WiscWind

U.S. Department of Energy
2022 Collegiate Wind Competition
Technical Design Report

University of Wisconsin-Madison

Electrical Sub-team: Michael Schmich *(EE Team Lead)* Ian Bormett Austin Christianson Zach Berglund Zach Zimmerman Sarah Gerovac Zach Hennen Natalie Skiest	**Mechanical Sub-team:** Elijah Asher *(ME Team Lead)* Matthew Chomniak Anthony Palmer Nicolas Moore-Barbosa Josh Delgado Joe Murphy	**Principal Investigator** Scott Williams **Faculty/Staff Advisors:** Randy Jackson Kyle Hanson **Overall Team Lead** Justin Casleton **Contact** spwilliams@wisc.edu

Table of Contents

Executive Summary

WiscWind is an interdisciplinary engineering student organization competing in the U.S. Department of Energy 2022 Collegiate Wind Competition (CWC), giving students real-world experience in the growing renewable energy industry. The mechanical and electrical sub-teams are tasked with designing and fabricating a wind-driven power system that maximizes power generation and can accomplish specific tasks as detailed in the competition rules.

The mechanical sub-team completed research on last year's design to improve results from the 2021 competition. The major tasks this year have mainly focused on the implementation of a more reliable active pitch control system and development of a substructure for the new competition regulations, while secondary focuses were on improvements to the blade and braking system designs. These factors have been worked on to improve the reliability and mechanical efficiency of the turbine. This will allow a greater speed of the shaft for a given wind speed, which creates a greater power output, as well as better control over the speed of the shaft throughout any wind speed range to help maintain a good power output. With greater control over the power output of the turbine, the team will improve upon the power curve of last year's design while also excelling in the durability and braking tasks.

The electrical sub-team focused on converting the mechanical energy captured by the wind into electrical energy. This year the team decided to further improve the generator that was used in 2021. Emphasis on testing and possible improvements allowed the team to focus more attention on the power electronic circuits to control high efficiency three-phase AC-to-DC conversion, emergency load disconnection, and emergency braking using an Arduino Uno microcontroller and a combination of hand-built and off-the-shelf circuitry. The fall semester was dedicated to verifying the generator as well as coordinating with the mechanical team regarding the active pitch control. The spring semester was dedicated to the creation of new braking and voltage regulation systems to meet the requirements of the competition. These systems were designed and verified piece by piece in a distributed team environment.

Our mechanical and electrical designs have been an iterative process. All parts had been purchased, machined, and assembled by members of the team. Most components have been tested individually both in the wind tunnel and on a dynamometer. The prototype of our turbine was run through all three competition tasks prior to the writing of this report, though the team has been unable to do a full test with substructure as the university wind tunnel is unable to accommodate the substructure. The tests that the team had been able to complete had promising results that lead us to believe that we will bring a very competitive turbine prototype to the 2022 wind tunnel test.

Introduction

WiscWind's development and design for the 2022 Collegiate Wind Competition's prototype turbine focused on optimizing performance, substructure integration, and maximizing power output over all wind speeds. Converting mechanical wind energy into electrical energy is accomplished with a custom-made three-phase axial flux generator. Power electronics control AC-to-DC conversion, power regulation, and emergency braking. Iterative testing validated our design choices to meet the needs of the competition. The team's substructure has been thoughtfully manufactured and has passed stability tests in sand and water. WiscWind has combined all of these components into a cohesive offshore clean energy mechanism that is ready to compete.

Mechanical

Mechanical Design Objectives

Design objectives for this year's competition focused on implementation of an active pitch control, generator optimization, developing a braking system, blade design, creating the substructure, and programming all the components to work together to complete competition tasks. The active pitch control will pitch the blades based on feedback from a rotary encoder that measures the rotational speed of the shaft. Two linear actuators are used to control the turbine's speed, one for pitching, and one for braking. During power curve testing, the pitching actuator actively adjusts the angle of the blades to a position that yields optimal rotational speed. During the safety test, the pitching actuator fully retracts the blades out of the wind, then the braking actuator drives a felt pad against the spinning shaft to further slow down the shaft. Both actuators and shaft speed are controlled and monitored by an Arduino. The substructure was manufactured by water-jet-cutting thin steel plates and then welding them together. Nacelle and yaw control were not considered to have as large of an impact on the overall performance of the wind turbine, therefore, more time and resources were put into the more crucial sub-assemblies. Moreover, the wind turbine has the ability to lock its rotation during competition assembly, so after the substructure is connected to the main turbine the turbine will be oriented into the wind then locked in place before competition testing. The final assembly of the prototype wind turbine can be seen in Figure 1 below. The final mechanical CAD drawing can be found in Figure A1 in Appendix A.

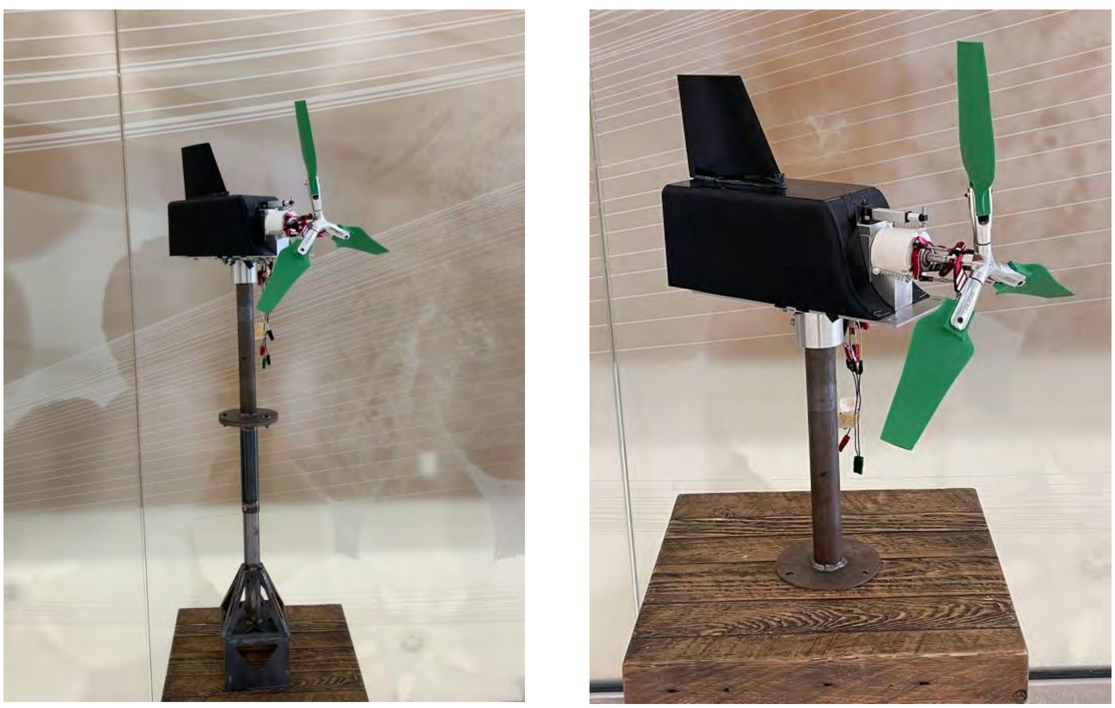

Figure 1. (L) Turbine prototype with substructure; (R) Prototype turbine assembly.

Turbine Blades

Research Concepts

The main goal of the turbine blade design is to choose an airfoil that can efficiently harvest energy from the wind. The blades allow the energy harvested from the wind to spin the generator shaft and create power in the generator. During the design process, it is important to find a balance between the aerodynamic properties and the structural integrity of the blade [1]. Blade geometry heavily influences the aerodynamic properties of the blade and is controlled by the airfoil, blade thickness, and angle of twist. The most important aspect of structural integrity is the connection between the blade and the pitch control.

During airfoil selection, the team researched multiple different airfoils, as well as previous airfoils used in previous competitions. The team ultimately made the decision to stick with last year's airfoil, the Wortmann FX 63-137, which can be seen below in Figure 2. This airfoil offered promising results under testing environments and was the strongest contender for this year's blade design.

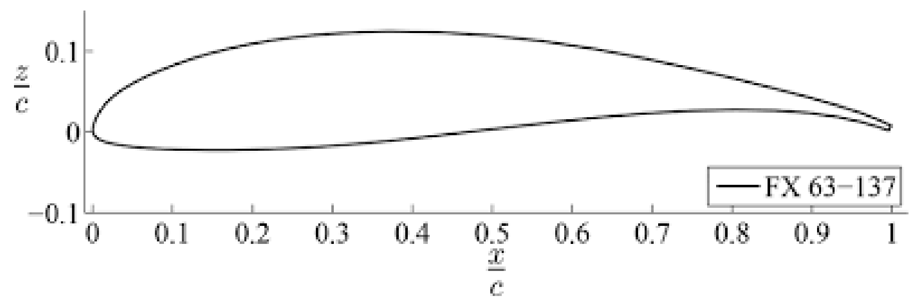

Figure 2: Wortmann FX 63-137 airfoil [2].

Efficient airfoils offer a high coefficient of lift to coefficient of drag ratio at optimal angles of attack. The lift forces on the blades increase the rotational speed of the blades and the shaft, however, the drag forces have an opposite effect and will slow down the blades. Increasing this ratio helps increase the rotational speed that the blades spin at. The Wortmann FX 63-137 airfoil is known for its strong coefficient of lift to coefficient of drag ratio, and the equations for each can be seen below in Equation 1 and Equation 2.

$$C_L = \frac{F_L}{\frac{1}{2}\rho V^2 A} \quad (1)$$

$$C_D = \frac{F_D}{\frac{1}{2}\rho V^2 A} \quad (2)$$

In the above equations, C_L and C_D are the coefficients of lift and drag, respectively. F_L and F_D are variables for lift force and drag force, ρ states the air density, V is the air velocity, and A is the surface area on the blade that the wind is hitting. With the Wortmann FX 63-137 airfoil, the coefficient of lift to coefficient of drag ratio peaks at a 7 to 8 degree angle of attack with a value of about 32. This shows an efficient airfoil when operating at optimal angles of attack that will spin the blades much more than they will slow them down.

The integrity of the blade structure must be able to withstand wind speeds up to 22 m/s without failure. The blades must have a sufficiently large cross section as well as a strong material to withstand the force from the wind. The wind force can be estimated with Equation 3 below.

$$F_w = \frac{1}{2}\rho v^2 A \quad (3)$$

Here F_W is the wind force, ρ is the air density, v is the wind speed, and A is the surface area of the blade in contact with the wind. The air density and maximum value of wind speed are known, and with an estimate of the blade area, the range of the wind force that the blade can experience can be determined to be between 2-6 N, depending on the surface area in contact with the wind. To withstand these forces, the blade material is essential in preventing failure. For testing, the blades will be 3D printed with PLA from an Ultimaker printer. The PLA is strong enough to withstand the wind forces while also remaining cost effective for printing multiple blade iterations.

Blade Design

The initial blade design was built off the blade model used by last year's team. The twist distributions and chord lengths stayed the same as last year, however, the overall length of the blade needed to be decreased to account for a larger pitch control. The biggest change came in the form of the connection between the blade and the pitch control. The connection was previously the biggest point of failure during testing and needed to be updated to prevent failure this year. The new pitch control and its mounts offered a strong solution that allowed the blades to be clamped into place, rather than pinned in.

The blades were designed with SolidWorks, using the airfoil on rising planes and connected with the loft feature. The connection was then added to the base of the blade using dimensions taken from the pitch control mount. The difference in blades can be seen below in Figure 3.

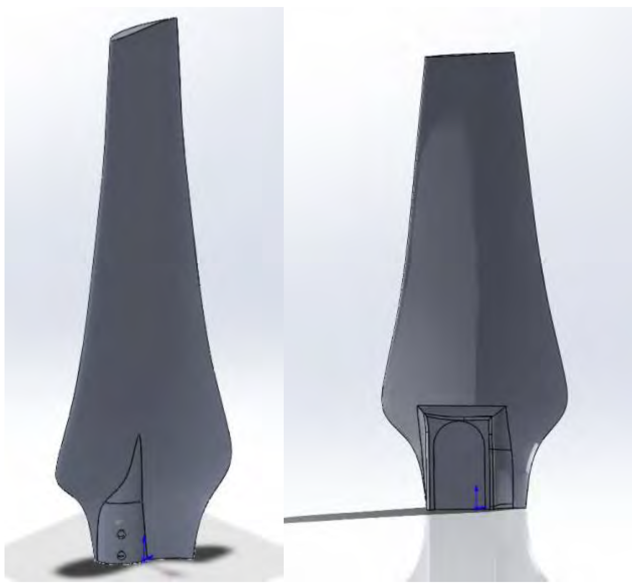

Figure 3: Previous blade design (L) and current blade design (R).

Blade Manufacturing

The initial manufacturing of the blades had some failure due to printing the blades upright. As the height of the blades increased during printing, any vibrations from the printer would cause the blades to fall over and the print would fail. To combat this problem, the blades were printed on their side, however, the support material from the printer would leave a rough surface on the blades which made them unusable. In order to have a successful print, the printing settings were modified and a set of successful blades were printed with a quality surface finish. With a set of successful blades, wind tunnel testing could be started. The 3D printed blade model with its respective pitch control mount can be seen below in Figure 4.

Figure 4: 3D printed blade model connected to pitch control

Pitch Control

Design Concept

The pitch angle of the blades plays a pivotal role in manipulating aerodynamic behavior of airfoils and power generation. One of the main competition objectives is to maintain a consistent power curve, so the design must accomplish this at different wind speeds and not exceed the maximum voltage of 48V. From research into past designs using active and passive pitch control, active pitch control systems were found to be more effective at maintaining a consistent power curve, so the team decided to implement an active pitch control system. For the active pitch control system, it was decided that a single motion should pitch all of the blades as opposed to pitching every blade separately because of the lack of space at the nose of the turbine. The idea of an active pitch control system was initiated in last year's WiscWind design in the form of a rack and pinion system, but the design suffered numerous failures when it was tested at the beginning of the fall semester.

Last year's design from WiscWind was based on the movement of a linear actuator, which was connected to a triangular pinion that actuated the three blades by rotating gears mounted to the root of the turbine blades, shown in Figure 5. The main issue this design encountered was the gears slipping from the toothed flats, preventing the rotation of the blades. On top of that, the design of the actuation system kept a mount from holding the shaft close to the head of the turbine. The large distance from the head of the turbine to the front shaft mount led to significant vibrations. Finally, as the components of the pitch control system were all made from 3D printed PLA, the parts had poor tolerances and were subject to wear. Due to the problems with the old design, new pitch control design concepts were formulated.

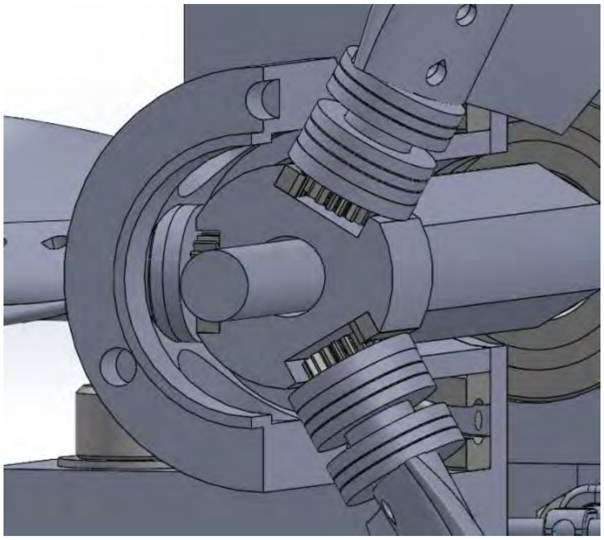

Figure 5 (L): Gears mounted to the root of the blades that rotate upon linear movement of the triangular pinion. **Figure 6 (R):** L12-P Micro Linear Actuator with Position Feedback (50 mm stroke length used for pitch control).

The new system investigated was a linkage system. There were concerns about the reliability of a linkage system built by the team, so the team searched for ways to outsource the pitch control system. RC helicopter rotors were found to work very similarly to the original rack and pinion concept. The RC helicopter rotor chosen for purchase used the same linear motion along the shaft to pitch the blades but used a linkage system as opposed to a rack and pinion design. With the pitch control system manufactured and designed professionally, the team thought this would fix the problems with reliability. The purchased RC helicopter rotor is shown in Figure 7.

Figure 7: RC helicopter rotor repurposed for turbine pitch control.

Pitch Control Implementation

With a new pitch control system, new parts needed to be designed to implement it. The one downside to the RC rotor was that it had too many degrees of freedom. Therefore, highest priority was given to designing a system to limit the pitch control to a single direction of motion: along the shaft. Many different designs were created, but each had their own shortcomings. Eventually, a design consisting of a bearing mount and a cylindrical slider was devised to limit the directional motion of the turbine while allowing for the motion along the shaft. The initial designs for those two components are shown in Figures 8 and 9.

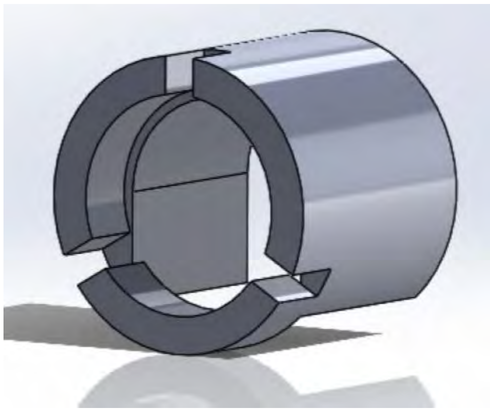

Figure 8: Initial design for pitch control slider.

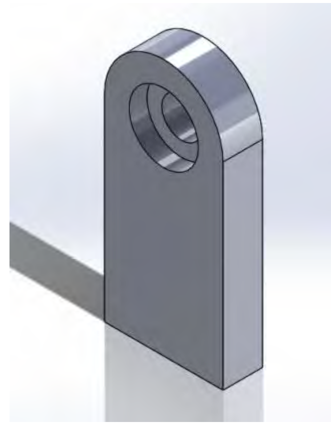

Figure 9: Initial design for bearing mount.

The grooves in the slider piece in Figure 8 are sized to provide a press fit on the joints at the base of the helicopter rotor. A cylindrical groove was cut into the slider to fit around the top of the bearing mount. When the slider is mated with the mount, the base of the rotor can no longer rotate or twist, limiting the base of the helicopter rotor to only move along the shaft and keeping the pitch of the blade connector uniform. With the pitch action fixed to motion along the shaft, the source of movement needed to be provided. To provide the movement, a linear actuator was purchased and is shown in Figure 6. As the linear actuator needs to mate to the helicopter rotor while also remaining fixed, a bearing mount was developed with a space on top for the linear actuator. The mounting piece is shown in Figure 10. With these systems fabricated, testing of the pitch control could be performed.

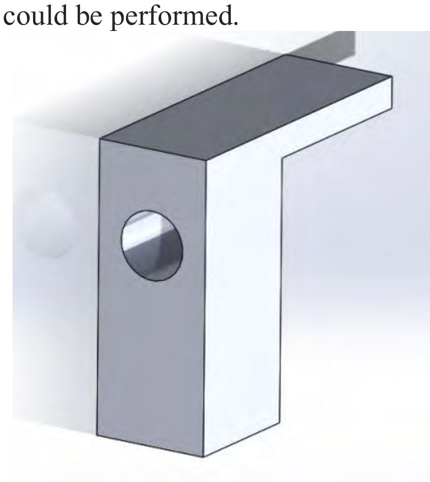

Figure 10: CAD model of mounting piece for bearings and linear actuator.

The initial design for the pitch control system was tested, and some problems with the design were discovered. The slider would come apart from the base of the helicopter rotor, the slider would rub up against a bearing, and the slider would turn down when pushed by the linear actuator. The design was iterated to fix these issues until a final design was reached. The final design for the slider and mount are shown in the final pitch control design in Figure 11.

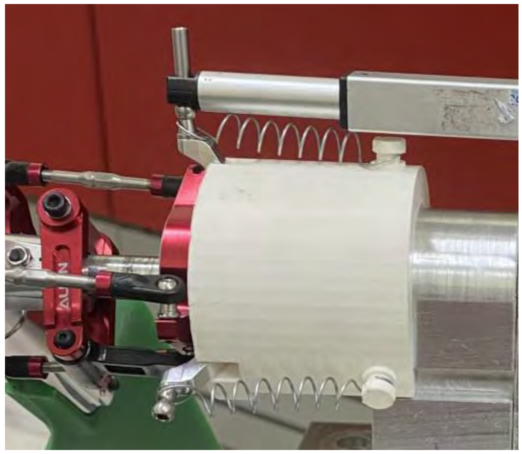

Figure 11: Final pitch control design containing the Helicopter rotor, slider, mount, and linear actuator.

Control System

With the pitch actuation designed, focus was shifted to tuning a control system to provide a pitch angle that maximizes the power output of the generator. To provide a shaft speed input to the system, a rotary encoder was used with a slotted wheel mounted to the driveshaft. The rotary encoder sends a duty signal to an Arduino, and the Arduino reads the RPM measurement. The Arduino sends a PWM signal to the linear actuator control boards, setting a displacement value for each linear actuator. The linear actuator then moves to the displacement value. The components of the control system are shown in Figures 12 through 15.

Figure 12: PQ12-P Linear Actuator with Feedback

Figure 13: LAC Board (Used for Braking)

Figure 14: WYC-H206 Encoder

Figure 15: Encoder Wheel

Substructure

WiscWind's substructure design was implemented to be water-jet-cut from steel plates, then welded together into a pyramid/truss structure. Due to weight being a graded criterion, the inside of the substructure was left hollow so sand and water could fill in the gaps and help keep the substructure stationary during turbine operation. Figures 16 and 17 below show the original CAD model and the fully assembled substructure.


Figure 16 (L): CAD model of the substructure
Figure 17 (R): Fully assembled substructure semi-submerged in testing vessel

The portion of the substructure that is submerged in sand focuses on preventing movement downwind of the turbine. The front and back plates protrude into the sand at an angle that collects more sand and water on top of it as the substructure gets pushed deeper. FEA analysis was performed on the substructure components to ensure that the selected materials and thickness can withstand the stresses that the substructure will be subjected to during competition. The results of the FEA studies are shown in Figure 18. From the analysis, the single truss was developed with a mass of 288g (0.63 lbs); while also having a safety factor of over 100. This truss design was implemented into the substructure assembly shown in Figure 16. The substructure could not be tested in the UW-Madison wind tunnel, therefore, the team applied force manually to the top of the structure to test its structural integrity. There are some factors like vibrations that could not be accurately simulated, so the design was created so the submerged portions would aid in dampening the vibrations caused by the wind turbine. The final result is a sturdy, yet lightweight design that is ready for competition testing.

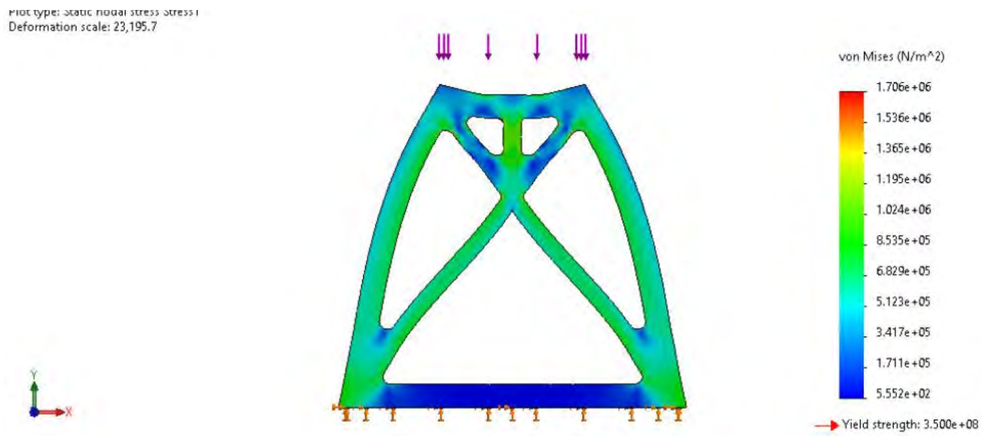

Figure 18. FEA analysis results of a single truss of the substructure

Turbine Braking

The braking system was originally going to rely on electrical braking from the generator, however, the new stator design this year did not provide adequate stopping power through electrical braking. The solution WiscWind came up with was to build a mechanical braking system around existing constraints from the internals of the turbine. In order to take up the least amount of space and still provide effective stopping power during the competition, a small linear actuator with a brake pad on the tip was mounted near the shaft. Figures 19 and 20 show the brake mount and the brake mount alongside the other internal components. A polishing tip from a Dremel kit was selected because it wouldn't wear down the shaft during braking.

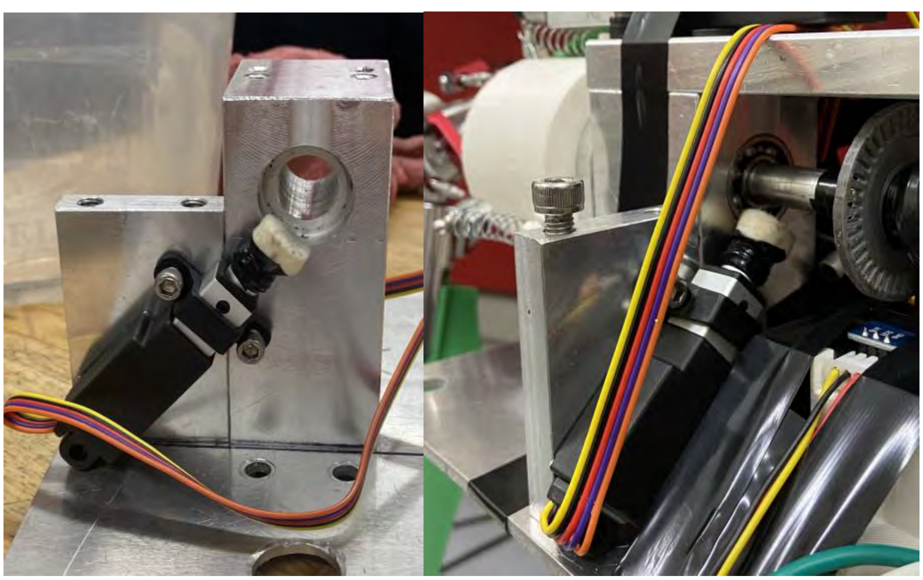

Figure 19 (L): Close up of mechanical braking system
Figure 20 (R): Mechanical braking system with all internal components assembled

Additionally, the braking actuator was mounted close to the bearing mount to minimize bending stresses to the shaft during operation. The brake was tested in the wind tunnel and was able to slow down the turbine's rotation by an additional 100 RPM. The current material does not provide a lot of friction, so more materials that provide high friction but low wear are being explored for competition use.

Electromechanical

Electromechanical Design Objectives

The generator was designed with ease of manufacturing, assembling, and maintenance in mind, while also attempting to keep friction extremely low and allowing it to be contained in one concise package for use on different turbine chassis in the future. Electrically, the generator was designed to have minimal cogging torque, create enough voltage at low speeds to remove the need for a gearbox, have large enough gauge wires to ensure high power output, and create balanced three-phase power. An axial flux generator allows a direct connection to the drive shaft, using two magnetic rotors and a stator containing the coils of the generator. The rotors spin on either side of the stator, which induces a magnetic flux through the coils–from the switching poles of the magnets around the stator radius. This drives current through the coils and produces a power output for the generator.

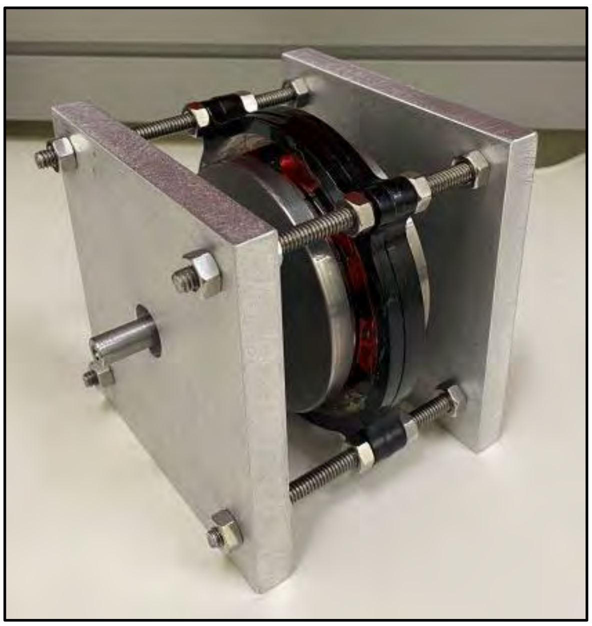

Figure 21. Fully assembled Generator

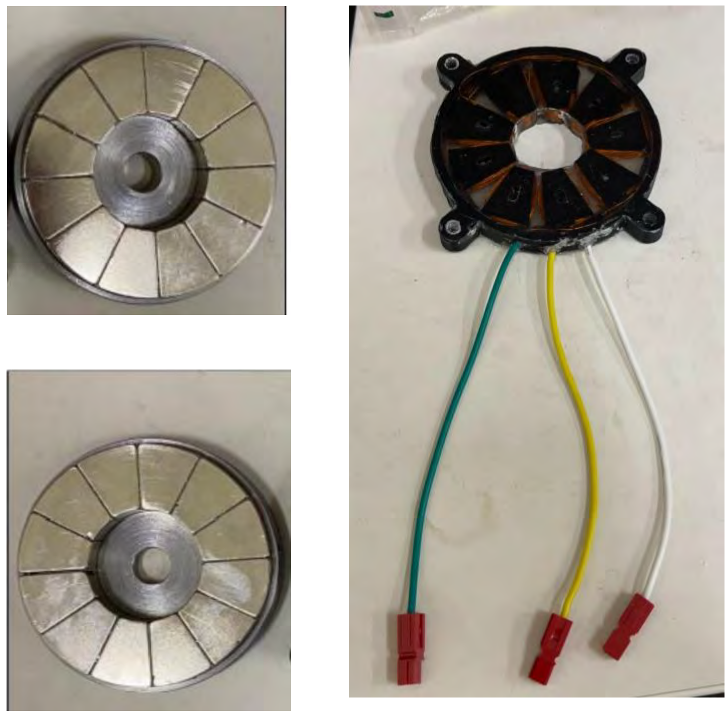

Figure 22. Generator Rotors (L) and stator (R)

Generator Improvements

This competition year, new stators were constructed in hopes to increase the turbine's power output. The new stators were constructed using the Wisconsin Electronic Machines and Power Electronics Consortium equipment that is located at our university. The stator coils were wound around 3D printed spools with a wire winding machine to around 90 turns–which was half of the previous year's stator. The wire used was the same gauge as the previous year's design – yielding a stator that is much thinner than the one used previously. This allowed the team to shrink the air gap between the two magnetic rotors in an effort to increase power, as the air gap is proportional to the strength of the flux going through the coils– meaning that a smaller air gap will yield a higher field strength and therefore more current induced in the coils of the stator. Additionally, the current generator layout uses an alternating polarity design, which is the most common design for an axial flux generator.

Electrical

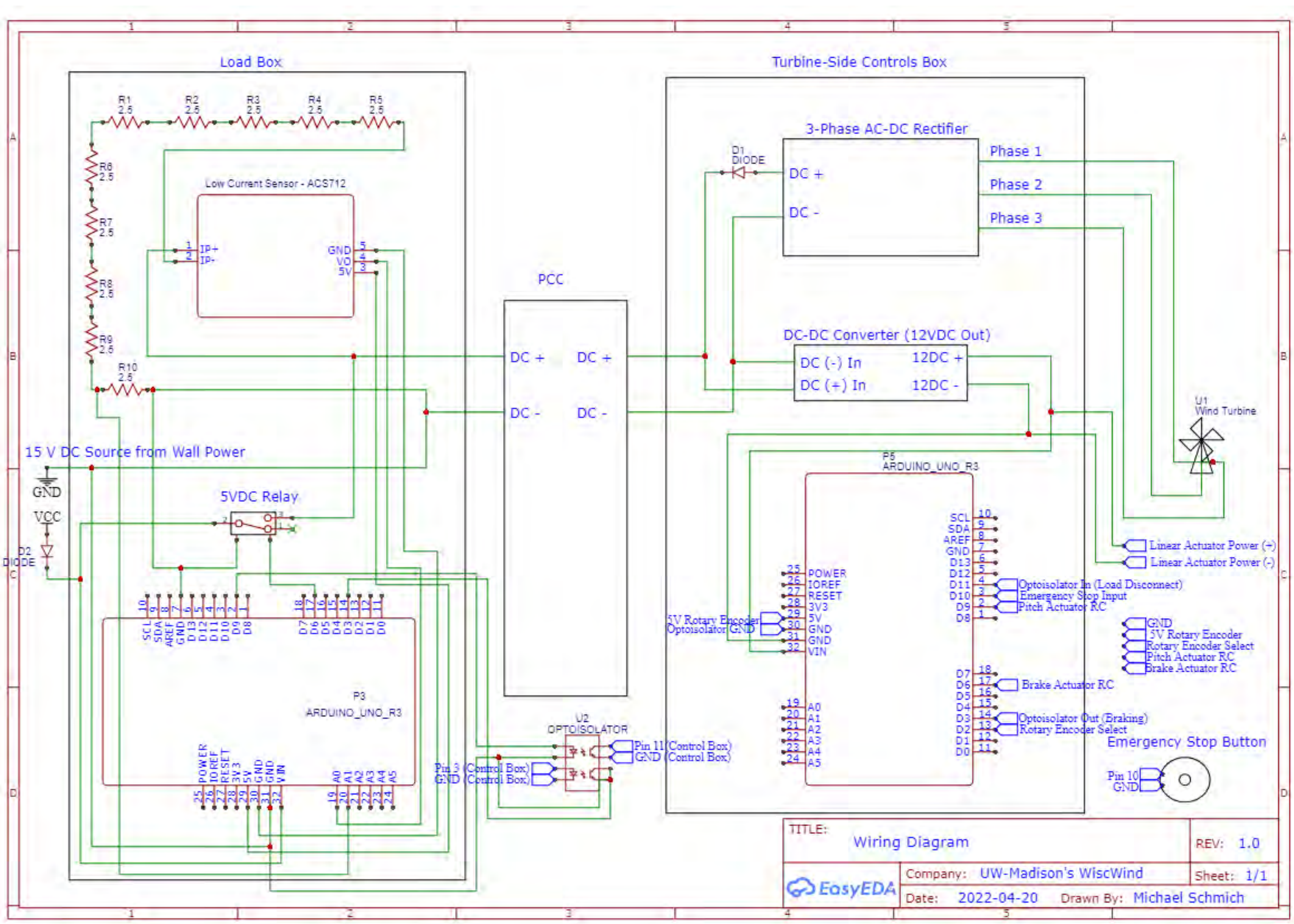

Figure 23: Electrical One Line Diagram

Introduction

Choosing to build off and improve the design from 2021 allowed the electrical team to focus on other systems in 2022. With the competition goals in mind, the team developed a voltage regulation system to power both the microcontroller and active pitch control, as well as a braking system to meet the safety requirements of the competition.

AC/DC Conversion

Since our generator produces 3-phase AC power, it must be converted to DC for both competition data collection as well as our power electronics. The 2020 and 2021 teams utilized the Linear Technology DC2465 board for AC to DC conversion. On the board, there are three LT4320 IC's, which are ideal diode bridge controllers that drive six low loss N-channel MOSFETs to tell when they are on and off. The FETs are used as switching regulators, which turn on automatically without any voltage drops. This design dramatically reduces power and voltage losses. It enables the overall system to be specified to operate with a smaller, more cost-effective power supply due to the enhanced power efficiency. Low voltage applications benefit from the extra margin afforded by saving the two diode drops inherent in diode bridges. Compared to traditional approaches, the MOSFET bridge enables a rectifier design that is highly space- and power-efficient. We found the DC2465 board to be an appropriate choice for our needs again this year and felt that using a proven solution for AC to DC conversion allowed our team to focus more on other areas of the turbine design.

Voltage Regulation

The voltage regulation system is necessary to ensure that the Arduino Uno Rev3 microcontroller and the Linear Actuator Control Boards operate effectively. A two stage Buck/Boost system was needed in last year's design due to the ESP32 microcontroller only accepting 3.3 V while the Linear Actuator Control board requires 12 V to operate. The Arduino Uno Rev3 and Linear Actuator Control board within this year's design both require 12 V to operate. To be more efficient, a single stage converter was used to deliver the necessary voltage. The regulation system consists of a 72W DC/DC converter with an input voltage range of 8V to 40V. This ensures that both the Arduino Uno Rev3 and Linear Actuator Control boards receive the expected voltage of 12 V DC. The 72W DC/DC converter was chosen as it is more efficient and cost-effective while also being less complicated to install. The voltage regulation system was verified to work using a benchtop power supply, a load, and multimeters.

Load Design

After load testing across various resistive loads using a dynamometer with our generator assembly at various speeds, it was found that a 25 Ω load was suitable for our team's design. The results can be found in the testing and results section of the report, where the difference between the old rotor/stator air gap and the new rotor/stator air gap figures are described. Initial testing indicated that during the braking task the electrical systems would not be able to restart the turbine at the appropriate times. Section 3.5.2 in the rules defines shutdown as 10% of the maximum RPM observed in the power performance testing. Initial tests showed roughly 2000 RPM could be expected at 11 m/s of wind speed. This means that the turbine must be spinning slower than 200 RPM at a minimum. At this low speed the turbine cannot provide enough power to correct the pitch and retract the braking actuator. For these reasons it was decided that the team would utilize the 120VAC wall outlet provided for the load and send power back through the PCC when in a braking state. To accomplish this, a 120VAC NEMA 15-R wall adapter to 15V DC converter is used to send 15 VDC back to the turbine side of the PCC when the Arduino in the load electrical box deems necessary based on external signals. This allows the turbine to return to normal operation when the load is reconnected or the E-stop button is pulled out.

Control Operation & Design

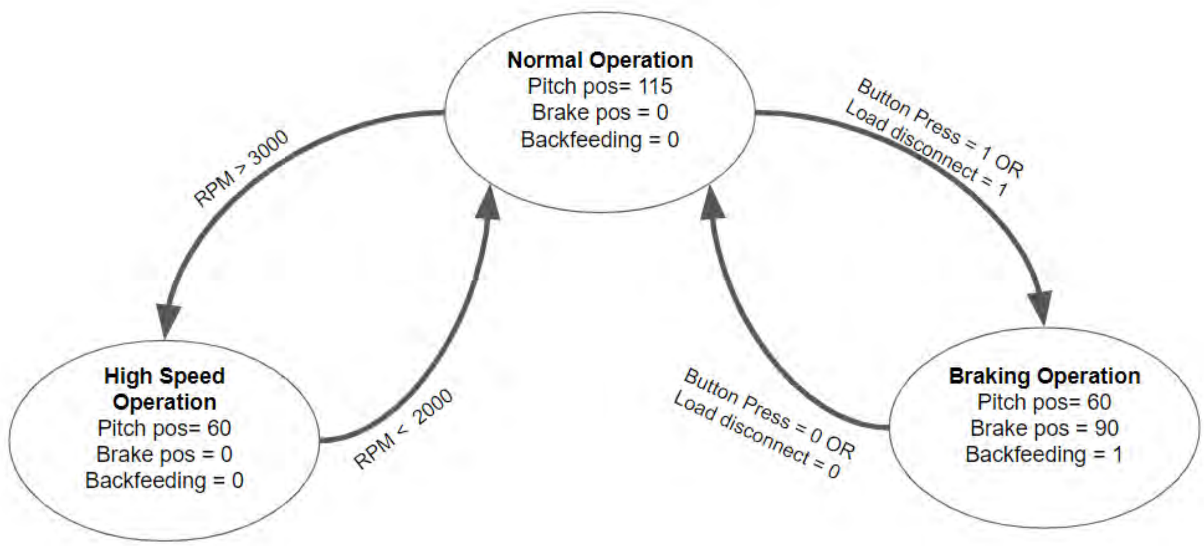

Figure 24. Control diagram

The turbine was designed with three main operational modes in mind, which can be found in Figure 24: normal operation, braking, and high speed. Normal operation is the state the turbine is in for the majority of wind speeds. This is operating with blades pitched fully into the wind with no braking applied. The goal of this state is to maximize power generated from the wind.

The second state of interest is braking. This state is entered if at any point the E-stop button is pressed, or if the load current is 0 (load disconnected). To monitor this, a ACS712 Low Current Sensor was used in conjunction with the load Arduino. When the zero current reading is observed, the load Arduino sends a signal to the control Arduino to initiate braking. Once braking has been initiated by either a button press or the received signal indicated load disconnect, the control Arduino pitches the blades out of the wind as far horizontal as the pitch mechanism will allow. Once the blades are pitched out and the turbine speed has been reduced, the control Arduino then activates the smaller braking Arduino which pushes on the shaft and causes the turbine to decelerate further. This mechanical braking was deemed necessary after wind tunnel testing proved the proposed electrical braking was insufficient to bring the turbine below 10% of max RPM. The last step of the braking state is sending a signal to the load Arduino. On signal reception the load Arduino activates the 5V Relay that allows power to flow from the wall outlet back through the PCC to the turbine. This is necessary so that control Arduino and both linear actuators have adequate power to return to normal operation.

The last state is high wind operation. In this state the blades are pitched out of the wind to slow the turbine down. Pitching occurs when the control Arduino receives a RPM reading above the set threshold of 3000 RPM. This is done to avoid the voltage limit of the PCC and avoid high rotational speeds that could cause the turbine to fail. Once the turbine returns to a RPM below the 2000 RPM the blades are returned to their normal position and the turbine resumes normal operation. These three states allow the turbine to complete the competition tasks.

Testing and Results

Testing a Reduction of Generator Air Gap

When the team was considering improvements on the generator in relation to previous year's design—apart from creating a new stator for the generator—one avenue that was explored was reducing the stator/rotor air gap. To maximize the electrical output of an axial flux generator, a great way to increase power at a relatively low cost is to reduce the air gap between the magnetic rotors and the stator coils so that the induced flux density is stronger through the coils. This creates a larger EMF and a greater generator output from that stator. Figure 25 shows the increase in power gained by decreasing the air gap by 4 mm (for a total reduction of 10 mm from last year's design) tested across different loads at different speeds. These tests were conducted using the dynamometer.

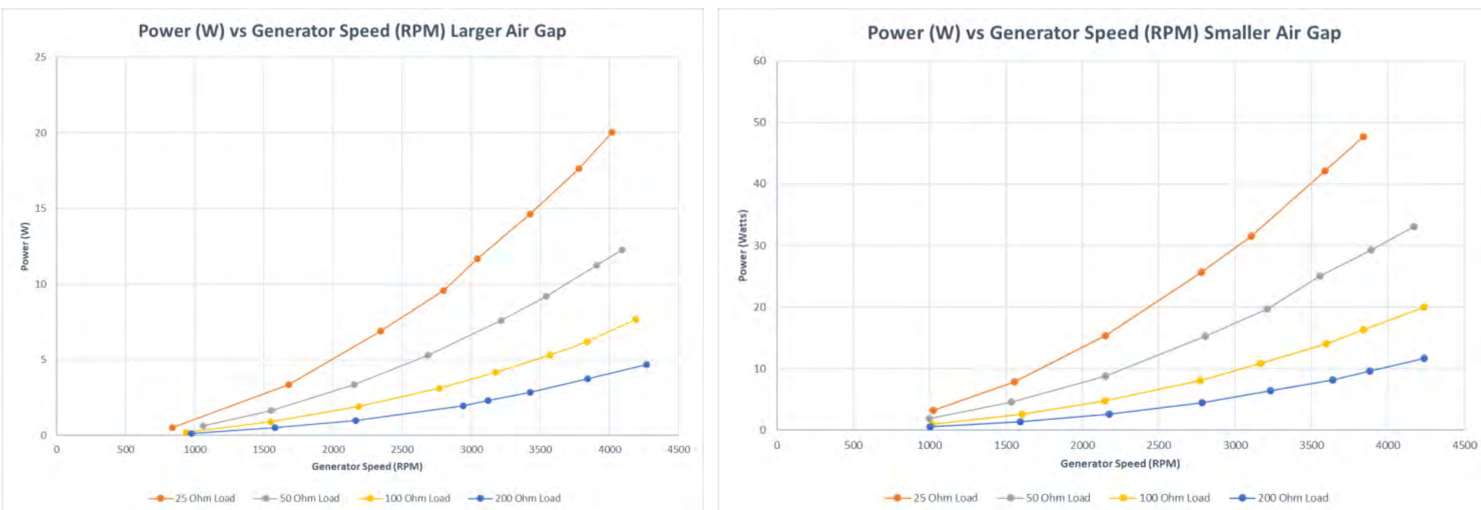

Figure 25. Speed vs Power for Original Air Gap (L) and Reduced Air Gap (R)

Testing of Emergency Braking

The braking system was tested at various wind speeds from 6 m/s up to 22 m/s and performed as expected in all cases. Engaging the pitch linear actuator and braking linear actuator with the braking system proved to be quite effective in reducing output power and also in reducing the speed. Due to the late change to a dual linear actuator system, concrete data was not able to be collected before the due date of this report, but in preliminary testing–the braking system was able to reduce the speed of the turbine to under 10% of the average speed at the top of the performance curve. Competition rules dictate that the turbine speed must be reduced to less than ten percent of rated value. The pitch actuator pitches the blades out of the wind, slowing the turbine down significantly, then a secondary linear actuator pushes a high friction material against the shaft to cause it to slow down to be under the 10% specification.

Testing of Generator Power Output

The generator was tested throughout the year, first on a dynamometer to test our subsystems and operating plans in the lab, then in the wind tunnel toward the end of the school year to test the combined sub-systems. The wind tunnel allowed for a real-world test of the completed turbine and showcased the mechanical improvements that allowed the axial flux generator to excel. Multiple tests were performed in the wind tunnel where the pitch control, blade design, and braking subsystems were all tested independently and then combined to create the final turbine. Figure 26 shows the power curve in relation to the wind speed tested in the wind tunnel. A smooth progression of power can be seen with the increase of wind speed.

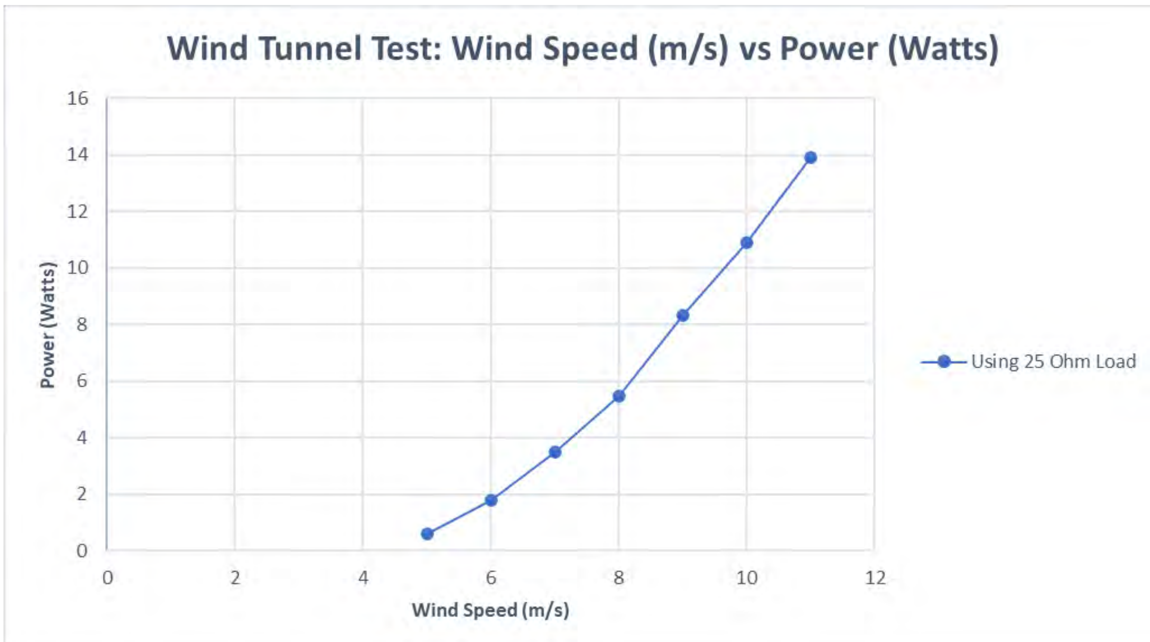

Figure 26. Generator power curve for wind tunnel testing.

Conclusion

This year's competition presented many challenges to our team but with hard work and good communication we were able to have a successful year. Our team had to be flexible and adapt when the initial electrical braking design proved unsuccessful. We learned how to leverage distributed manufacturing to test separate electrical subsystems separately and bring them together in one cohesive unit. We were able to validate these design choices with an iterative testing process which showed that our turbine could produce power meeting the competition requirements. Our successes include designing and implementing an active pitch control system, designing a new mechanical braking system and improving on previous generator designs. There is still room for improvement with respect to substructure and yaw control. These systems ran into time or equipment constraints, but we hope our minor success will encourage next year's team. Our last success has been our team's ability to adapt and overcome obstacles as they arise while building on knowledge and experience of prior years.

Appendix A: Final Mechanical Drawing

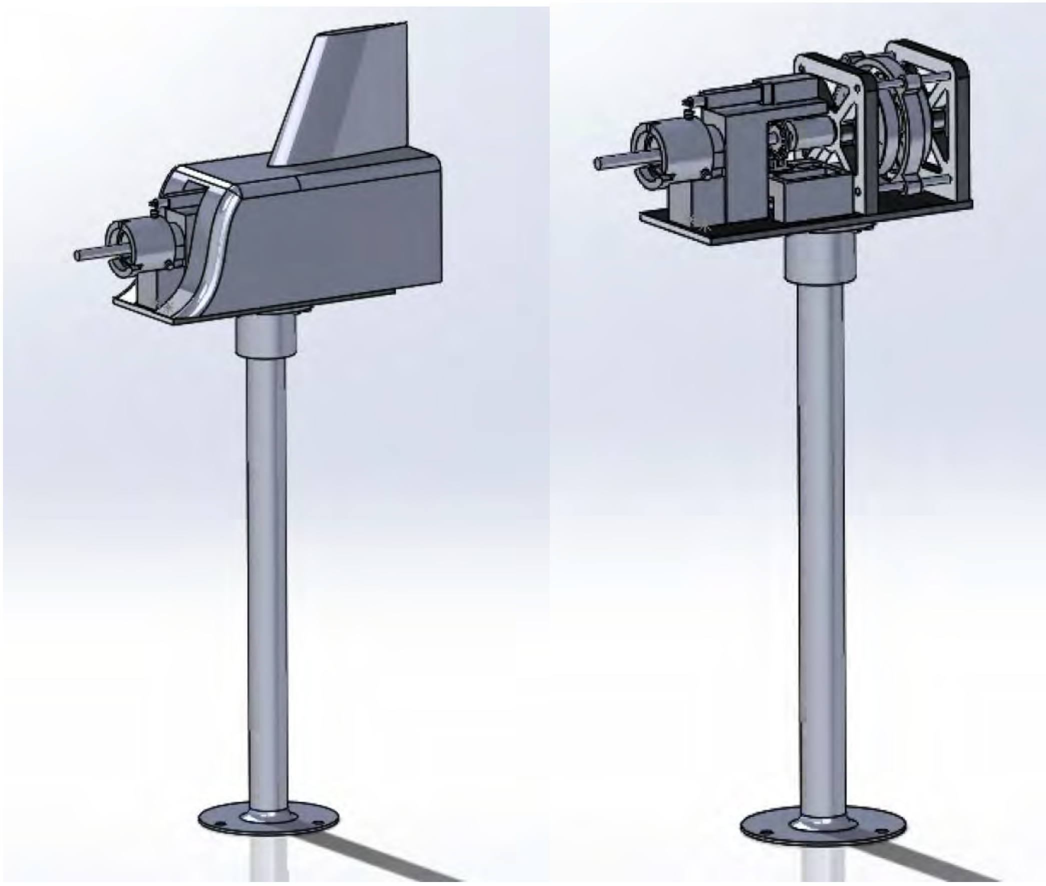

Figure A1. Final Mechanical Drawing with nacelle housing (L) and without nacelle housing (R)

Appendix B: Commissioning Checklist

1. Before approaching tunnel
    a. Verify Electrical Connections
    b. Upload final code to control Arduino
    c. Upload final code to load Arduino
    d. Verify starting positions of bother pitch and braking actuators
    e. Close and secure both load and control boxes
2. During tunnel installation
    a. Install substructure
    b. Secure tower to adapter stub
    c. Verify orientation of turbine in tunnel
    d. Connect loop wire from nacelle to turbine box.
    e. Connect turbine box to PCC and data acquisition
    f. Connect PCC to load
    g. Plug load into wall outlet

References

[1] Burton T. et al, "Wind Energy Handbook", *John Wiley & Sons, Ltd*, (2001).

[2] Ellis R. et al, "Design Process for a Scale Horizontal Axis Tidal Turbine Blade," *Cardiff University*, (Cardiff, United Kingdom, rep., 2018).

[3] Selig, M and McGranahan, B, "Wind Tunnel Aerodynamic Tests of Six Airfoils for Use on Small Wind Turbines" *Department of Aerospace Engineering, University of Illinois at Urbana-Champaign"* November 2004.