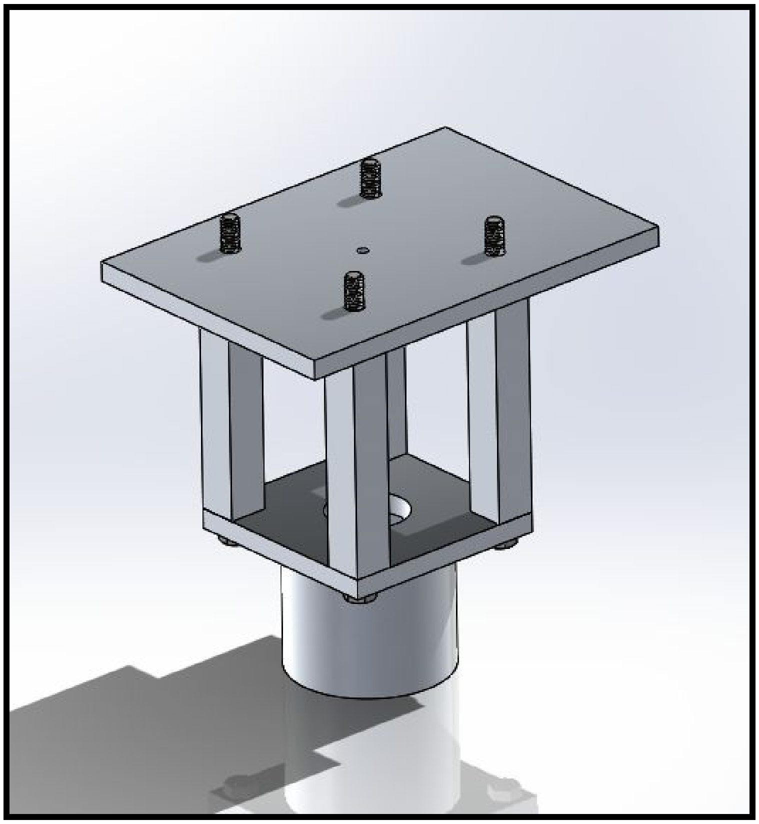
8.11 Appendix D: BOM

System	Function	Description	Qty	Manufacturer Name, Part Number	Link to Estimated Cost	Ind. Part Cost	Total Part Cost
Electrical							
	Generator						
		generator	1	Turnigy XK-4082 1450KV Brushless Inrunner	https://hobbyking.com/en_us/turnigy-xk-4082-1450kv-brushless-inrunner.html	51.5	51.5
	Rectifier						
		diode	24	STPS20L15	https://www.digikey.com/product-detail/en/stmicroelectronics/STPS20L15G-TR/497-6578-1-ND/1865320	2.1	50.4
		capacitor	4	Nichicon UWT1H101MNL1GS	https://www.digikey.com/product-detail/en/nichicon/UWT1H101MNL1GS/493-2226-1-ND/59020	0.47	1.88
		MOSFET	8	EPC EPC2016C	https://www.digikey.com/product-detail/en/epc/EPC2016C/917-1080-1-ND/5031696	2.63	21.04
		resistor	4	Bourns Inc. PWR263S-35-R270F	https://www.digikey.com/product-detail/en/bourns-inc/PWR263S-35-R270F/PWR263S-35-R270F-	4.07	16.28
		Gate Driver (and other components)	4	Texas Instruments UCC27611DRVT	https://www.digikey.com/product-detail/en/texas-instruments/UCC27611DRVT/296-35639-1-ND,	2.62	10.48
		Driver resistor (1 ohm)	4	Riedon PCR1206-1RJ1	https://www.digikey.com/product-detail/en/riedon/PCR1206-1RJ1/696-1397-1-ND/3507300	0.35	1.4
		Driver Resistor (0.35 ohm)	4	Panasonic Electronic Components ERJ-8RQFR33V	https://www.digikey.com/product-detail/en/panasonic-electronic-components/ERJ-8RQFR33V/P.	0.24	0.96
		Driver Capacitor	4	KEMET C1206C104K5RAC7867	https://www.digikey.com/product-detail/en/kemet/C1206C104K5RAC7867/399-1249-1-ND/4115	0.11	0.44
	Boost Converter						
		MOSFET	24	EPC EPC2016C	https://www.digikey.com/product-detail/en/epc/EPC2016C/917-1080-1-ND/5031696	2.63	63.12
		Inductor	12	Wurth Electronics Inc. 7447017	https://www.digikey.com/product-detail/en/7447017/732-1418-ND/1638823?utm_medium=ema	2.63	31.56
		Capacitor	4	Nichicon UUD1V151MNL1GS	https://www.digikey.com/product-detail/en/nichicon/UUD1V151MNL1GS/493-2291-1-ND/590266	0.68	2.72
		Arduino (DUE)	2	Arduino DUE	https://store.arduino.cc/usa/arduino-due	37.4	74.8
		Current sensor Vers 2	4	Allegro MicroSystems, LLC ACS710KLATR-12CB-T	https://www.digikey.com/product-detail/en/allegro-microsystems-llc/ACS710KLATR-12CB-T/620-1335-6-ND	5.69	22.76
		Gate Driver (and other components)	24	Texas Instruments UCC27611DRVT	https://www.digikey.com/product-detail/en/texas-instruments/UCC27611DRVT/296-35639-1-ND,	2.62	62.88
		Driver resistor (1 ohm)	24	Riedon PCR1206-1RJ1	https://www.digikey.com/product-detail/en/riedon/PCR1206-1RJ1/696-1397-1-ND/3507300	0.35	8.4
		Driver Resistor (0.35 ohm)	24	Panasonic Electronic Components ERJ-8RQFR33V	https://www.digikey.com/product-detail/en/panasonic-electronic-components/ERJ-8RQFR33V/P.	0.24	5.76
		Driver Capacitor	24	KEMET C1206C104K5RAC7867	https://www.digikey.com/product-detail/en/kemet/C1206C104K5RAC7867/399-1249-1-ND/4115	0.11	2.64
		inverter	12	ON Semiconductor NC7SV04P5X	https://www.digikey.com/product-detail/en/on-semiconductor/NC7SV04P5X/NC7SV04P5XCT-ND,	0.41	4.92
	Sensors/brakes						
		Current sensor	4	Allegro MicroSystems, LLC ACS710KLATR-12CB-T	https://www.digikey.com/product-detail/en/allegro-microsystems-llc/ACS710KLATR-12CB-T/620-	5.69	22.76
	H Bridge						
		MOSFET	16	EPC EPC2016C	https://www.digikey.com/product-detail/en/epc/EPC2016C/917-1080-1-ND/5031696	2.63	42.08
		Super Capacitor	1	Maxwell Technologies Inc. BMOD0058 E016 B02	https://www.digikey.com/product-detail/en/maxwell-technologies-inc/BMOD0058-E016-B02/118	120.64	120.64
		Load Resistor	2	TE Connectivity Passive Product HSA50820RJ	https://www.digikey.com/product-detail/en/te-connectivity-passive-product/HSA50820RJ/A1024	4.47	8.94
	Voltage Sensor						
		30K	8	Yageo RT1206BRD0730KL	https://www.digikey.com/product-detail/en/yageo/RT1206BRD0730KL/YAG5064CT-ND/6617220	0.56	4.48
		7.5K	8	Susumu PRG3216P-7501-D-T5	https://www.digikey.com/product-detail/en/susumu/PRG3216P-7501-D-T5/408-1849-1-ND/4917	0.66	5.28
	Arduino Power						
		Boost Converter 0.3-5.5	1	LiPower - Boost Converter	https://www.amazon.com/Electronics123-com-Inc-LiPower-Boost-Converter/dp/B01DCMTRB0/ref=sr_1_1?	17.82	17.82
		Boost Converter 2-12	1	Yeeco 2577 DC DC Boost Converter Step-up Voltage Regulator Voltage Stabilizer Adjustable Power Supply DC 2-24V to 5V 9V 12V 24V 2A with Micro USB Input	https://www.amazon.com/Yeeco-Converter-Regulator-Stabilizer-Adjustable/dp/B011EBSKK0/ref=sr_1_10?i	7.76	7.76
	Load						
		HS50 R82 J	2	Resistor	https://www.mouser.com/ProductDetail/ARCOL-Ohmite/HS50-R82-J?qs=sGAEpiMZZMtbXrIkmrvi	3.35	6.7
	Sub Bost converters						
		LiPower	1	Boost Converter	https://www.amazon.com/Electronics123-com-Inc-LiPower-Boost-Converter/dp/B01DCMTRB0/re	17.82	17.82
		Yeeco DC-DC	1	Boost Converter	https://www.amazon.com/Yeeco-Converter-Regulator-Stabilizer-Adjustable/dp/B011EBSKK0/ref=	7.76	7.76
	Connectors						
		Phoenix 1715734	2	Connector	https://www.digikey.com/product-detail/en/phoenix-contact/1715734/277-1264-ND/260632&?g	1.87	3.74
		Phoenix 1715721	2	Connector	https://www.digikey.com/product-detail/en/phoenix-contact/1715721/277-1263-ND/260631&?g	1.27	2.54
		Heavy Duty Power Connectors PP1	2	Connector	https://www.mouser.com/ProductDetail/Anderson-Power-Products/1327G6?qs=sGAEpiMZZMtjz\	0.46	0.92
		Heavy Duty Power Connectors PP1	2	Connector	https://www.mouser.com/ProductDetail/Anderson-Power-Products/1327?qs=sGAEpiMZZMtjzVb	0.43	0.86
		Heavy Duty Power Connectors PP1	4	Contact	https://www.mouser.com/ProductDetail/Anderson-Power-Products/1332?qs=sGAEpiMZZMtjzVb	0.25	1
		JST connect	2	contact f	https://www.digikey.com/product-detail/en/jst-sales-america-inc/SYF-001T-P0.6-LF-SN/455-2652	0.11	0.22
		JST connect	2	Housing F	https://www.digikey.com/product-detail/en/jst-sales-america-inc/SYP-02T-1/455-2654-ND/22068	0.2	0.4
		JST connect	2	contact M	https://www.digikey.com/product-detail/en/jst-sales-america-inc/SYM-001T-P0.6-N/455-1909-1-	0.11	0.22
		JST connect	2	Housing M	https://www.digikey.com/product-detail/en/jst-sales-america-inc/SYR-02T/455-2653-ND/240949	0.22	0.44
	Extra						
		Panasonic Electronic Components ERJ	24	resistor .33	https://www.digikey.com/product-detail/en/panasonic-electronic-components/ERJ-8RQFR33V/P.	0.24	5.76
Mechanical							
	Tower						
		Slip Ring	1	180A 6 wire Slip ring	http://mwands.com/store/180-amp-6-wire-slip-ring	39.98	39.98
		Tower	1	1.625" OD X 0.375" WALL	http://www.onlinemetals.com/merchant.cfm?pid=21552&step=4&showunits=inches&id=250&to	$110.43	110.43
		Tower Bearings	2	1.5" ID x 2.625" OD	https://www.thebigbearingstore.com/r24-2rs-radial-ball-bearing-1-1-2-bore/	5.46	10.92
		Tower Sleeve	1	3" OD x 0.188" wall x 2.624" ID	https://www.metalsdepot.com/aluminum-products/aluminum-round-tube?product=340	17	17
		Baseplate	1	1'x1'x1/4	https://www.metalsdepot.com/steel-products/steel-plate?product=1407	19.29	19.29
	Shaft						
		Shaft	1	7075 aluminum 1" diameter, 2 feet long		71.98	71.98
		Bearing Spacer	1	2" OD x 0.250" wall x 1.50" ID	https://www.metalsdepot.com/aluminum-products/aluminum-round-tube?product=332	$8.95	8.95
		Lower Main AL	1	5" x 5" x 0.375"	https://www.metalsdepot.com/aluminum-products/6061-aluminum-sheet-plate?product=399	$17.10	17.1
		Main Spacer	1	3/4" x 3/4" x 1/8" wall	https://www.metalsdepot.com/aluminum-products/aluminum-square-tube?product=262	$6.90	6.9
						Total:	1014.63

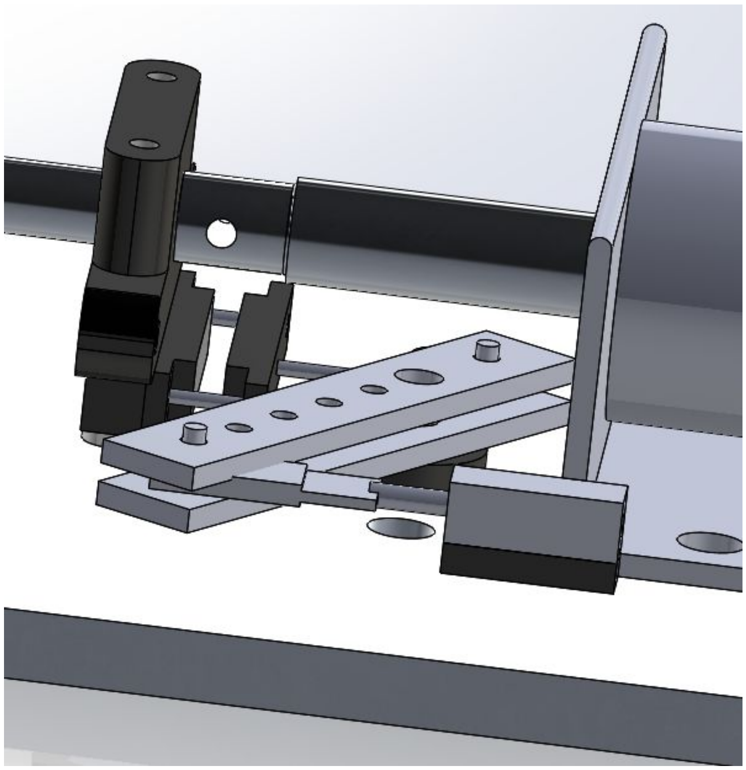
11.5 Appendix D: Gantt Chart



11.6 Appendix E: Implementation



Redesigned Nacelle



New Braking Mechanism