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Collegiate Wind Competition (CWC)

Students

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Sponsors

Naval Nuclear Laboratory (Kelly Harter)   Lockheed Martin (Beverly Walker)

Table of Contents

Executive Summary

The team was tasked with researching, designing, and building a mechanical, electrical, and aerodynamic wind turbine that is safe for deployment in the high wind environment of eastern Colorado. The turbine must have the ability to automatically cut off, produce power in variable wind speed conditions, and withstand wind up to 25 meters per second. In order to accomplish this task, relevant engineering design processes were followed. These included research, discovery, and measurement tasks performed to produce a low cost, high performing, and overall efficient turbine design able to generate upwards of 2.17 kilowatts of maximum power.

Introduction

Most modern wind turbines stand more than 300 feet tall, feature 100 feet blades, and are thus able to generate 6 million kilowatts per hour a year, enough to power more than 1,000 households. This need has resulted from the desire to reduce usage of fossil fuels given their impact on climate change and finite supply. The US Department of Energy (DOE) and the National Renewable Energy Laboratory (NREL) established the Collegiate Wind Competition in 2014 for this very reason. According to the U.S. Department of Energy's (DOE's) *Wind Vision* report, wind energy could supply 20% of the nation's electricity by 2030 and 35% by 2035. [1] The competition contributes to the creation and maintenance of American leadership in the transition to a global clean energy economy.

Specifically, the competition's objective is to prepare students from multiple disciplines to enter the wind energy workforce by providing real-world technology experience. Competition participants will need to develop an effective mechanical, electrical, and aerodynamic wind turbine that safe and reliable for testing in an on-site wind tunnel. Each team was asked to design and build a prototype wind turbine. The turbine must be designed to withstand continuous winds of up to 22 m/s during operation and up to 25 m/s when parked. Each turbine prototype must be designed for testing inside the Collegiate Wind Competition wind tunnels.

There are guidelines that students must follow when developing each part. There are detailed constraints and specifications provided by the wind competition in the following areas: physical design constraints outside the tunnel, electrical requirements, specifications for the turbine side of the point of common coupling (PCC), for the load side of the PCC, and interfacing with the competition data acquisition system.

Mechanical Design Introduction

The main priority of the team was to complete a design that first and foremost performed in line with the typical power curve. This meant designing a rotor that operated close to a coefficient of performance of 45% at a Tip Speed Ratio (TSR) around 4. In addition to these base criteria, the turbine was also designed to optimally operate at lower wind speeds. Being able to fulfill these design requirements required research into the blade geometry and yaw control which would have the greatest impacts on performance stability. The blade geometry would be the

deciding factor for power curve of the turbine impacting the coefficient of performance, tip speed ratio, and rotation speed of the main shaft. A passive yaw control system was also included to further maximize the potential power captured by the wind energy. Other systems within the nacelle box included a gear ratio and mechanical braking systems that further ensured stable workings of the turbine. All components were assembled to make the turbine design that can be seen in Figure 1 below as well as a detailed exploded view in the appendix.

Figure 1. Tuskegee Wind Turbine CAD Model

Blade Design

Initial Concepts

There is an incredible tool available at our disposal created specifically for the purpose of wind turbine design via BEM: QBlade. QBlade utilizes programs familiar to the group (XFOIL, XFLR5, etc.) to generate performance data based on designs. There is even opportunity for in-program optimization.

Initially, one-off airfoil analysis was done independently in XFLR5, and some in MATLAB, but upon availability of this tool, nearly all analysis up to this point was done in QBlade.

Design Points

All meaningful design must start with some basic design points. These are values or parameters that we are either shooting for or constrained by. Aside from the obvious values given in the rules (20 cm radius limit, etc), many of these design points were missing from the total turbine analysis, and thus had to be generated and iterated at this stage. Based on the research conducted in previous studies[1,2] and the guidelines set by the competition, these values were chosen as a baseline. Of importance is that it is favorable to shoot for a lower cut-in wind speed.

Table 1-1. Blade Design Requirements

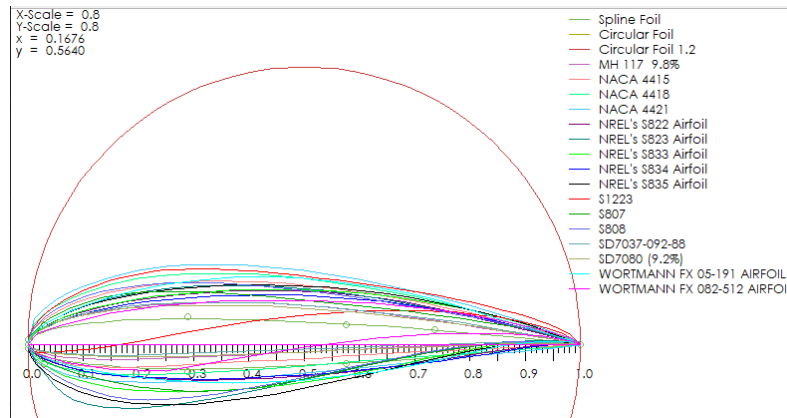| Dimensions	Limited to 20 cm rotor radius
Wind Speeds	0 - 25 m/s (5 – 22 m/s graded)
Reynolds Number	Low End: 50,000 High End: 150,000
TSR	1 - 6
RPM	500 RPM – 3000 RPM

Airfoil Selections

Figure 2. 18 Airfoils imported for Design and Analysis

Eighteen airfoils were analyzed in their respective aerodynamic iterations seen above in Figure 2. Selection was done by prioritizing high-C_l, low speed, low Re airfoils, with preference given to airfoils either in previous studies or designated by research authorities as wind-turbine airfoils. NREL developed a few airfoils (the S8—series) for wind turbines specifically that were also analyzed. Using Qblade, the next step was to generate polars for each airfoil:
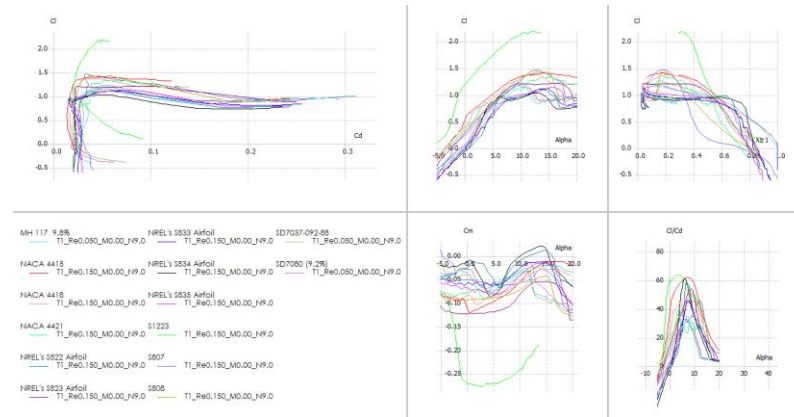
Figure 3. QBlade Airfoil Polars

In summary of airfoil selections moving forward, we narrowed the 18 options down to 4 seen in Table 1-2 below. With these airfoils in mind, various blades could be generated given the nature of QBlade. The general limitation we applied, was the rotor radius limit of 20 cm. About 15 different blades were iterated (with various combinations of the 18 airfoils mentioned before). This was narrowed to 5 primary blade designs at 50,000 Re. QBlade allows you to design your blades and even optimize them to various design points. We typically designed for a TSR of 3 to 5, and for the blade to be stall limited at 5 to 6 TSR. The table below summarizes each of these options:

Table 1-2. Blade Airfoil Considerations

Blade	Airfoil (s)
Design 1	SD7037-092-88
Design 2	SD7080
Design 3	MH117
Design 4	MH117, SD7037-092-88
Design 5	NREL's S833

Multi-parameter Boundary Element Method (BEM) simulation then followed. Each blade design was applied to an actual turbine simulation, with a designated range of wind speeds, and a design operating RPM.

Table 1-3. Blade Design RPM Comparison

Turbine Option	Blade Design	Design RPM
A	Design 5	1500
B	Design 3	1200
C	Design 1	2300

Each of these RPM values was selected based on the Multi-Parameter BEM simulation, as the optimal design point for each blade. The Power generated vs wind speeds plot is presented below:
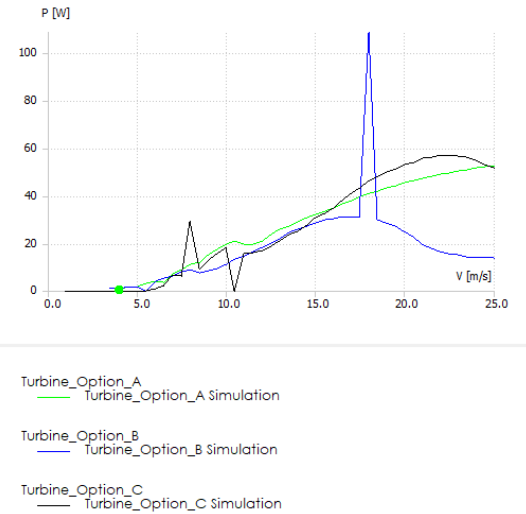
Figure 4. Power vs. Windspeed Comparison Plot

From this analysis, a blade design was selected. We preliminarily selected Design 5 and completed the exhaustive analysis - Nonlinear Lifting Line Simulation within QBlade. This simulation takes a wind field you define, among many other parameters, and runs a full-scope turbine simulation. Design 5 (at the wind speed of 5 m/s) produced the most optimal results based on current analysis, and the images/data is presented below.
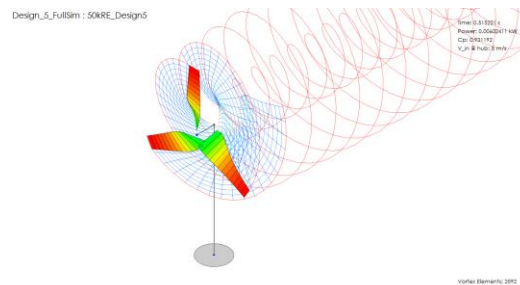

Figure 5. Design 5 Wind Field Simulation

Important design points included a TSR of 4, with an RPM of 1164. The wind field was not turbulent (though this analysis can be run as well). Though promising, it is important to note (in the top right corner) a C_p value of 0.93 is indicated. This certainly is significantly higher than the theoretical limit, and thus must be investigated (the current tasking of this week). Otherwise, this represents the current extent of blade design for the CWC wind turbine.

Further Design Iterations

Table 1-4. Blade Airfoil Considerations (Cont.)

Name	Airfoil	Design RPM
0519_Design_A	SD7037-092-88	1200
0519_Design_B	FX 63-137	1200
0519_Design_C	S1223	1200

Analysis

Each blade's performance across various TSr's can be found in Figure 6 below. What is important to note, is that they each have a very similar max C_p, across a similar range of TSr values. Where they differ significantly is their high TSr performance. Design C has the second highest max C_p, by a narrow margin, but falls flat around a TSr of 6. From a low speed performance aspect, it is a great option since it would appear to be limited to a TSr of 6 (a passive speed limitation).
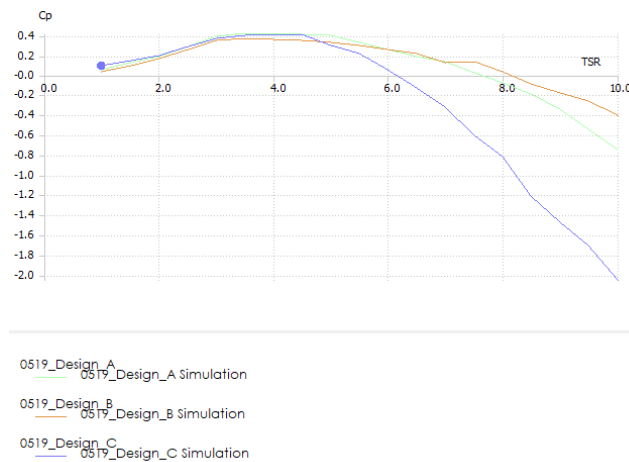

Figure 6. Coefficient of Perforamance vs. Tip Speed Ratio Airfoil Comparison

Table 1-5. Coefficient of Performance Comparison

Design Option	Max C_p
0519_Design_A	0.416 at 3.5 TSr
0519_Design_B	0.371 at 3.5 TSr
0519_Design_C	0.409 at 4.0 TSr

Now, each blade design was analyzed as a turbine, with a design RPM of 1200. The wind speeds analyzed were from 0 to 30 m/s, at an approximate hub radius of 0.16 meters. Design A proved to generate the greatest wattage at the lowest wind speed.

Structural Considerations

We then elected to analyze the structural characteristics of each leading blade design using QBlade's own FEA tool. Each design was simulated to be made of ABS plastic (considering this

is our leading print option). ABS plastic has a tensile yield strength of around **48.3 MPa** [1], making our choices above well within a safe loading range. Deflection was kept to an extreme minimum (on the order of **~ 0.0003 meters**).

Table 1-6. Blade Design A Stress Simulation

5 m/s	11 m/s	22 m/s
Max Stress: 0.70 MPa	Max Stress: 1.57 MPa	Max Stress: 3.56 MPa

Table 1-7. Blade Design B Stress Simulation

5 m/s	11 m/s	22 m/s
Max Stress: 0.74 MPa	Max Stress: 1.23 MPa	Max Stress: 2.71 MPa

Table 1-8. Blade Design C Stress Simulation

5 m/s	11 m/s	22 m/s
Max Stress: 0.48 MPa	Max Stress: 0.90 MPa	Max Stress: 2.75 MPa

Final Selection

Based on the analysis below, Blade Design A was ultimately selected based on its low-speed and midrange performance and load tolerance against Designs A and C. The blade design was exported from QBlade, into Autodesk's Inventor where it was integrated with the hub and spinner assembly. A summary of this design can be seen in Table 1-9.

The design is optimized for low speed performance, and is stall limited towards a TSR of 6 (via a fixed pitch selection). The C_p vs TSR graph from QBlade can be found below. Given the current scenario, this represents the fullest extent of design and construction for the blade. However, to compensate for the fact that we would not be able to construct a full-scale model more exhaustive simulation was completed, as will be detailed below.

Table 1-9. Blade Design A Specifications

Parameter	Value
Radius	174.02 mm
Theoretical C_p	0.416
Design TSR	3.5
Airfoil	SD7037-092-88
Image	

Yaw Control

Yaw control is used in a turbine to orientate the rotor and nacelle to ensure the airflow is perpendicular to the blades as often as possible. The orientation is required to ensure the maximum amount of kinetic energy available in the wind is transferred to the rotor. In a vertical axis wind turbine, the most popular yaw control utilized is the forced yaw system. This system works as the bottom of the nacelle has multiple gear and electric motor attachments. The top end of the main turbine shaft is also equipped with a gear on the outside diameter with the nacelle rotating around that gear. However due to the time constraints and additional costs associated with this system, a passive yaw system was chosen instead.

A wind turbine will instinctively yaw to a "corrective" position depending on the orientation of the wind. [5] In order to allow this rotation of the nacelle box and motor, a coupler had to be made that fit and rotated around the main shaft tower. The coupler was then equipped with space for multiple ball bearings that allowed for a stable rotation around the shaft tower as can be seen below in Figure 7.
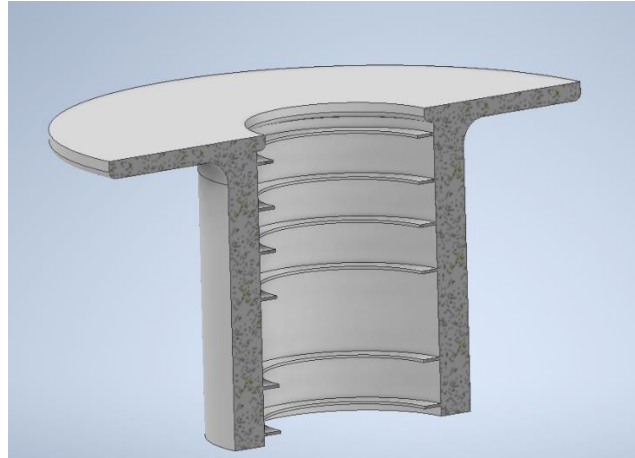
Figure 7. Cross Section View of Nacelle Coupler

After attaching the coupler to the nacelle box, the nacelle can easily rotate around the main shaft. In addition, two fins were attached to the end of the box the ensure stability for the exposure to high winds.

Nacelle Box

The nacelle is one of the most essential elements of a wind turbine as it is where the power conversion and subsequent generation occurs. Thus, it is essential that everything from the dimensions to the components inside the nacelle are meticulously considered. The major components located inside the nacelle box were the gears, mechanical braking system, and AC generator than can be seen labeled in the figures below.
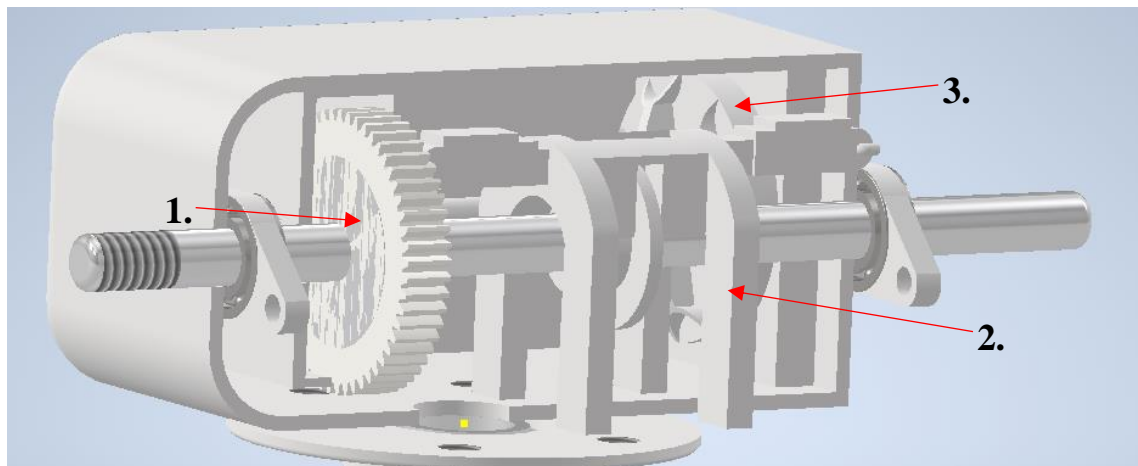

Figure 8. Nacelle Box

1) Gears 2) Mechanical Braking System 3) AC Generator

As the team was not able to use a direct drive generator that was seen in the market version, a gear relationship had to be made. The gear relationship is essential to convert the low speed from

the main shaft to a high speed that can be accepted by the generator. To do this a 1:2.7 gear ratio was used.

The main shaft was also equipped with a mechanical braking system in order to allow for quick stoppage as is required by the "Safety Task". This was achieved through an unconventional disk brake system. The main shaft was equipped with a disk break with a structure surrounding it. Fitted through slots in the structure were linear actuators equipped with brake pads on the ends of the actuators as seen below in Figure 9.
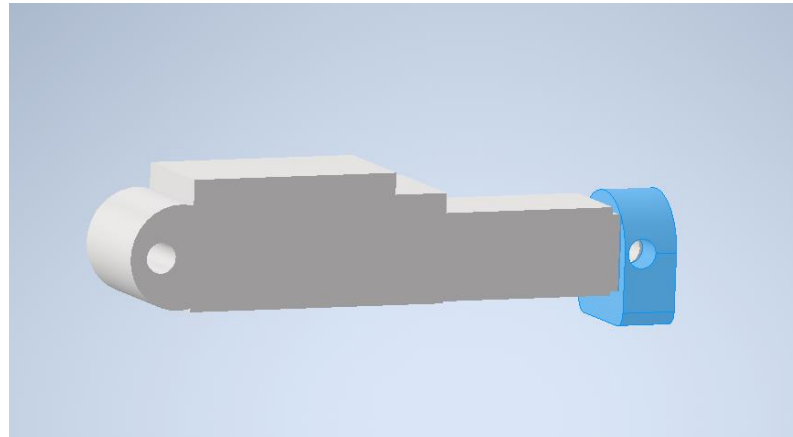

Figure 9. Linear Actuator with Brake Pad Attachment

Through programming the actuators, highlighted in blue in the figure below, would extend appropriately to contact the brake disc and thus stop the main shaft. The layout can be seen below in Figure 10.
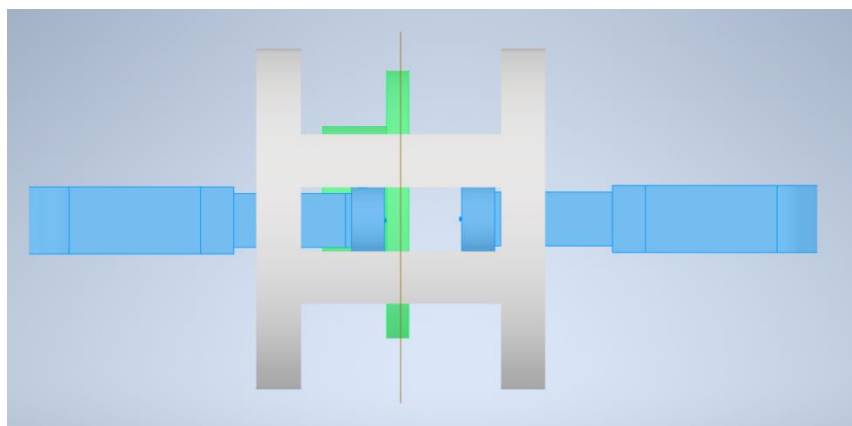

Figure 10. Brake Disc (Highlighted Green) and Linear Actuators with Brake Pad Attachments (Highlighted Blue)

The generator was then connected to the secondary shaft with the decreased torque and rotational velocity. This made sure that possible failure of the generator was avoided, and

maximum power generation was ensured. Finally, bearings were installed on each shaft to ensure stability and mitigate possible energy loss.

Electrical Design Introduction

The purpose of the electrical system is to maximize power, system efficiency, and to safely conduct electricity to the load. It does this by converting kinetic wind energy to rotational mechanical energy. This is done by the turning of the turbine blades caused by the wind which causes the turbine shaft to rotate. The shaft is connected to the generator. The magnet and wires in the generator change the rotational mechanical energy from the shaft into electrical energy, which is sent to the load. Our electrical system consists of an AC generator, AC/DC converter, several measuring and sensing components, an Arduino Microcontroller that acts as our control for the subsystems, and our braking systems. A block diagram (figure 11) is shown to illustrate the concept of the system's operation. The schematic for the electrical system is shown in Appendix A.
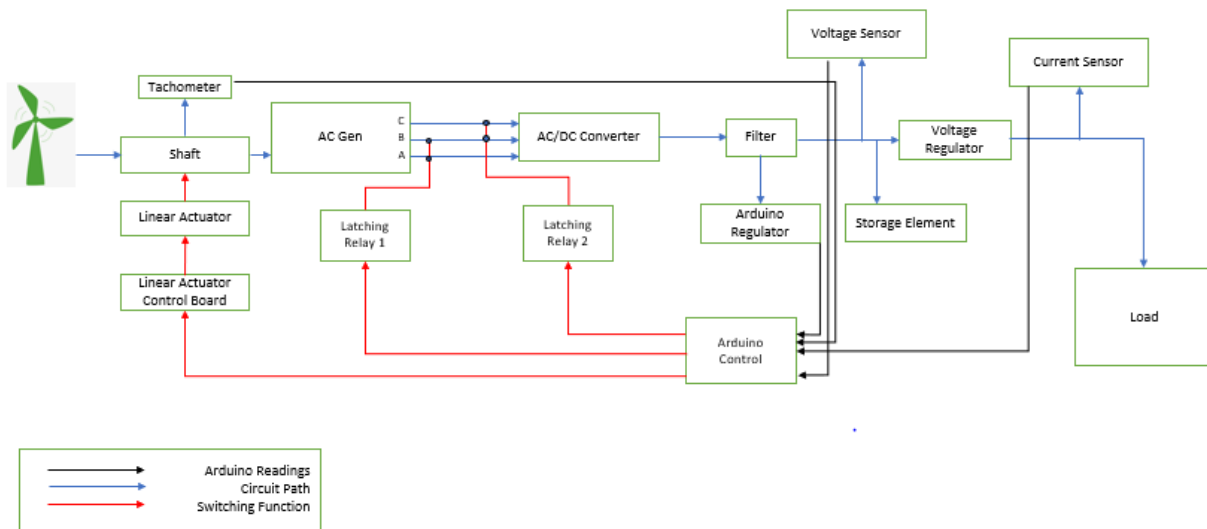

Figure 11. Electrical System Diagram

Generator Selection & Analysis

The generator, an integral component of the wind turbine system, was selected based on a combination of projected "goal" parameters, competition requirements, and industry standards. During the generator selection process, our team began with the turbine rotor hub and worked inwards. Through calculations from the mechanical team, we were able to obtain a set of projected characteristics for our turbine to have (shown in Table 2-1). After calculations were performed, we confirmed our results adhered to the competition tasks given in the rulebook. As such, wind speeds in the range of 5 m/s (the cut-in wind speed) to 25 m/s were explicitly considered.

Table 2-1. Power Generation Calculations

Wind Speed	Blade RPM	Gear Ratio	High Speed RPM	Low Speed RPM	Power Generation (Watts)
5 m/s	1164	1:3.5	4074	332.57	3.75
11 m/s	1205	1:3.5	4217.5	334.29	25.09
25 m/s	1350	1:3.5	4725	385.71	66.93

The team researched the standards of generators used by both the industry and for commercial use. Ultimately, we chose to emulate the wind turbine system of the industry adopting the frequently used permanent magnet synchronous AC generators. Interestingly, several of the AC generators found did not give most of the desired motor ratings, therefore, the team chose to examine alternative forms of power generation. We found that most brushless permanent magnet DC motors can generate AC power when used as generators. As the brushless DC motors had the most ratings available, we moved forward with this design and obtained two final generator choices (shown in Table 2-2). Lastly, as our system for braking the turbine (discussed later in this document) requires a set of electrical connections, we sought to minimize the space taken up by the generator within our nacelle. The generator option chosen is summarized below:

Table 2-2. Generator Specifications

Parameter	Option 1: Turnigy Multistar Brushless Multi-Rotor Motor	Option 2: Moon Industries S80 Series Brushless DC Motor
Weight (in kg)	0.674	0.98
Motor (Total) Dimensions DiamXLength (cm)	9.2x3.9	8x5
Shaft Dimensions Diam X Length (cm)	0.3x0.5	1.2x3
Rated Voltage (V)	-	24
Max Voltage (V)	45	-
Rated Current (A)	-	5
Max Current (A)	57	-
Rated Speed (rpm)	4500	4000
Max Speed (rpm)	-	5000
Rated Torque (Nm)	-	0.24
Rated Power (Watts)	2800	100

Measuring and Sensing

To meet the task requirements for the competition we decided to have our system design to operate in three modes. These modes are controlled by the microcontroller. In the table below, each of the modes have a description of their function, the task that it satisfies for the competition, and what conditions are needed to be met before it changes to a different mode.

Modes	Description and Function of State	Test Tasks Satisfied	State Change Conditions
Cut-in	-Default when Arduino turns on - Takes measurements and makes decisions from this state	- Cut- in wind speed	- Safety button engaged, or load disconnected, go to safety state
Power Curve	- Monitor power generated at wind speed under 11m/s - Maintain system stability below 11 m/s wind speed - Brakes engaged until RPM at 90% MAX Power	- Power Curve performance - Control of rated power and rotor speed - Durability	- Safety task button pressed, or load disconnected, go to safety state
Safety	- Immediately engage braking system to 10% max RPM. - Maintain system ability to produce power	- Safety - Cut out	- Safety button disengaged, go to Cut-In - Load is reconnected, go to cut-in state

Figure 12. Modes of Operation

Control Subsystems

Two modes decide if the braking system needs to be engaged to maintain target RPMs within the system. If the mode states are high for either the safety mode or the power curve mode, then the brake is engaged within the parameters written in the states code. If the mode states are not high, the system remains in a continuous loop where the specifications are constantly measured.
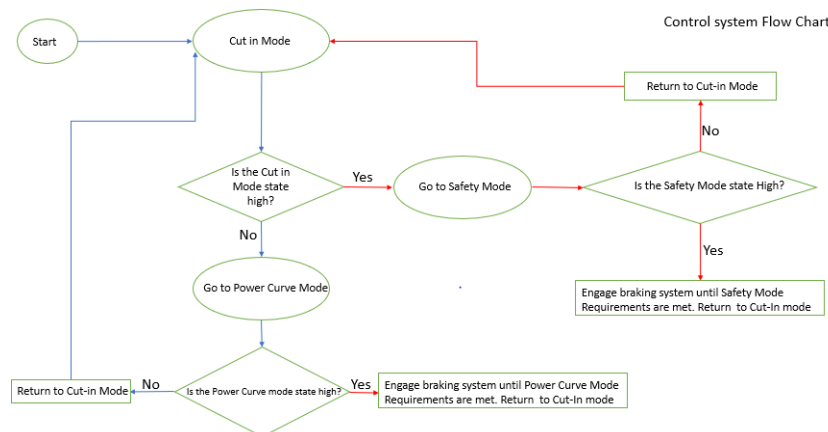

Figure 13. Control System Flow Chart

Brake System

Initially, the braking system chosen was the "generator braking" method. While larger, commercial wind turbines rely on mechanical braking methods, it was believed that our smaller turbine can perform necessary braking in the form of electrical braking. Advantages of electrical braking include less problems with friction and fewer additional components. Multiple

calculations were completed to analyze the torque necessary to shut down the turbine and the heat that would be dissipated. We determined that there would be too much heat dissipated for the system to avoid possible overheating of components resulting in damage. [7] After a lot of analysis, the final configuration we used was a combination of the electrical braking and friction braking.

Implementation/Integration

The generator brake method involves applying high impedance loads to two phases of the generator to perform electrodynamic braking. These loads are only applied at the desired instances (high wind speed and "emergency shut off") therefore, an Arduino module can be integrated in a circuit using a pair of switches (Boolean logic) to apply the impedances when the conditions are met.

Circuitry Breakdown-

Controlled by two modules from the Arduino (figure 14)-

a) Module 1- connects to the output of phase A and phase B
b) Module 2- connects to phase B and phase C.

Each Module has latching relays- controlled by a 5V impulse signal input.

a) Impulse signal- generated by control logic written in Arduino.
b) Impulse signal= wire OFF would switch the state of the relay from on to off
c) Impulse signal= wire ON would switch the state of the relay from off to on.
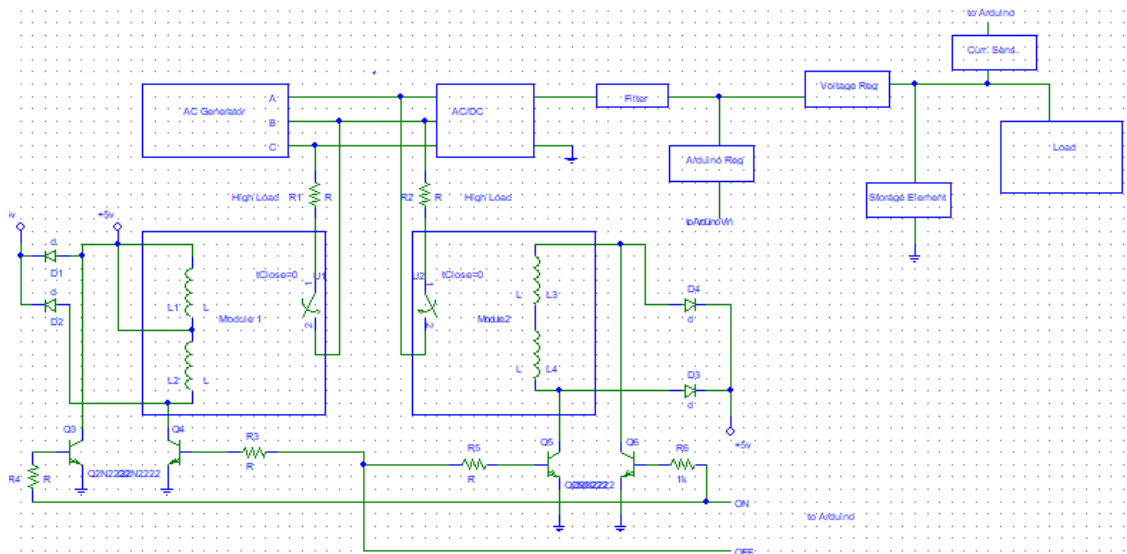

Figure 14 Electrical Circuit Schematic

This allows the circuit path across the relay to switch between open circuit and closed circuit.

Output at open circuit- The low impedance/high load resistor is disconnected, normal operation.

Output at closed circuit- The circuit applies a large load and small resistance between the phases. This causes a very large load to be present between phase A and phase B, and between phase B and phase C. The torque of the rotor is increased greatly to the point of almost stopping, and the generator power is transferred to the resistors in the safety circuits without transferring to the load. The wind turbine brakes and stops if the relay is maintained closed.

Requirement 1- Brake on Command (Pushbutton)-

The Arduino Uno board is connected to a push button for signaling manual emergency shutdown, a current sensor for sensing load disconnect, and the relays in the safety circuits for shutting the turbine. Its power pin is also connected to the regulated output of AC/DC to make sure the control logics are always working under its rated voltage.

Requirement 2- Load disconnect

A current sensor in series relays to the load. At the state of 'normally operating', when the current sensor's current reading is 0 or close to zero, there exists an open circuit at the load and the load has been disconnected. The state transitions to 'load disconnect', and an impulse signal is outputted to the relay to close it and shut down the turbine. Only when the load is connected and the current reading becomes non-zero would the state transitions back to 'normally operating', and an impulse signal is outputted to the relay to open it and resume the turbine.

Friction Brake Integration

After analysis, we decided that the generator braking alone would not suffice in meeting our braking requirements and decided to add an additional friction brake as the primary means to shutting the turbine down. We conducted an analysis of the force necessary for the actuators to shut the system down. [6]

Option	Ratio	Max Force(N)
1	50:1	22
2	100:1	42
3	210:1	80

Table 2-3 Force parameters of the Actuators
* Stroke lengths can range from 10mm, 30mm, 50mm, and 100mm.

Arduino Control Logic

The Arduino takes multiple signals as inputs and determines whether a 5V pulse signal output needs to be sent to the safety circuits to toggle the state of the relay and activate or deactivate the safety circuits.

The control logic uses finite state machine to represent the state transitions and outputs needed under various input conditions. Initially, the state is set to 'normally operating', and the relay is opened. When the push button is pressed, the state transitions to 'button pressed', and a pulse signal is outputted to the relay to close it and shut down the turbine. Only when the button is pressed again would the state transition back to 'normally operating', and a pulse signal is outputted to the relay to open it and resume the turbine. Therefore, repeatedly pressing the push button switches the state between manual/emergency shutdown and normal operation.

Other Considerations

We attempted to integrate an Active Blade Pitch System instead of the friction brake but ultimately decided that due to the complexity of the integration, it would not be practical. The concept was to involve a Linear Actuator (LA) with Control Board (LAC) along with a rotor from an RC helicopter. The concept is shown in the block diagram in the figure below.
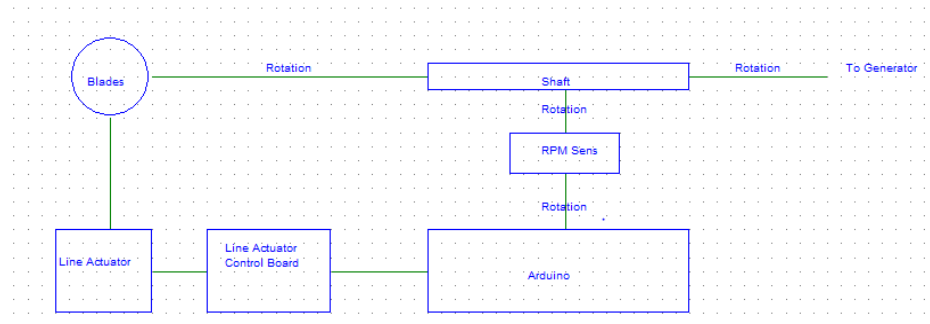

Figure 14. Active Blade Pitch System

The actuator used was the Actuonix L12-P Linear Actuator with Position Feedback. The L12-P line of linear actuators features an internal potentiometer for position feedback. This actuator was kept and integrated into the friction braking portion of the brake system.
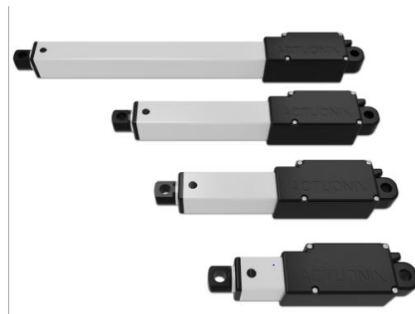

Figure 15. Actuonix L12-P Linear Actuator

An Actuonix Linear Actuator Control Board (LAC) is used to control the linear actuator. The same V_{DC} used to power up the LAC will be sent directly to power the linear actuator. As the linear actuator input must be less than 7V, a $7V_{DC}$ is used to power up the LAC to keep the linear actuator safe as well as maintain the stability of the LAC.
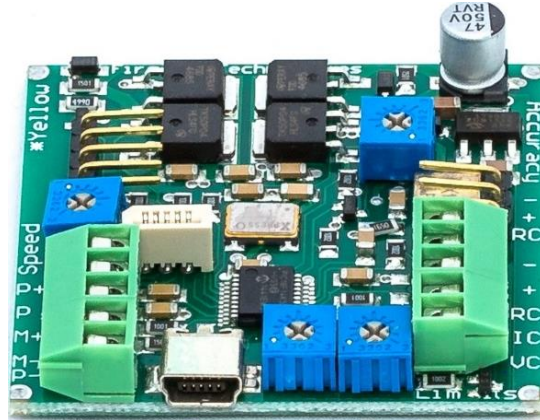

Figure 16. Actuonix Linear Actuator Control Board

Conclusion

Overall, the wind turbine constructed is expected to be fully operational and would have been ready for action in the competition. All disciplines came together to design, calculate, and research the parameters and elements necessary for the turbine. Through effectively exchanging information and thoroughly understanding the purpose of each component, an assembly was created for the task of accomplishing each goal of the competition. The result is a genuine turbine design started from simply drawings and thoughts into a device with the necessary components to fully operate and satisfy the design objectives.
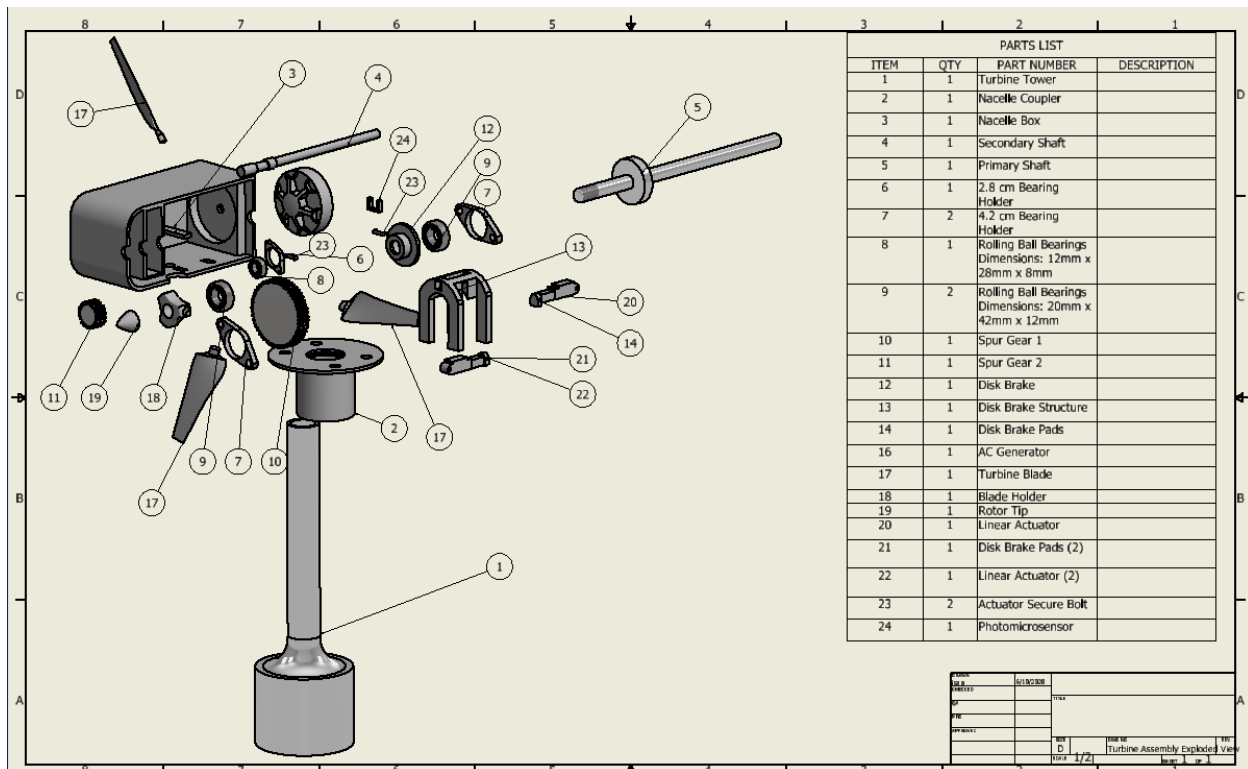
Appendix

Figure 18. Wind Turbine Exploded View & Bill of Materials

References:

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