University of Colorado Boulder Department of Mechanical Engineering

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Director - Roark Lanning
Claire Isenhart - Project Manager
Simon Grzebien - Finance Manager
Alec Kostovny - Logistics Manager
Aaron Schwan - Systems Engineer
Anika Levy - Manufacturing Engineer
Charles Candon - Test Engineer
Graham Blanco - CAD Engineer
Kirollos Gerges - Electromechanical Engineer
Erik Feiereisen - Electromechanical Engineer
Luke Walker - Electromechanical Engineer
Mariam Gopalani - Civil Engineer

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I Executive Summary

The University of Colorado Wind Competition Team has detailed the technical design of a small-scale wind turbine in this report. The turbine specifications follow the rules and regulations outlined by the U.S. Department of Energy (DOE) Collegiate Wind Competition (CWC). This is the first time the CU Wind Competition Team is competing at the Collegiate Wind Competition after qualifying from a learn-along team. The fundamental design philosophy of the team is to achieve success through simple solutions. The team took the approach of success instead of optimization due to the lack of previous competition experience. In doing so, the team designed an elegant and reliable solution to a complex problem. Detailed below is the design of the various components of our small-scale wind turbine. The blade design required extensive research, iteration, and prototyping before settling on an optimized NACA 4412 airfoil design (Kale et. al.). Furthermore, the iterative design process produced a specific blade for the rotations per minute (RPMs) the turbine will be operating at during the competition testing. The pitching mechanism is a purchased radio control (RC) helicopter pitching mechanism that is customized to accomplish the necessary pitching on the turbine. The pitching algorithm is designed to change the angle of attack in order to optimize the power output of the system. It was determined through testing that the minimum angle of attack (closest to the bearing) is ideal for system startup as it is associated with the lowest cut-in speed. Once rotation begins, the pitching algorithm moves the servo arm and positions the attached mechanisms to the optimal angle for the highest power output. Due to the increased complexities of the new offshore foundation component of the competition, the yaw requirements were reduced and a passive yaw system is capable of meeting the requirements. Because of our design philosophy and the reduced requirements, an inexpensive turntable bearing provides a successful solution for the yaw mechanism. The turbine tower is a composite fiberglass tube to provide structural stability, while also reducing the load on the foundation due to the lightweight characteristics of fiberglass. Supporting the turbine is the foundation. Based on research, prototyping, and industry standards we designed a suction bucket foundation that provides the required support at high wind speeds and is low weight for the structural stability it provides. The report details how we iterated on past designs, and which parts we integrated from off-the-shelf components. Finally, the assembly and commissioning of the turbine tower is outlined in detail.

II Technical Design

II.A Blades

II.A.1 Dynamic Loading Analysis

The turbine blades are one of the most important parts of a turbine and in order to design for success in the competition, analysis of the blades is crucial. Taking into account the wind speeds, blade geometry, and loading on the blades is paramount to making sure this important subsystem works. In order to determine the loads on the blades, a dynamic loading analysis was conducted. To simplify the process, it was assumed that blades were rectangular with equal density throughout, making the center of mass half the overall length assumed to be 9 inches. This agrees with the assumed worst-case condition of a flat plate. In reality, the blade will be a consistent density with a tapering chord diameter such that the center of mass will be located closer to the base of the blade than indicated. Using the centripetal force equation shown below, it is clear that as the radius of the blades increases, the force will increase.

$$Fc = mr\omega^2 \tag{1}$$

For the properties of the blade, the team used last year's blade design as a mass estimate which was approximately 1.1 oz per blade. To adjust this value for an increased safety factor, the total mass for the blades was assumed to be around 2 oz. Based on these calculations, the rotor hub can take a maximum of 2000 RPM before fracture. This RPM value is used in the centripetal loading calculation shown above, with the associated values for the mass and radius in Fig.1 and was found by backing out the minimum safety factor of 1.

m = 1/8 lb
r = 4.5/12 in
ω = 2000 RPM = 209.3 rad/s

The centripetal force is approximately bounded by $F_c \approx 2053.4$ lbf. This can be used as a upper estimate for the forces the pins experience which is analyzed in the following section.

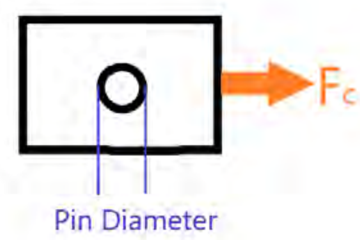


Figure 1: Force on Pitching Mechanism Pin

The pin area is characterized as a through-hole and therefore the effective area is twice the cross-sectional area of the pins. Due to the fact we are buying the rotor hub, we have an assumed pin diameter of 1/8th inch and a max shear comparable to many screws available on McMaster Carr of 84,000psi.

$$Ac = 2 * A_{pin} = \frac{1}{2} * \pi * D^2 = \frac{1}{2} * \pi * (1/8)^2 = \frac{\pi}{128} in^2 \quad (2)$$

$$\tau = F_c / A_c = 2053.4/(\pi/128) = 83663 psi \quad (3)$$

$$N = \tau_{max}/\tau = 84000/83663 \approx 1 \quad (4)$$

Although a safety factor of 1 is unacceptable, this assumes that the blades are roughly twice the weight expected from last year's tests and that a speed of 2000 RPM is met. This max RPM is 500 RPM faster than last year's tests. These factors along with a radially closer center of gravity are expected to lower the centripetal forces. The safety factor value is also believed to be acceptable as the blade is the most likely component to fail (instead of the pin connection) due to the soft 3D printed PLA material and the high forces it experiences. Therefore, pin fracture is unlikely to be a contributing factor to failure.

II.A.2 Blade Design

We based the blade design on a NACA 4412 Aerofoil due to the high availability of public data. The NACA 4412 has good lift to drag ratios for the wind speeds of under 25 m/s that will be tested at the competition. Furthermore, this airfoil design combines its useful lift characteristics with being structurally durable which is something that was highly considered, since the 3D printed blades will be under high loads outlined in section 2.1A. Using Kevin et. al. we used an optimized blade design for different tip speed ratios. This design controlled the chord length as well as a set angle of attack per section of the blade. In order to transfer the equations to a physical design, we created a python script that could create an STL file from a set of calculated coordinates. From this STL we could implement the design into our 3D model and print them for testing. Due to the physical limitations of our design we know we have to operate below 2000 RPM and looking at previous years we found that the range was roughly down to 1000 RPM. From the range we selected 3 possible RPMs 1200, 1500, and 1800. The optimal blade for our design will be selected by testing the full turbine with the electrical systems.

II.B Pitching and Controls

The pitching mechanism is necessary to change the angle of the blades in order to optimize and stabilize the power output of the turbine. Given the complexity of the mechanism, this component was purchased from Blade, a model helicopter producer. The CFX 250 pitching mechanism is designed for larger, more robust RC helicopter blades which is ideal for the heavier turbine blades in our design. Given the material constraints of the shaft, it was determined that 2000 rotations per minute (RPM) is the maximum rotational speed of the rotor. This design constraint caps the rotational speed of the rotor and prevents the tear-out of the screw holding the blades in place. The pitching system is connected to a servo motor by a 3D printed linkage. As the servo arm swings backward and forwards, the pitching system will move linearly along the axis of the shaft (Fig.2). Blade pitching occurs at different set points during operation. When the system is in startup mode, meaning little to no power is being generated, the blades are pitched to the minimum angle with respect to the direction of the wind (blades are parallel to the direction of the wind). This pitch angle promotes the start of the rotation. Once the rotation speed has reached a certain threshold, then the blades are pitched to the optimal pitch angle. This angle will be determined from repeated testing conducted prior to the competition. The point at which blades are pitched is determined by the rotational speed. Since voltage is proportional to RPM, the control system will monitor the voltage at the output of the rectifier (detailed in electrical section). When the voltage reaches 0.5 volts it indicates that the optimal pitch angle is needed to increase RPMs. The testing to determine the optimal angle will proceed by iterating the angle of the blades from the minimum angle of attack to the maximum. The orientation that yields the largest power output will be set as the optimal angle for all wind speeds. After E-stop has taken place, the same algorithm can be used to restart the turbine.

Figure 2: Pitching Mechanism CFX 250

II.C Generator/Electronics

II.C.1 Generator

The generator was carefully chosen by following a number of specifications that we understood to be crucial to the optimal function of the turbine. The main specifications we looked for were a low-speed constant (number of RPMs it takes to generate one-volt output), a minimal cogging torque and rotor inertia (to allow the turbine to begin rotating at lower wind speeds), and a low terminal resistance (minimal resistance through the wires of each phase of the generator to allow for more power output). The generator chosen was the EC-i 40 brushless, 3-phase 100-watt motor from Maxon. This motor, when used as a generator, features a speed constant kn of 127RPMV and rotor inertia of 44 gcm^2, which are both relatively low values as compared to many other generators. Another reason a 3 phase brushless DC motor was chosen was that it is crucial in the function of our emergency stop system where all three phases of the generator are shorted together to add counter torque to the shaft.

II.C.2 Rectifier & DC-DC Converter

The generator has three phases each producing AC power. Therefore, a 3-phase, full-wave rectifier is needed to change this into DC power. As mentioned previously, the voltage at the output of the rectifier is proportional to the RPM of the generator. This DC power is sent to the load to be dissipated. The voltage that the load experiences is varying. Based on the speed constant of the generator and the maximum allowable RPM before mechanical failure, the maximum voltage that the load (and similarly the PCC) will experience is 15.75 volts. This is well below the allowed 45 volts specified in the rules and regulations.

The turbine controls system (Fig.3) consists of several circuits (emergency stop, mode switch, microcontroller) that require a constant 5 volts to operate. This necessitates the use of a DC-DC converter that will output a steady 5 volts with varying input voltages. To capture the widest range of voltages, the DC-DC converter was designed to function with input voltages from 3-20 volts. The single-ended primary-inductor converter (SEPIC) topology was selected as the DC-DC converter because it has buck-boost capabilities. This means that the output voltage will always be 5 volts.

II.C.3 Emergency Stop

The emergency stop system is a crucial component of the functionality of the turbine and the competition requirements. This system was designed to use the least amount of power possible to ensure that all other components will still function properly, especially when the load is disconnected. When the emergency stop sequence is initiated, a signal from the microcontroller is outputted to the gate of a MOSFET. When the threshold voltage of this MOSFET is met, the current is allowed to flow through an optoisolator. When current flows through this optoisolator, it opens another gate on the opposite side of the optoisolator which shorts each of the three phases of the generator together. When these three phases of the generator are shorted together, a significant counter-torque is added to the shaft of the generator thus slowing the turbine down.

II.C.4 Mode Switch

There are two main modes that the electrical system will operate in Startup and Normal Operation. This is needed because the turbine does not generate sufficient power to sustain the controls at low wind speeds. Thus, there is no way to pitch the blades to a better angle of attack and therefore the turbine will not function properly. To fix this issue, the "Startup" mode of operation is used. In this mode, power from the load, which is plugged into the wall, is sent to the controls PCB to power the necessary components such as pitching and the microcontroller. The microcontroller then monitors the output voltage of the turbine as it speeds up (using a voltage divider), and when a threshold voltage is reached, a mode switch occurs. During the mode switch, the controls PCB will send a signal to the load PCB. The signal is fed into a MOSFET that controls the state of a relay. The relay connects/disconnects wall power. The threshold voltage represents the point where the turbine is generating sufficient power to power the controls, and excess power to be sunk in the load. This setpoint will be measured in testing by finding the speed at which the turbine generates more than the draw of the controls (~1.25 watts).

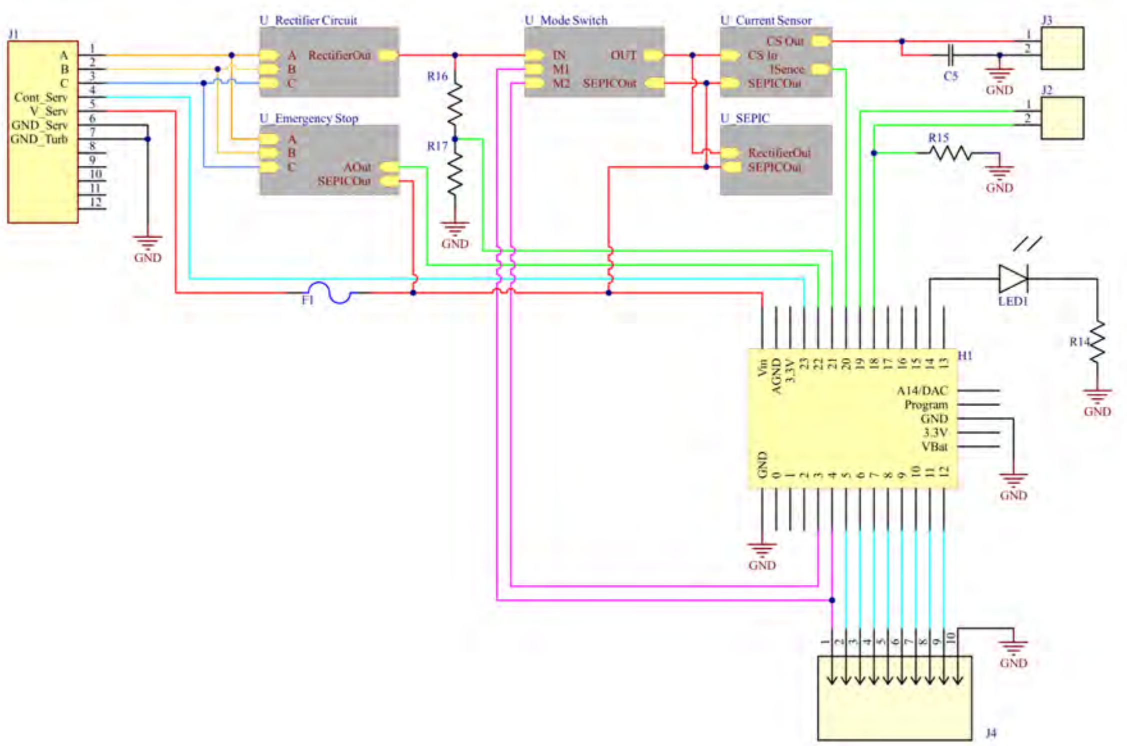


Figure 3: Schematic of the turbine controls

Color	**Description**
Red	Power
Black	GND
Orange, Yellow, Blue	Generator terminals
Light Blue	PWM signal to control pitching servo, load resistor control signals (Figure 3, J4)
Pink	Mode switch signals
Green	Voltage read, current read, E-stop input signal from button, E-stop output signal to shorting circuit

Table 1: Net colors and corresponding meaning from Fig.3

II.C.5 Load

The load is designed to allow excess power not used by the controls PCB to be sunk through a series of resistors (after passing through the PCC). Each power resistor is connected/disconnected by signals from the microcontroller. The amount of power that needs to be dissipated by the load is determined by taking the total power generated and subtracting the power needed by the controls. The amount of power generated changes at different wind speeds so the amount of power that needs to be sunk is variable. The power resistors are connected in parallel to achieve many different effective resistances. There are only 8 power resistors on the load whose resistance values are chosen as powers of two. This allows for a binary representation of the powerful resistance, and thus, the generation of the maximum number of power resistance values (256 power resistance values/combinations from the 8 power resistors utilized in the load board). Fig.4 shows the simplified schematic of the load design.

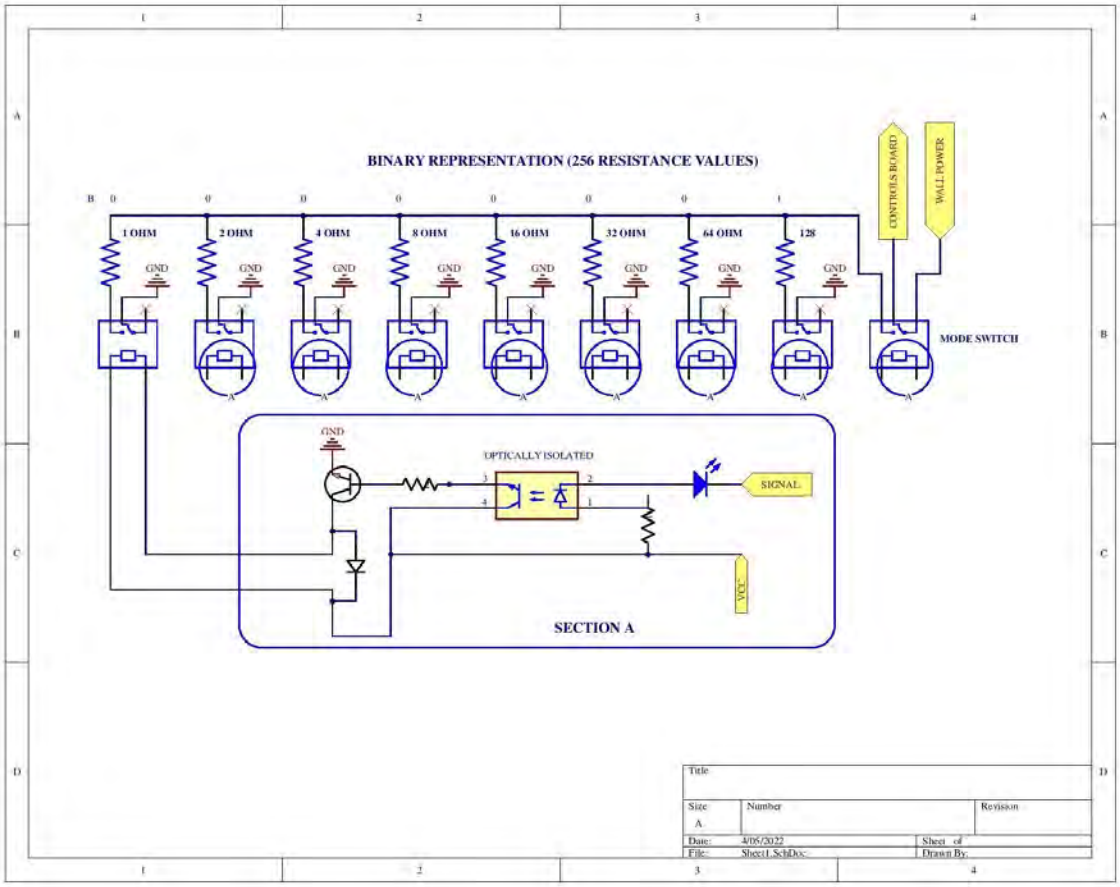


Figure 4: Load Schematic

II.D Yaw Mechanism

The yaw system was designed such that the nacelle could be manually positioned in the direction of the wind. To achieve this goal, a turntable (seen in exploded view of Fig.13) bearing was attached underneath the nacelle for 360° rotation. Once the ideal orientation is reached, a set screw is screwed down onto the top of the bearing to increase the internal friction. This process prevents rotation of the nacelle.

II.E Tower

The design of the tower is based on the two major components. First, the tower should be lightweight for ease of transportation and to reduce the load on the foundation. Second, it is required that the tower is hollow to allow for the wiring to travel down the interior. Both objectives are accomplished using a fiberglass tube sourced from Rock West Composites. Fiberglass is less expensive, and is safer compared to Carbon Fiber, given that it is not conductive. The tower design is hollow with an inner diameter of 1.5" to provide space for the wiring of the electronics and proper integration with the transition piece (stub) and yaw mechanism. Integration of the tower with the stub and yaw mechanism requires adapting the sourced components from Rock West Composites to the custom design of both systems. The adapter plate from the stub to the tower and the tower to the yaw mechanism utilizes a connection piece provided by Rock West Composites. The adapter plate is a custom design to integrate the purchased components with the yaw mechanism, and the stub provided by the competition. Based on basic hand calculations and Finite Element Analysis (FEA) the tower assembly was deemed structurally sound for this application. The fiberglass tube provides high stiffness and high torsional stability under the maximum loading conditions of wind speeds at 22 m/s.

II.F Foundation

This year's competition places an emphasis on the foundation design of the turbine as this is a change from previous competitions. Therefore it was important to create a robust foundation design that would provide stability to the turbine above the water and align with the many competing requirements for design and installation. Early on in the foundation design process, it was deemed necessary to create a mechanism that would account for the constraints in the rules and regulations dealing with distance from the sand and tolerance between the top of the tank and the top of the foundation.

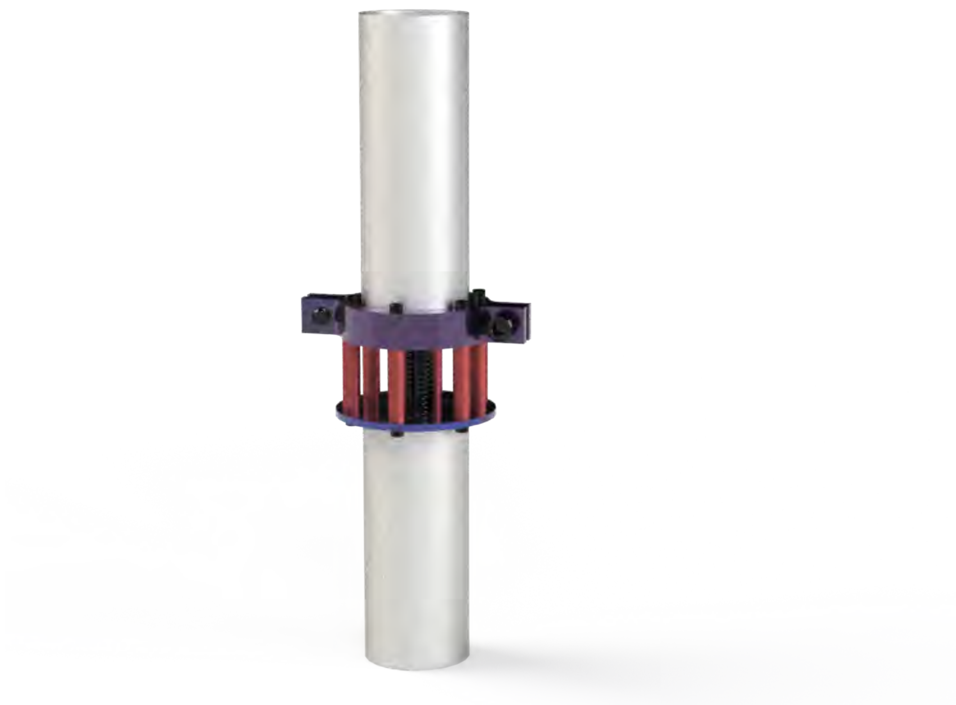


Figure 5: Height adjustment design

The height adjustment section of the foundation is designed to be easily adjustable and maintain the strength and stability of a solid tube. The design utilizes a central set screw that allows the top post to rotate in order to precisely control the height of the foundation and a clamping mechanism to allow free movement during adjustments and no movement during testing. The clamps (shown in purple) are designed to be easily tightened and loosened by ¼"-20 screws that only need to be rotated one to two times by long hex keys that can be handled above water during foundation installation. This means that finalizing the foundation height before the transition piece is installed can be done by rotating the top portion that extends above the water and tightening two screws in the water with a long hex key, simplifying the installation process. Below the height adjustment was the design for interaction in the sand, an upside-down bucket of welded sheet metal.

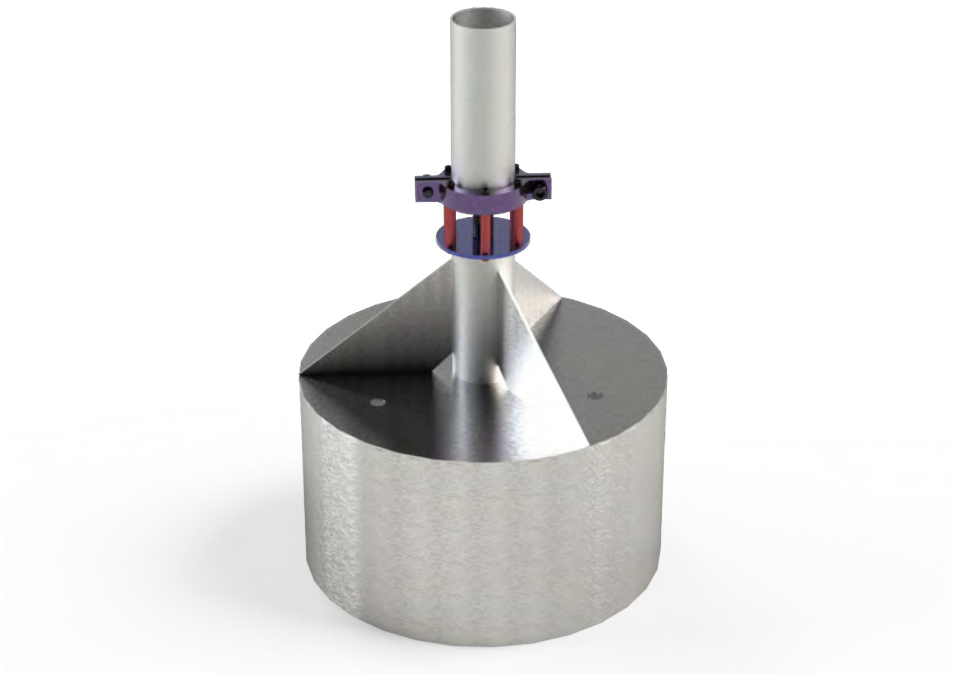


Figure 6: Foundation with bucket and height adjustment design

Early prototyping showed that a monopile and tripod design of tubing was not sturdy enough, and a bucket design with a diameter equal to the maximum allowed cross-section in the sand was much more stable. The final design uses thin steel sheet metal to form the bucket outline with gussets around the bottom post to aid in stiffness. Three bolts are held by nuts on the top flat surface of the bucket that will be loose during installation and then tightened to create a suction seal. The bucket design provides a large amount of surface area interacting with the sand to create stability under the max force from the wind.

In order to analyze the foundation design the loading on the entire turbine needed to be calculated. To calculate the maximum forces exerted on the base of the tower, a square geometry was assumed for the nacelle, blades, and tower. This will yield the highest forces due to the high drag coefficients on a flat plate. The dimensions are the absolute maximums for the blades and tower where the nacelle is a reasonable approximation of the largest area that would be required to house the generator and will likely be smaller making the total force smaller.

$$A_{nacelle} = 3*4 = 12in^2, A_{blade} = 2*9 = 18in^2 \tag{5}$$

$$A_{hub} = A_{nacelle} + 3*A_{blade} = 12 + 3*18 = 66in^2 \tag{6}$$

$$A_{tower} = 1.5*24 = 36in^2 \tag{7}$$

The forces can be broken into two components when analyzing the forces on the base of the tower.

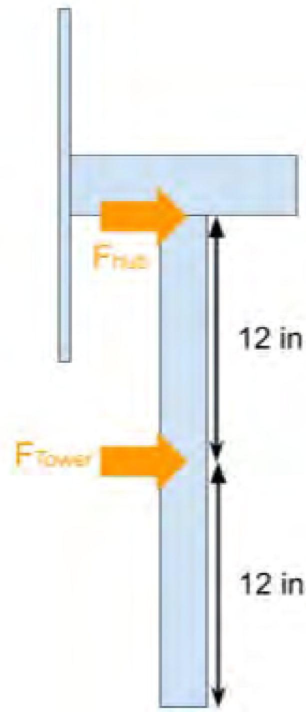


Figure 7: Diagram of forces on turbine

To calculate the force exerted on the tower base we have to convert the worst-case situation of max airspeed pressure to the force

$$P = 0.00256 * 50^2 \approx 6.4psf = 6.4/144lb/in^2 \tag{8}$$

From the pressure, we can calculate the forces by multiplying the pressure by area.

$$F_{hub} = PA_{hub} = 6.4 * 66/144 = 2.93lbf \tag{9}$$

$$F_{tower} = P * A_{tower} = 1.6lbf \tag{10}$$

The reacting force from the base of the tower is the total force

$$F_{base} = F_{hub} + F_{tower} = 4.53lbf \tag{11}$$

The moment can be calculated using the distances from the base for the two forces

$$M_{base} = 1.6 * 12 + 2.93 * 24 = 89.52lbin \tag{12}$$

One of the main considerations for the foundation design was to minimize the movement of the bucket when a force from the wind was applied during testing in the wind tunnel. Not only would large movement in the sand be catastrophic for the turbine, but there is a regulation that the turbine cannot exceed 6 mm in movement measured at the top of the CWC transition piece. An analysis of the foundation was performed in ANSYS to give a preliminary idea of what deflection would be expected from a worst-case scenario force from the wind of 4.53 lbs. The CAD model of the foundation was defeatured to simplify analysis and was put into an ANSYS static structural analysis with a force applied to the top of the foundation where the deflection would be measured during competition. Each component was fixed to its mating part as the main goal of this analysis was to see the max material deflection, and an assumption was made that parts connected by bolts or fasteners would be per-loaded and torqued sufficiently to allow minimal movement. This assumption allowed for a simpler analysis and cut down on run time significantly.

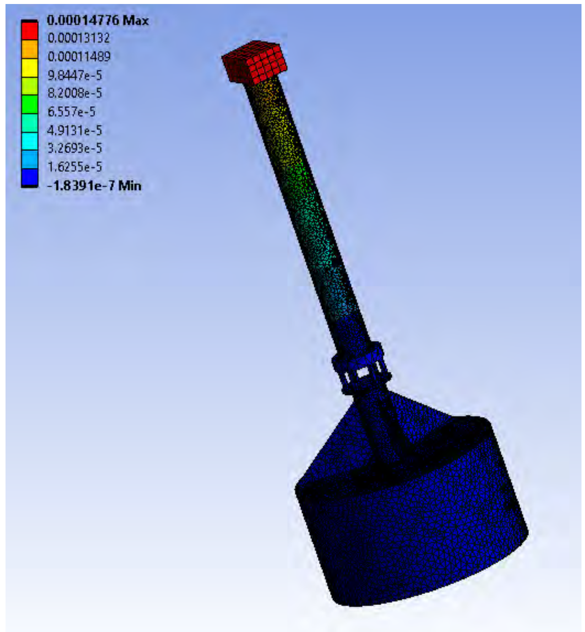


Figure 8: Max deflection of foundation

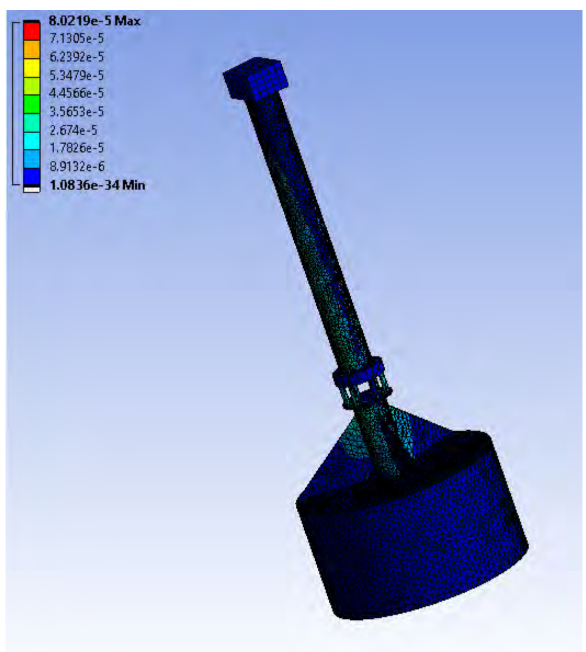


Figure 9: Von Mises strain in foundation

The results of the analysis showed that the total material deflection at the top of the transition was 0.1 mm. This is obviously below what was required, but the takeaway from this analysis must be altered due to some limitations of the analysis. The first is that this was a purely structural analysis, and therefore the interaction of the foundation and sand was unable to be portrayed. This was a decision that had to be made after extensive research showed a geological analysis of this type would not fit in the timeline and experience of the team. This means that the result of a 0.1 mm deflection is purely due to the material deflection in the metal of the foundation. This analysis can only go as far as to say that the structural element of the foundation design is strong enough to not deflect under the load of the wind. The analysis cannot prove how far the structure will move when installed in the sand and water tank. In the future, a further analysis in a geotechnical software program would be used to see if a combination of the material deflection and movement in the sand is larger than the allowed deflection in the regulations. Analysis of the Von Mises strain in the foundation shows where the concerning points on the foundation are located. Looking at Fig.9 above it can be seen that the tops of the gussets and the standoffs in the height adjustment are experiencing the highest strain relative to the rest of the foundation. This analysis resulted in placing higher torque on the fasteners connecting the standoffs to the other components of the height adjustment (shown in Fig.9 above) to achieve better pre-load on the standoffs. Spreading internal stresses from the fasteners throughout the subassembly by increasing pre-load torques and distributing loading into the entire structure.

II.G Past Iterations and Contributions

The University of Colorado at Boulder has only had one previous wind energy learn-along team. That team was able to create an onshore turbine based on the 2021 competition rules. From this model of the turbine, the 2022 team was able to identify many key components that could be made more efficiently or lighter in order to create a turbine that could be held up by an offshore foundation more easily. The first was the size of the nacelle, then the weight of the tower, and finally the blades. These changes were enacted because the nacelle was not efficient in the use of its space and each of the components it held such as the motor, pitching mechanism, and nacelle block itself were much larger than this year's team believed they needed to be. The team purchased an RC helicopter pitching mechanism and integrated it into our pitching design. This solution has been used in the past by multiple teams and is much smaller and lower mass than the previous machined one. The motor for this year was chosen to be one that met the team's electrical requirements and was also noticeably smaller. These changes allowed the team to choose a nacelle block that is 3" x 3.5" x .25" and weighs less than a quarter of the original nacelle block.

The next issue was the weight of the tower. This aluminum pole that was used by last year's team was identified as an easy location to cut weight and was replaced with a fiberglass tower which showed to be equally structurally sound. The next component was the flange bearing that was used for the yaw mechanism, which weighed over 5 lbs. This was replaced with a turntable bearing that weighs less than 1 lb. Overall, the weight of the tower was reduced significantly without reducing the structural integrity.

Finally, the blades were iterated on because the previous team had flat blades with a very high cut-in speed. This year's team wanted to lower the cut in the speed and make changes to the wind speed optimization since 2021 had different wind speed requirements. That helped this team create a durable blade using the NACA 4412 airfoil with twist and chord length that has been optimized for 7 m/s.

These changes have allowed the 2022 offshore turbine to be about 1/3 of the weight of the previous year in total and have mechanisms that are more efficient.

III Testing of Components

III.A Pitching/Controls

In order to gain a better understanding of the impact pitching can have on the power production of the turbine, 3 different angles of attack were tested in a wind tunnel. The first angle was the point at which the pitching mechanism is closest to the bearing. According to the graph in Fig.10, this location is defined as the minimum pitch angle. This is the point with a minimum cut-in speed and a consistently lower RPM value compared to the maximum (i.e. the angle associated with the pitching mechanism located closest to the blades). This fact contributed to the pitching sequence as the minimum pitch angle was subsequently defined as the starting position of the mechanism. This allows for a startup at lower wind speeds. Furthermore, given that the maximum RPM is smaller compared to the speeds achieved at the maximum pitch angle, the minimum angle will be used as the E-stop position to slow the blades. The maximum pitch angle is used to ramp up the RPM once a startup has occurred. As mentioned previously, the normal operation of the turbine will occur at an optimal pitch angle that will be defined with testing ahead of the competition.

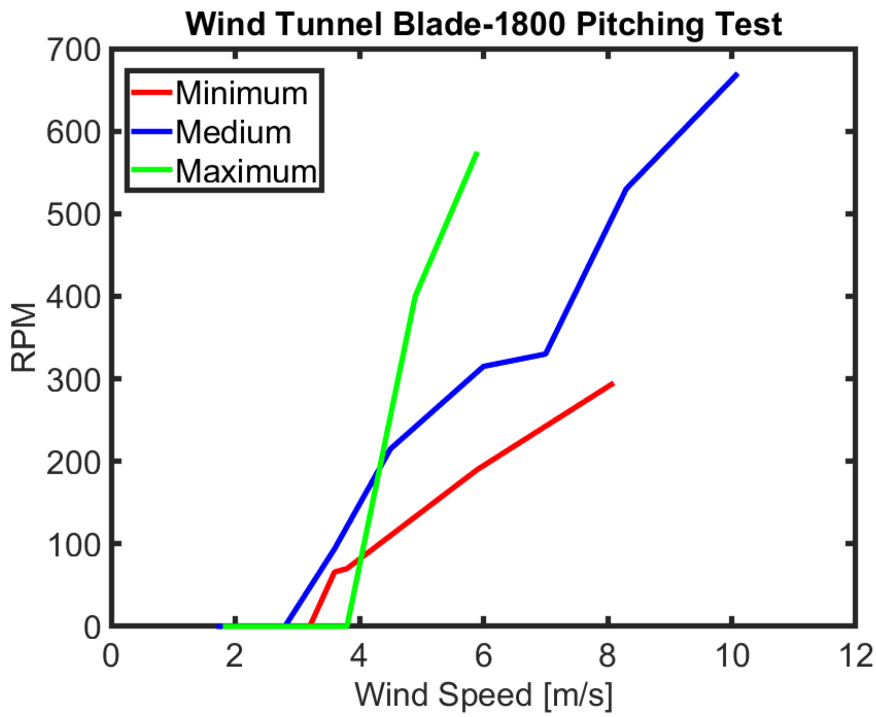


Figure 10: Pitching Test

III.B Electronics

The testing of the electrical system was divided into two steps. The first set of testing was used to determine if the circuit had the basic functionality intended by the design. This testing was performed on our first draft PCB. The goal of this first round of testing was to discover errors in the PCB design. The next part of testing focuses on validating numerical benchmarks needed by the competition. The next version of the PCB was designed using what was learned from the testing described below.

III.C SEPIC

To test the SEPIC, a constant voltage ranging from 2-15 volts was applied to the output of the rectifier to simulate the normal turbine function within the designed operating RPMs. The reason a range of voltages was tested was to see if the SEPIC maintained a 5-volt output at varying input voltages from the generator. Varying input voltages are analogous to varying wind speeds and thus varying RPM of the turbine shaft. A multimeter was connected to the output of the SEPIC to monitor the output voltage from this circuit.

III.D Emergency Stop

To test the emergency stop system, the PCB was first connected to the turbine. The turbine was then spun with a fan. A switch was connected in the place of a button to simulate pressing the button to initiate an emergency stop. As seen in Fig.11, the turbine was operating normally between 650-700 RPMs for about 30 seconds. At the 30-second mark, the switch was turned on and the turbine shaft slowed down substantially. The results were well within the requirements of the rules and regulations. As the regulations state for the safety test, the turbine must be capable of a shutdown that limits the rotations per minute to 10% of the average rotations per minute within a 10-second period and remains below that limit for an unknown amount of time. The emergency stop was successful by showing that starting at an average of 675 RPM it was able to drop to 38 RPM, within 3.38 seconds. This reduction in rotations per minute was able to remain that way indefinitely and stayed at 2.54 RPM for the remainder of the one-minute test. Once the test was incurred the turbine was able to successfully restart operations. This test showed that the emergency stop exceeded the expectation to reduce the rotations per minute to 10% of the previous average within 10 seconds. We were unable to test the emergency stop during the load-disconnect scenario because this relies on data from the current sensor (which was connected incorrectly). However, this scenario is very similar to the other in that it is activated through software.

Thus, we can be confident that once the current sensor is functioning properly, the emergency stop will work during the load-disconnect.

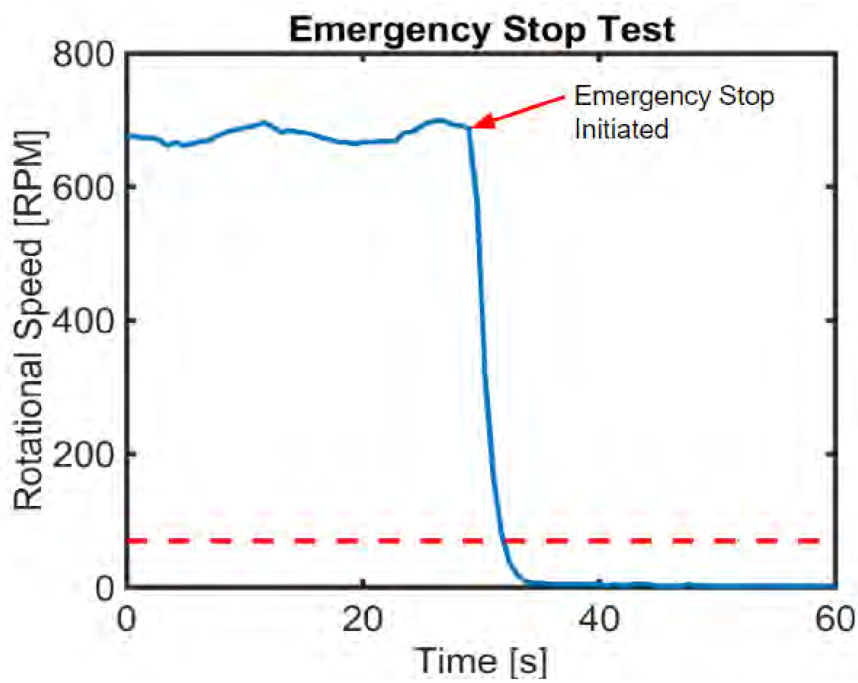


Figure 11: RPM's as a function of time during the emergency stop sequence. The sequence was initiated at 30 seconds and dropped well below the necessary requirement in the necessary amount of time outlined in the rules and regulations.

III.E Mode Switch

This initial mode switch design incorporated a single N-channel MOSFET that, when powered, would allow current to flow from the output of the rectifier to the load. Due to a lack of understanding of MOSFETs during the design phase, this mode switching idea did not work. Instead, a new design incorporating a relay and two MOSFETs was implemented in our second version of the controls board (Fig.3). To test this idea, a simple breadboard circuit was created. Using a power supply, a set voltage was applied on one side of the relay. When the MOSFET was powered by a signal from the microcontroller, the current was allowed to flow through the coils of the relay thus closing it and creating a short circuit between the rectifier output and the load. This circuit worked as intended.

The new mode switch design is still in testing, but the initial results are very promising. As mentioned above in section 2.3, the mode switch will occur at a threshold voltage where the turbine will be able to power the controls PCB by itself and sink the excess power to the load. The optimal voltage where the mode switches from startup to normal operation is still being tested, but we have been able to move from startup mode to normal operation and continue operating each PCB individually. The next steps in testing the mode switch include integrating the sinking of the excess power through the PCC into the load power resistors.

III.F Load

It is very important to verify that the mode switching is working properly for the movement from the startup mode to the normal operation mode and vice versa. Therefore, the functionality of the mode switching is tested by monitoring the terminal that goes to the PCC (and the controls) from the load. At startup, the voltage across this terminal is measured and it comes out to be 5V (as expected) (Fig.12). At the normal operation when the mode switch relay is triggered, if the load is not connected to the controls, it is expected for the power to be zero (because there is no sinking of power from the controls) across the terminal and this is seen in Fig.13 . Finally, the resistance across the terminal is measured with a multimeter, and as the power resistors combination are changed, the resistance changes correspondingly (This is to test the functionality of the variable resistance of the load).

III.G Foundation

Per CWC guidelines, the foundation has a limited radius of deflection of 6 mm (measured from the transition piece). Therefore, testing was necessary to ensure the stability of the structure. The foundation deflection was initially tested by driving the structure into a bucket of sand (both with and without water) using a mallet. The transition piece and turbine were then assembled on top. Using Eqn.11, the force on the turbine was approximately 5 lbs. Therefore, the deflection at the transition piece was measured under applied forces of 2.5 lbs, 5 lbs & 7.5 lbs as well as after the load was removed. At 5 lbs, the maximum deflection was 26 mm. However, after the force was removed, the turbine rebounded to 1.5 mm. This rebound value is of major importance as this is measured and recorded at the competition. As 6 mm was the maximum value, 1.5 mm is an acceptable result. Finally, it was necessary to test if the height adjustment was within regulation. After a redesign process of increasing the length of the top post of the foundation (shown in Fig.6), 8 cm of space is now available for the attachment of the transition piece.

IV Assembly and Commissioning

IV.A Assembly Instructions

The turbine subassembly and installation will be completed outside of the wind tunnel testing room. To start, the tower is permanently assembled, so those components will be kept together. Next, the team will attach the turntable bearing that acts as our yaw mechanism using 4 fasteners. Afterward, the nacelle will be attached to the bearing where all of the nacelle components will be added: the 3-phase generator, coupling, servo, and linkages. At this point in time, the wires will be brought together by a zip tie and funnel down through the turntable bearing and the tower in order to have them prepared for the attachment to the foundation. Separately, the pitching mechanism which has been attached to the rotor shaft will be attached to the blades using 1 Loctite screw each. Next, the rotor shaft will be attached through the bearing and into the coupling on the motor. The foundation will be placed into the offshore simulation tank and pushed level. The competition-provided transition piece will be tightened onto the foundation and the tower will be attached to the competition-provided transition piece. These subassemblies were each created or purchased by subteams of 2-4 people. These subteams have been working together throughout the year to focus on each subassembly in order to make sure that it is a thoughtful design that would meet competition standards, work efficiently and identify and meet the goals of each subassembly. The people assigned to each subassembly were able to focus their technical knowledge without being distracted by other subassemblies of the turbine. The pieces were created to integrate with each other by being given an outline for how they must be attached early on. This system worked well to develop each individual part of the turbine.

IV.B Electronics

There is two parts of the electronics that need to be assembled during the installation of the turbine in the wind tunnel. First, outside of the tunnel, the generator and servo wires will be fed through the tower and into the transition piece to connect with the controls PCB outside of the tunnel. Once the turbine is moved into the wind tunnel, the wires will be fed through the PCB enclosure and into the PCB sitting next to the tunnel. The controls PCB will then be connected to the PCC through the Anderson Powerpole connectors as well as to the load through optically isolated cabling. Once all PCBs are connected, the load PCB will be plugged into the wall to begin startup operation for competition.

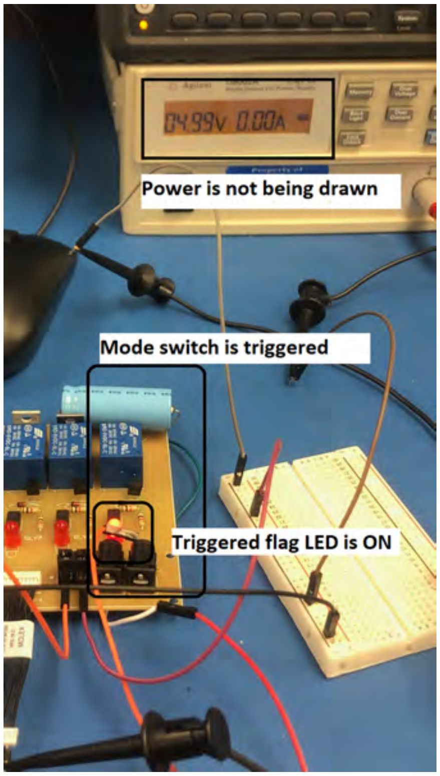
IV.C Foundation

The foundation will be installed in the offshore simulation tank, without anybody part touching the water per the rules and regulations. Initially, the foundation will be outfitted with the team's manufactured transition piece. The purpose of the transition piece is to be able to push the foundation down without touching the water. The whole structure will be placed into the water and sand by hand until it can no longer be safely pushed downward without damaging components. At this point, the team will use a mallet and a wooden dowel to drive the foundation down until the top of the foundation is flush with the sand. Throughout this process, screws that cover holes on the top lid of the bucket will be loosened to allow air within the bucket to escape. These screws will then be tightened to achieve a suction effect once the foundation is fully in place.

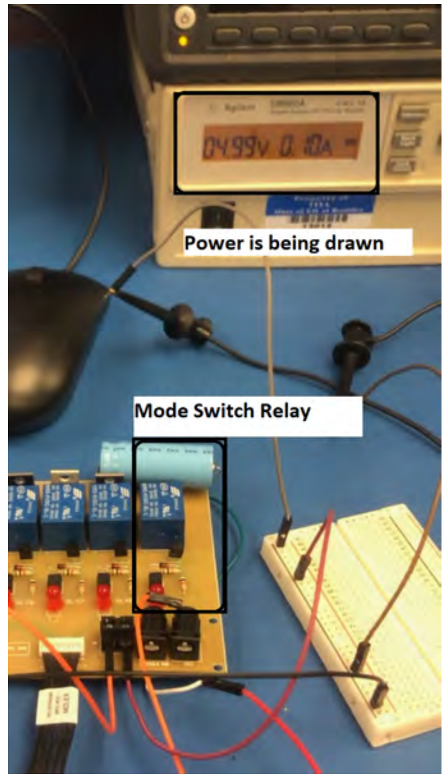
IV.D Assembly and Commissioning Checklist in the Wind Tunnel

Complete?	Item
	Mount foundation installation clamp onto height adjustment using clamping mechanism
	Loosen all three foundation suction screws using a socket head
	Grip foundation installation clamp with two hands
	Push foundation into offshore simulation tank
	Circle the transition piece while simultaneously pushing down to stabilize the attached foundation
	Make sure foundation is level using bubble level mounted on the foundation installation clamp
	IF NECESSARY adjust height using the clamping mechanism and rotating the foundation installation clamp
	Tighten foundation screws using a socket head
	Remove foundation installation clamp by loosening clamping mechanism
	Attach competition stub using clamping mechanism
	Place pre-assembled turbine through wind tunnel turbine door onto stub assembly while simultaneously feeding wires through stub assembly as it is lowered
	Tighten stub assembly wing nuts to secure turbine
	Use T-bracket to align yaw mechanism in the direction of wind and tighten set screw
	Attach wires and connectors to electronics that will be placed on the table next to the wind tunnel

V Appendix



(a) Test 1



(b) Test 2

Figure 12: Load testing

(a) Assembled

(b) Exploded

Figure 13: Full Turbine

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