CU BOULDER WIND TEAM
2022 - 2023

TECHNICAL DESIGN FINAL REPORT

Prepared for Collegiate Wind Competition 2023

STUDENT LEAD:
Jeremiah Pare – Project Manager
jeremiah.pare@colorado.edu

TECHNICAL DESIGN TEAM:
Regan Barton – Environmental Engineer
Ariana Carmody – Financial Manager
Chris Holladay – Environmental Engineer
Will McConnell – Electromechanical Engineer
Lauren Mullen – Logistics Manager
Luis Munoz – Environmental Engineer
Rhett Nutter – Systems Engineer
Amanda Shields – Test Engineer
Ethan Smith – Electrical Lead
Ryan Stoltz – Manufacturing Engineer
Ryan Tasto – CAD Engineer
Heather Walker – Electromechanical Engineer

FACULTY ADVISOR:
Roark Lanning
roark.lanning@colorado.edu

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1. 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 third time the CU Wind Team will be participating at the Collegiate Wind Competition, and the second time competing in phase two. This year's team has been able to build on previous years' successes and learn from their failures. The main design goals for this year were consistency and robustness.

To meet these design goals, several areas of the design were prioritized. Namely, an in-depth blade analysis, an upgraded pitching system, increased focus on emergency stop, and the addition of an anemometer to simplify the control theory. Blade design had a slight oversight last year, and so the team started the design with an in-depth analysis of several airfoils and blade configurations. The idea was to design everything else around the blades. Using Qblade, the team analyzed over 30 different configurations and landed on the E216 blade design with a maximum C_L/C_D ratio of 43 and a maximum power coefficient of 0.54 at a tip-speed-ratio (TSR) of 3. After taking advice from the trials faced by the wind team last year, the team realized that designing a strong active pitching system would be critical to both the power generation and the emergency stop function. This active pitching system combines an original mechanical design with an optimized controls system to maximize consistent power generation at various wind speeds. The pitching system is also a critical piece in the emergency stop solution. Last year's team struggled with the emergency stop test during the competition, so this was a focus for the team. The emergency stop is accomplished using a triple redundancy system. When activated, the system will short the generator, pitch the blades to a negative angle, and a mechanical brake will be activated. To simplify the control theory, an anemometer, which will be mounted on the turbine tower, was added to the turbine design. The controls use this wind speed input to determine which control state to operate in. These additions and upgrades have helped to increase the robustness and consistency of the turbine's performance.

Other iterations in the turbine design include the foundation, simplified height adjustment, addition of a nacelle cover and the use of one microcontroller. The "offshore" turbine foundation builds on last year's suction bucket design but includes further optimization and manufacturing through thorough testing and prototyping. The team was able to hire a professional welder to manufacture the new suction bucket. The height adjustment piece was simplified to being a simple concentric steel insert with multiple configurations to adjust the height. Once the nacelle was fully assembled, a cover was designed, and 3-D printed to keep the enclosure secure and reduce drag on the components. To simplify the electronics, the team also opted to use a single microcontroller.

Overall, the turbine design has been upgraded from the previous years by consulting with industry experts, other team's final reports and team members from last year. Important lessons were learned through previous successes, failures, and rigorous testing. The team is confident the new design will perform as advertised during the competition. A large focus this year has been to create the CU Wind Team legacy both at the University of Colorado Boulder and in the CWC space.

2. DESIGN OBJECTIVES

Last year's team was the first CU team to compete in Phase Two of the CWC and their goal was to design mainly for functionality. The objective of this year's design was to design a small scale "offshore" wind turbine that will perform at competition robustly and consistently. This year, the team prioritized power generation optimization in order to make the highest performing and consistent small-scale wind turbine. This year's design focused heavily on the pitching system, blade design, emergency stop, and the controls systems. The team designed an original mechanical pitching system focusing on durability and creativity. Blade design included several iterations and explorations of different airfoils and chord lengths that were optimized to maximize the C_p value in Qblade. The emergency stop includes three different functions in order to ensure proper stoppage. The controls system was prioritized early in the academic year by implementing more sensors, namely an anemometer, to simplify the control theory. With these additions, the team was able to make a fully functional, robust turbine that is more consistent in its performance than in previous years.

3. NEW THIS YEAR

Building on the previous year's design, the team determined early that the focus of the turbine design was to increase consistency and performance during testing, increase the design's robustness, and overall aesthetic. To begin improvements for this year's design, the team first discussed points of failure from last year as well as points of emphasis that team members felt passionate about improving. The previous year had issues with their pitching mechanism, mostly due to outsourcing the assembly from a toy helicopter that was built of many fragile plastic components. Additionally, they failed to properly perform the emergency stop function during the competition. Further sources of improvements are presented in the list below and explained in more detail in their corresponding sections:

- Iterated foundation design, early testing, outsourced welding
- Simplified height adjustment piece
- Extensive blade design analysis, including 30+ iterations
- Redesigned original pitching system to be more robust
- Wind speed sensor integration through a hot wire anemometer
- Constant resistance load instead of variable resistance
- Earlier emphasis on control theory
- Single microcontroller for simplicity
- Triple redundant emergency stop system
- Addition of nacelle cover for aerodynamics
- Emphasis on overall aesthetic of design
- Emphasis on team dynamics and culture

4. ROTOR DESIGN

4.1 Blades

The blades are designed to maximize power output while considering parameters that reflect the scale of the turbine and competition conditions. A horizontal axis wind turbine (HAWT) was chosen for the prototype design due to the high energy conversion efficiency compared to other turbines, resulting in a higher power output. Three blades were chosen for the turbine to increase stability and energy yield. Qblade simulations were used to finalize the blade design since the software effectively utilizes blade element momentum (BEM) theory to optimize the chord length and angle of twist at each cross section of the blade to yield the maximum power output possible. Multiple blade designs were considered by uploading various airfoils and applying parameters consistent with competition conditions to obtain accurate results.

Competition conditions input into Qblade included a range of wind speeds, rotor size, Reynolds number, and tip-speed-ratio (TSR). A wind speed of 8 m/s was used to determine the appropriate Reynolds number and TSR since this is the average of the critical wind speeds that the team will be tested at during the power curve test. A Reynold's number of approximately 50,000 was chosen based on air density, the average wind speed, the average chord length of the blade, and the kinematic viscosity of the air. The team also decided to design the blades around a constant TSR to maintain a consistent airflow angle over each blade element. A TSR of 3 was chosen due to the turbine's small rotor radius of 20 cm, average RPMs expected, and average wind speed expected in competition. Typically for 3 bladed, full-scale turbines, a TSR of 4-5 is chosen, but since the turbine is so small, a TSR of 3 was more suitable. This decision was confirmed by running simulations in Qblade, which proved that optimizing the blades to a TSR of 3 maximized the power output and C_p more than any other value (Figure 1). In addition, power output, C_p, speed, and torque data from QBlade provided information that helped the team determine generator requirements. After deciding the correct parameters to design the blades around, the next step was to choose the appropriate airfoils.

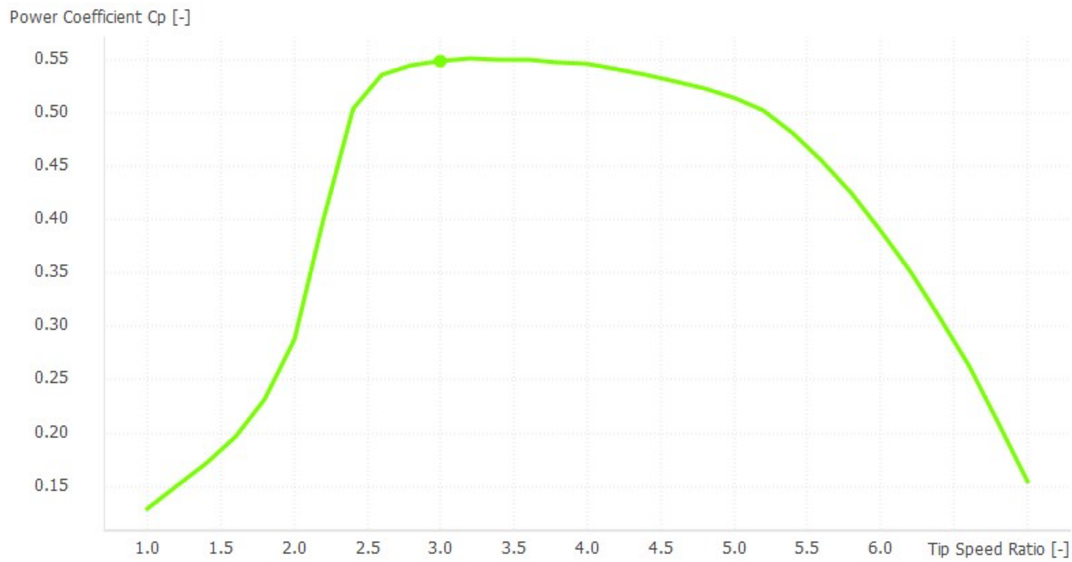


Figure 1: Cp-Lambda Curve for Final Blade Design

Four design goals were considered when designing the blades. The first design goal was to select airfoils with a thickness range between 10%-14% since the blade must be structurally sound yet still aerodynamically favorable. The second design goal was to pick airfoils with high C_L/C_D ratios since more lift creates more torque, which results in a larger power output. The third design goal was to only use one airfoil throughout the whole blade since using two or more airfoils of different thicknesses for such a small turbine can cause a disturbance at the transition [3], which noticeably increases drag. The last design goal is to pick blades that maximize the power output since this is the critical component for the power curve test in the competition. The airfoils considered for the final design were all downloaded from airfoiltools.com, which allowed us to sort through thousands of airfoils by applying the "Max Cl/Cd @ RE = 50,000" filter and inputting the desired range of thickness airfoil. Approximately 20 of the top airfoils on this list were uploaded into Qblade and were analyzed for maximum power production. The top performing airfoils included the E216, GOE79, Wortmann FX-160 126, and SG6042. The top three blade designs meeting each of the design goals were chosen and a decision matrix was created that weighed the importance of each goal and then scored each blade design for how well it met the design goal (Figure 2). The blade that scored the best was made of the E216 airfoil throughout the whole blade. The E216 blade design had a maximum C_L/C_D ratio of 43 and a maximum power coefficient of 0.54 at a TSR of 3.

			Score (1-3)	
Design Goal	**Weight (1-5)**	**Wortmann FX-60 126 & SG6042**	**E216**	**GOE79**
Structurally Sound (Thickness ≥ 10%)	5	3	2	1
High Cl/Cd	4	2	3	3
1 Airfoil	3	1	3	3
Power Output	5	2	2	1
	Total:	**36**	**41**	**31**

Figure 2: Blade Decision Matrix

To manufacture the blades, the team used a SLS Formlabs Fuse 1+ printer and printed the blades in Nylon 12 material because of its high strength and smooth surface finish (Figure 3). Nylon 12 was ideal for the blades because it is impact resistant and can withstand fatigue during high frequency cyclic loading. Bending and centripetal force tests were conducted to ensure that the blades did not break or detach from the rotor when subject to the maximum wind speeds of 22 m/s.

Figure 3: Rendering of Final Blade Design

Blade Deflection Test

The maximal normal load a blade is expected to experience at 22 m/s was calculated using Qblade to be 17 N. Additionally, a deflection test was performed to ensure the blade does not fracture or deflect enough to hinder the turbine's performance. For this test, the bushing was connected to the blade via a shoulder bolt, and a table clamp secured the bushing to the table with the rest of the blade hanging over the edge (Figure 4). The team tied a rope to the tip of the blade and connected a force gauge to the other end, slowly increasing the force until failure occurred. The blade failed at the root once the blade was subjected to 34.1 N (2" deflection), giving us a F.O.S. of 2.01. Because the F.O.S. was greater than 2, the team concluded that the blade design was strong enough to avoid failure at maximum wind speeds.

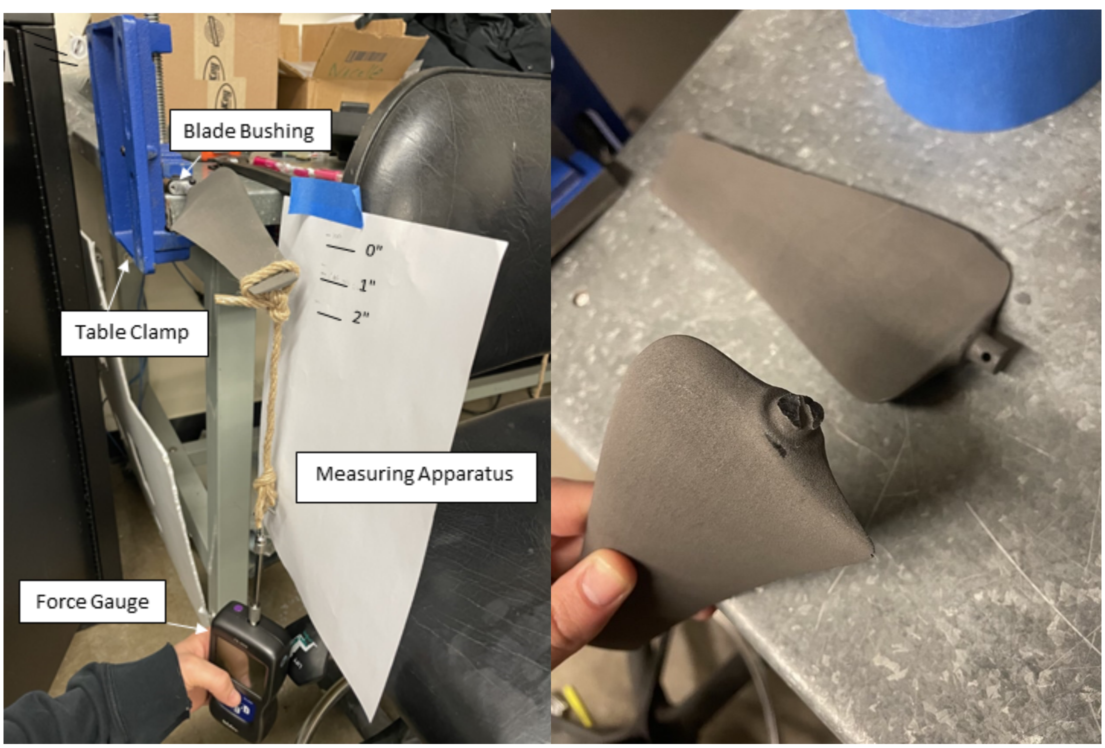


Figure 4: Deflection Test Set-up and Location of Failure

Centripetal Force Test

The purpose of the centripetal force test was to simulate maximum wind speeds of 22 m/s to confirm the blades and rotor assembly are strong enough to withstand all testing conditions. The highest expected

RPMs is less than 2000, but the team tested up to 2500 RPMs to take a conservative approach in case pitching fails. For this test, the team fully assembled the turbine and enclosed the rotor in a wooden box for safety purposes (Figure 5). The team used a battery to increment the RPMs by 200 up to a maximum of 2500. The team decided that if failure occurred before the turbine reaches 2500 RPMs, the design would have to be modified accordingly. The results concluded that the design is robust enough to withstand maximum wind speeds even if pitching fails since there was no failure from the blades or rotor at 2500 RPMs. This test discovered that the actuator screws loosen at high RPMs, but the team remedied this issue by applying Loctite to the thread.

Figure 5: Centripetal Force Test

Static Performance Analysis
A static performance analysis was conducted based on data collected from the area encompassing the proposed leasing blocks off the coast of Louisiana at a hub height of 1 meter. Specifically, the projected power curve of the turbine, including losses, was compared to the wind speed frequency histogram data collected in the project development portion of the competition to calculate the annual power production of the turbine. Using this analysis, the calculated annual energy production (AEP) was 44 kWh.

4.2 Pitching System
In order to both maximize the power during the power curve test and minimize the power during the emergency stop, the thrust produced by the blades needed to be controllable which was achieved through an active pitching system (Figure 6). Based on the previous team's performance, a robust yet simplistic design was the main objective which is why a custom metal subassembly was chosen. The active pitching centers around a swash plate design since the entire plate can translate linearly while each side of the plate has independent rotation. This allows for a device that is fixed to both the swash plate and the nacelle to translate the swash plate, while the other side can independently spin with the shaft. The linear movement of the swash plate is transferred through ball joint push rods that rotate L-shaped bushings upon which the blades attach to. Due to concerns of the push rods binding from becoming out of phase with the hub and swash plate, a splined shaft with broached hubs was chosen. The tight clearances between the broach and shaft minimize backlash and allow for smooth sliding of the swash plate.

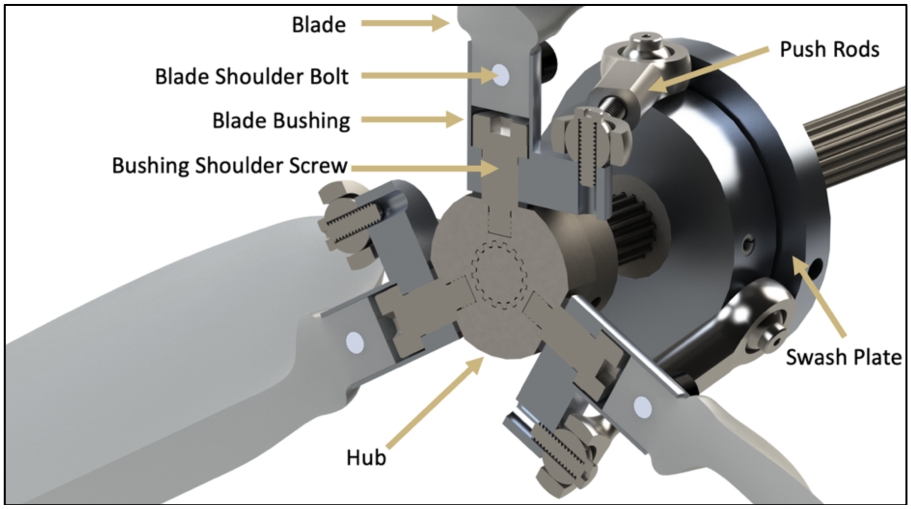


Figure 6: Pitching System Render with Cross Section of Hub

The linear translation of the swash plate is controlled by two linear actuators. In selecting a linear actuator, the back drive force, stroke length, and voltage were considered. To achieve both zero thrust for the emergency stop and maximum thrust, 100 degrees of pitching rotation is needed. Using the geometry shown in Figure 7, the change in length of b to achieve 100 degrees of rotation of θ was found to be 2.3 cm. Since the actuators need to hold their position even without power being supplied, the back drive force is crucial. The force on the actuator would be a function of the moment created by the blades and the geometry of the push rods. Using the coefficient of moment, C_m , from QBlade, The moment from the blades, M, was calculated using Equation 1 and the force on each actuator was then calculated using Equation 2 to be 35 N.

$$M = \frac{1}{2} C_m \rho_{air} \int_0^R ({U_{wind}}^2 + (r\omega)^2) c^2 dr \quad \textbf{Equation 1.} \qquad F_A = \frac{3M\cos\alpha}{2\sin\gamma\alpha} \quad \textbf{Equation 2.}$$

To minimize the power drawn from the generator during operation, a voltage of 5V was chosen. Based on the above parameters, the Actuonix L16-50-150-6-R was chosen.

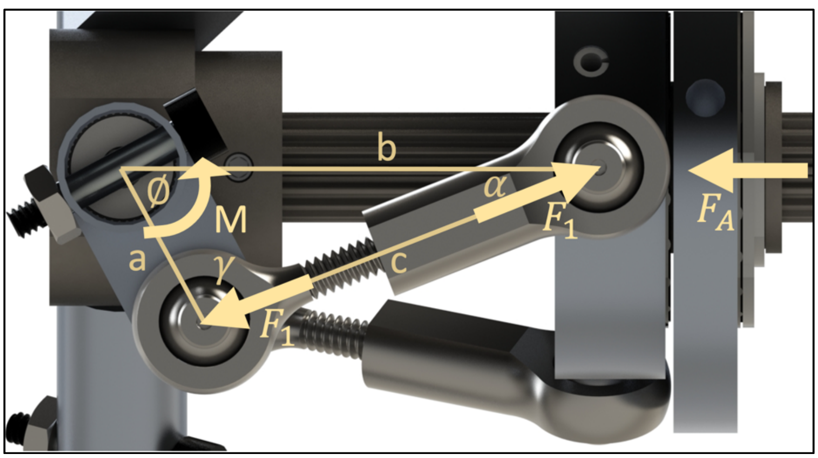


Figure 7: Pitching System Geometry and Forces

Due to the high centripetal forces that will be exerted on the blades and attachment pieces from the predicted 1600 RPM, the shear forces on the tapped holes in the hub were analyzed. Using the center of mass of the blade and bushing, the centripetal force calculated provided a safety factor of 3.1 which was verified during centripetal force testing where the rotor got up to a max speed of 2500 RPM without failure.

$$F_{cent} = M_{blade}\omega^2 r_{blade} + M_{attachment}\omega^2 r_{attachmennt} \quad \textbf{Eq. 3} \qquad \tau_s = \frac{F_{cent}}{A_s} \quad \textbf{Eq. 4}$$

Figure 8: Centripetal Force Diagram

With last year's teams running into issues with binding of the pitching system during competition, The team wanted to start testing the design from the very beginning to prevent a critical system from failing. To check for initial design issues that could lead to binding, a prototype was built using off the shelf components and SLA prints for custom components shown in Figure 9. No issues were discovered in the prototype, so manufacturing of the design was moved forward.

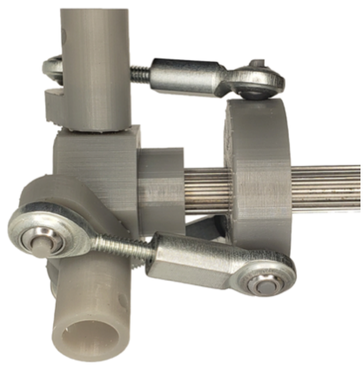


Figure 9: Pitching Prototype

Most of the components were custom and required in house manufacturing using lathes and mills. Due to the complexity of the blade bushings, they were made on a CNC mill. All components were made from 6061 aluminum besides the shaft, hub, and swash plate sleeve which were made from 1015 steel due to its higher strength and higher wear resistance. During manufacturing, one issue that came up was the manufacturability of the swash plate sleeve which required changing from a set screw collar to a retaining ring to assemble the swash plate.

4.3 Nacelle

The nacelle houses the electronics and mountings for the rotor which is fastened onto a baseplate and surrounded by the nacelle cover (Figure 10). The nacelle cover was printed from nylon 12 and comes in two halves that fit around the base plate and is fastened together with bolts.

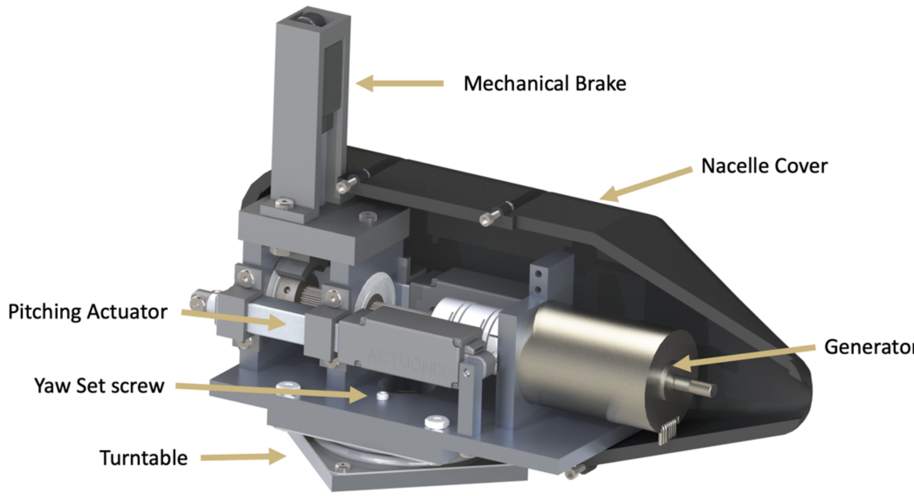
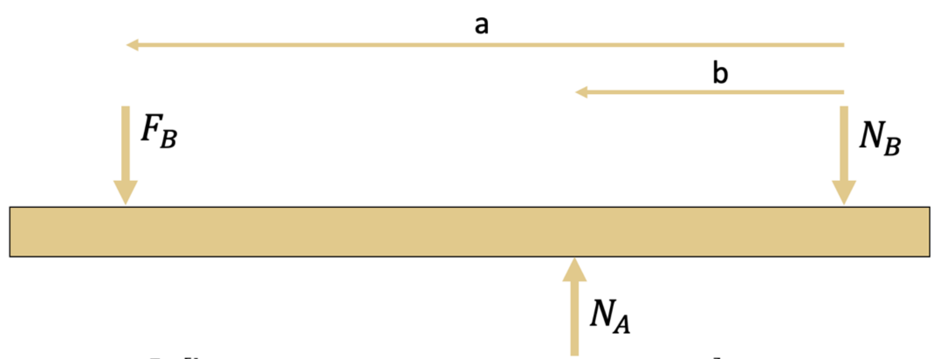


Figure 10: Nacelle Rendering

The shaft is supported by two custom pillow blocks which were milled, and press fit with ball bearings. Using predicted radial loads and rotational speeds, the basic life cycle was analyzed and found to be acceptable for the applications. Due to the use of a splined shaft, broached adaptors were needed between the inner bore of the bearing and splined shaft which were then press fit into the bearing inner bore. When trying to minimize binding in the pitching system, the deflection in the shaft needed to be minimal. With a shaft diameter of 0.79 cm, the maximum deflection was analyzed as a simply supported beam shown in Figure 11 and found to be 0.018mm which results in a safety factor of 3 for the allowed deflection of 0.005mm.



$$y = \frac{F_B}{6EI}\left[\frac{b-a}{b}\langle x\rangle^3 + \frac{a}{b}\langle x-b\rangle^3 - \langle x-a\rangle^3 + b(a-b)x\right] \quad \textbf{Eq. 5}$$

$$I = \frac{1}{4}\pi\left(\frac{D}{2}\right)^4 \quad \textbf{Eq. 6}$$

F_B= Weight of Rotor
$N_A = N_B = Bearing\ support\ forces$
D= minor diameter of spline shaft
E= Modulus of Elasticity

Figure 11: Deflection Diagram of Shaft

Initially, the yaw system was an active system utilizing a tail fin that aligned the rotor with the predominant wind direction, but during testing there was excessive amounts of wobble. This led the team to pivot to a passive system that is manually aligned in the tunnel and then set in place with two set screws.

The nacelle also houses the mechanical brake which will be utilized as a backup during the emergency stop test. It consists of a linear actuator that is mounted above the shaft with a neoprene rubber pad attached on the end. When needed, the actuator presses against the shaft creating a friction force to slow the spinning. The back drive force of the actuator is 25 N so at a minimum when unpowered will provide a braking torque of 0.19 Nm.

5. STRUCTURE AND FOUNDATION DESIGN

The structure consists of everything below the nacelle and includes the tower, tower plugs, anemometer mount and sensor, base flange, stub, nominal tube, height adjustment piece and the foundation. The purpose of the structure is to support the turbines weight and to maintain stability during the durability test.

5.1 Tower

The tower is made from 1.5" outer diameter, 1/8" thick 6061 aluminum tubing and is sized such that the rotor hub is at the center of the wind tunnel. The tower connects to the nacelle and base plate via tower plugs which are custom concentric aluminum inserts. The tubing allows for all electrical wires to pass down through the tower and out the foundation. Attached to the tower tubing is the anemometer sensor which is located just below the swept area of the rotor and mounted via a 3D printed mount and hose clamp (Figure 12). A hole in the tubing allows for the wiring to pass down to the turbine PCB. The tower attaches to the base flange which sits on the provided competition stub and below the stub is a nominal steel tubing with the required 1.5" outer diameter. This nominal tube then attaches to the height adjustment piece, a concentric steel insert with 3 threaded holes and 5 different configurations, 0.25" apart. This redesigned height adjustment piece was chosen for its lightweight and simple design (Figure 12). The bottom half of the height adjustment piece connects to the foundation's upright post. The tower is designed to have clearance for all electrical cables to pass down from the nacelle and out the height adjustment piece.

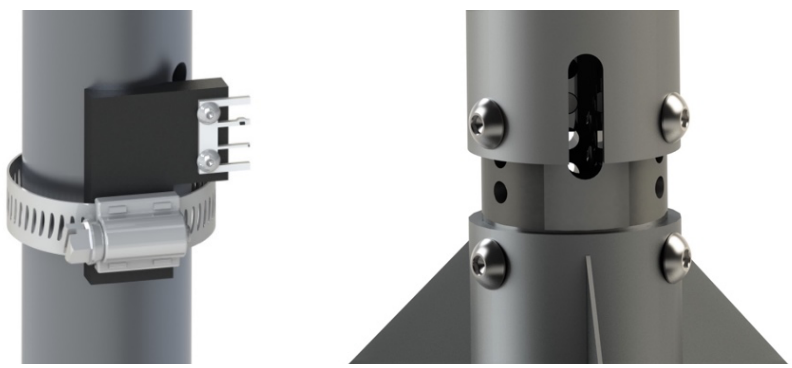


Figure 12: Anemometer Mount and Height Adjustment Piece

5.2 Foundation

The foundation design selected for the turbine model is a single monopile suction bucket caisson commonly used in industry. The design selection was based on the success of last year's foundation and an extensive literature review. The mechanism that drives the foundation design is a pressure differential between the inside and the outside of the suction bucket [2]. The suction force is created during installation by drilling three holes on the top face of the foundation, allowing water to escape from the inside of the caisson as it penetrates the sand. Once the top face is flush with the sand, the holes are sealed with bolts that create a water-tight seal. After fully tightening the bolts, the pressure differential between the inside of the suction bucket and the outside drives the foundation into the seabed, creating a stable support for the turbine. Through the research conducted, the team discovered that the mathematical model for suction buckets relies heavily on empirical data collected from testing, so the team conducted prototype testing to determine the feasibility of the foundation design.

Multiple prototype designs were created and tested by subjecting them to the expected forces from the competition's maximum wind speeds. The team underwent three stages of prototype testing, constructing suction buckets from varied materials and subjecting them to static loading under conditions identical to competition testing parameters, modeled in Figure 13. The prototype testing confirmed that the suction bucket design is stable during testing, and the volume of the suction bucket was directly correlated to its stability indicating bigger is better. When testing the final design, the foundation achieves a safety factor of 2.1 with a weight of 4.1 pounds.

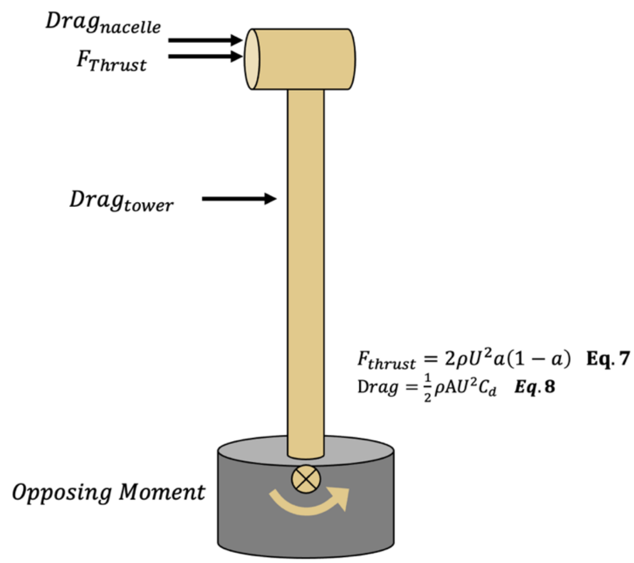


Figure 13: Engineering Diagram of Foundation

The team constructed the foundation using 0.036” 4130 alloy steel, which was welded together by a professional welder to form the thin-walled pressure vessel. From prototyping, the team concluded that a large volume would produce the most stable design, and so the dimensions of the suction bucket were designed near the maximum allowed constraints. The diameter is 28 cm, and the height is 18 cm, leaving a 2 cm buffer on both the height and area to account for any deformation during welding. Designing towards the maximum depth also maximized the surface area in contact with the sand which further increases stability by allowing for more frictional forces to be applied to the foundation that help restrict the movement of the foundation. To ensure that the welded joints between the upright tube and the top face are stable enough to withstand the dynamic loading of the wind, the suction bucket has three welded support gussets that connect the top face of the foundation to the upright tube that connects to the bottom of the transition stub. Welding strength calculations indicated the requirement for extra support to prevent any joint degradation in the upright tube [4].

6. ELECTRICAL DESIGN

The electrical design for the turbine is comprised of the electrical components within the nacelle and two custom printed circuit boards (PCBs), one for the turbine side and one for the load side. The nacelle components include a Maxon EC-i 40 three phase brushless DC motor and three Actuonix linear actuators [1]. The motor serves as the turbine generator by converting the rotational energy from the shaft into electrical AC power. Additionally, the electrical system uses the hall effect sensors on the motor to measure the RPMs of the turbine shaft. Two of the linear actuators within the nacelle are used to pitch the blades back and forth depending on the wind speed, while the third one is used as the mechanical braking mechanism. Each actuator requires a 5-volt input to operate effectively. Finally, both PCBs were designed using Altium Designer and manufactured by JLCPCB. Each of them contains several components that are critical to the functionality of the turbine.

6.1 Electrical Diagram

Figure 14 below shows the general layout of the electrical system. The left side of the diagram shows the turbine side electronics, while the right side shows the load side.

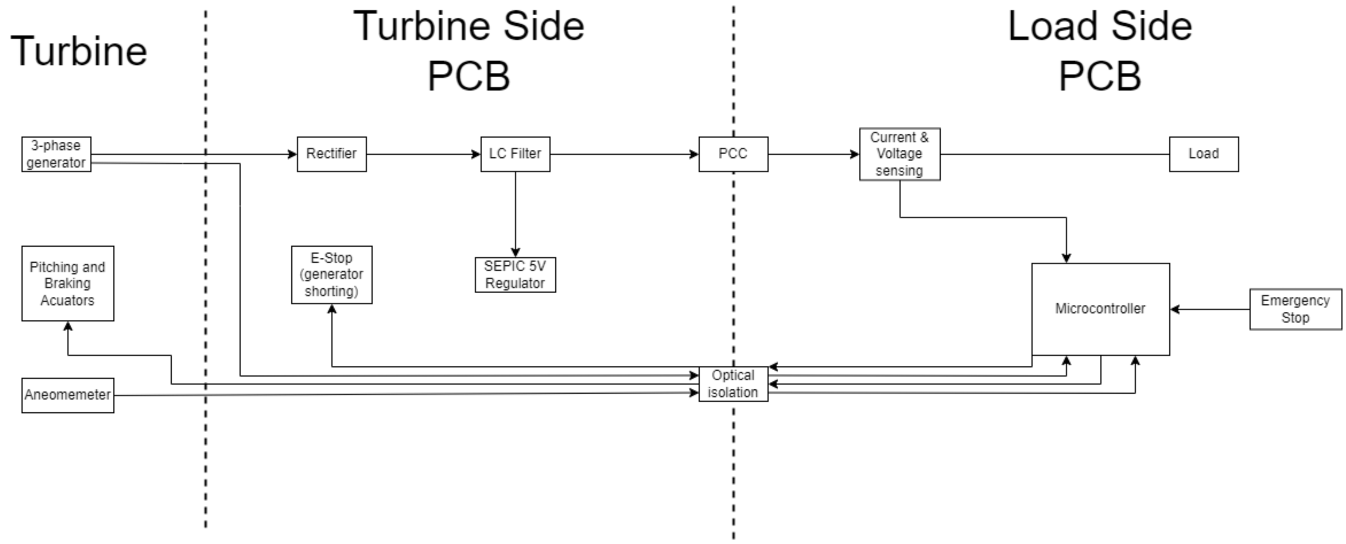


Figure 14: Electrical Diagram

6.2 Turbine PCB

The turbine side PCB shown in Figure 15 can be broken down into five key components. The first is a three-phase rectifier that converts three-phase AC power from the generator into DC power (1). Next is an LC filter that smooths out current and voltage ripples (2). Through testing, the team determined that the voltage that leaves this filter is less than 35 volts for all expected speeds of the rotor. The third component of the PCB consists of the three emergency-stop solid state relays, which act as switches to short the three phases of the motor (3). The fourth component on the turbine PCB is a single-ended primary-inductor converter (SEPIC), which bucks or boosts the power generated by the turbine to a consistent five volts (4). The five-volt output is then used to power the linear actuators and various sensors throughout the system. The final component on this PCB is the “brain” side of the anemometer (the sensor side is mounted on the turbine tower), which is used to amplify the wind speed analog values so the microcontroller can easily read and interpret the sensor’s data (5). The three-phase rectifier, LC filter and SEPIC were initially simulated using LTSpice and then tested on a breadboard before being implemented into the PCB design.

6.3 Load PCB

The load side PCB shown in Figure 15 has seven main components. First, the voltage sensor, which is a voltage divider circuit that scales the voltage down to values that the microcontroller can read. Second, is a SparkFun current sensor that monitors the amount of current traveling through the PCC (1 & 2). The current sensor and voltage sensor are vital to the system because the readings are used to measure the power travelling through the PCC. The next components are the digital and analog optical isolators, which are used to ensure that power does not cross through the signal wires to the turbine side electronics (3). The largest component is the SparkFun Reboard Turbo microcontroller, which manages the input and output signals of the system (4). The actual turbine load, a metal-oxide semiconductor field-effect transistor (MOSFET) operating in the ohmic region, has a large heat sink attached to dissipate the heat it produces (5). Additionally, the load side has a boost converter (6* - underneath) to boost the input voltage from five to 28 volts to power the turbine side SEPIC during startup. Finally, there is a relay that can be turned on during turbine start-up to send power to the turbine side PCB (7).

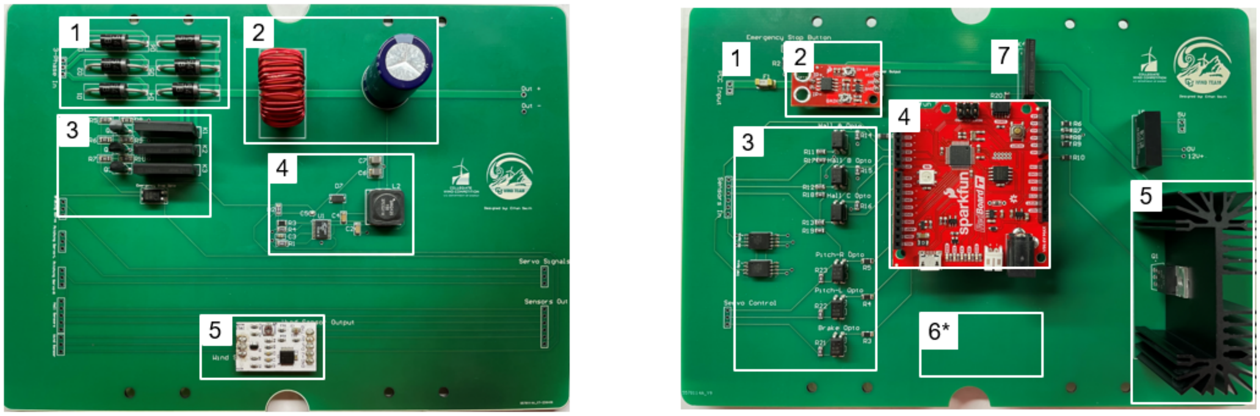


Figure 15: Turbine PCB (left) and Load PCB (right)

6.4 Control Model Analysis

There are five main control states for turbine operation shown in Figure 16. The control system, which is run on the microcontroller, switches between the control states depending on the wind speed and the emergency stop condition. The wind speed is measured using a hot wire anemometer that is mounted to the front of the wind turbine tower. This speed determines when the controls switch between the first four states. To determine if the emergency stop is triggered, the microcontroller reads the voltage from the emergency stop button circuit to decide if the button is actuated. Additionally, the controls use a current sensor and hall effect sensor to determine if the load is disconnected. If the current sensor reads zero current and the speed of the rotor shaft is above a threshold level, then the microcontroller knows that the load is disconnected, and engages the emergency stop.

There are different functions that occur during each separate control state. In the first control state, the power relay is actuated so that power is transferred from the load side to the turbine side. Additionally, the load MOSFET is turned off and the blades are pitched to the optimal cut-in angle. In the second control state, the load is turned on and the blades are pitched to maximize the power output of the turbine. For the third control state, the blades are pitched to maintain a constant power output and rotor speed. In the fourth control state, the blades are pitched back in order to limit the torque on the rotor. This pitching position will produce a low rotor speed, so there will still be a positive power output of the turbine. Finally, the last control state pitches the blades back to produce zero thrust and, if necessary, engages the mechanical brake and generator shorting relays.

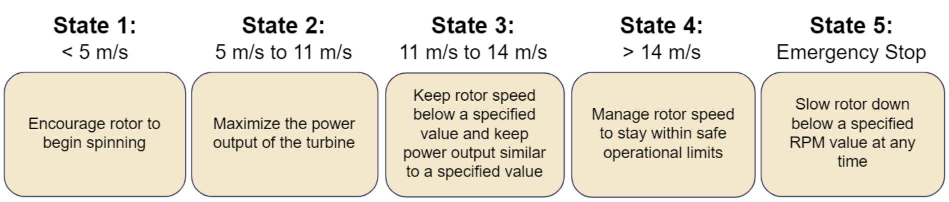


Figure 16: Turbine Control State Goals

6.5 Software Architecture

To control the turbine actions, the team decided to use Arduino to program the SparkFun Redboard Turbo microcontroller. This controller will act as the DAQ for all the sensors in the system and adjust all control surfaces accordingly.

The inputs to the software through the microcontroller are signals from the anemometer, current sensor, voltage sensor, and hall effect sensor (for readings of the generator shaft speed). The anemometer, current sensor, and voltage sensor all output analog voltage signals that are discretized by the microcontroller. The software uses the 12-bit value from the sensors as well as calibration equations to calculate accurate values of wind speed, current, and voltage. The hall effect sensor works in a different way in that it outputs digital pulses to the microcontroller that signify each rotation of the generator shaft. The Arduino code measures the time between pulses and converts this value into rotations per minute of the rotor.

The output signals from the microcontroller affect the functions of the pitching actuators, the braking actuator, the power relay, the generator shorting relays, and the load MOSFET. To control the position of the actuators, the software outputs a pulse width modulation (PWM) signal to set the distance of the linear actuator arms. The relays are controlled with a digital voltage signal that sets the state of the relay. Finally, the load MOSFET is controlled with an analog voltage signal that comes from the software as a 10-bit value. This analog signal sets the resistance of the load because the MOSFET operates in the ohmic region.

The team decided to use maximum power point tracking (MPPT) Arduino code in order to pitch the blades during state 2 (power performance). The design was inspired by the concepts of proportional-integral-derivative (PID) control, but it uses a feedback control system that was made specifically to match the requirements of the competition and the components of the assembly. This code fuses blade pitch adjustments in order to maximize the power output of the turbine. The system waits for the wind speed to stabilize before beginning the MPPT code to prevent any confusion during changing tunnel wind speeds. This stability is evaluated using a record keeping system that tracks when recent measurements deviate from a moving average by a specified figure. After determining a constant wind speed from the anemometer, the pitch is set to an estimated ideal position that was attained from testing. Then, the code performs a pitch adjustment and evaluates the power change from the adjustment. By comparing the original and new power values, the system determines the direction to move the actuators to increase power (if not already at a maximum power point). The code then moves the actuators incrementally in the chosen direction, taking readings after each adjustment and keeping a short record of recent measurements. The system constantly searches these records for a displayed peak in the output power. When a peak like this is found, the system stops and moves to that pitch position, thus finding the maximum power point at said wind speed. This process repeats while the wind speeds are between the designated speeds for state two.

For state 3, the team has implemented code in order to maintain a constant rotor speed and power output. The main function of this code is to monitor the power output from the turbine and to adjust the pitching accordingly. The software constantly compares the instantaneous power output to the power output determined at 11 m/s. The power output at 11 m/s will be measured through testing and will be stored as a variable in the control code. If the instantaneous power is higher than the set value, then the controls pitch the blades away from the wind, which will lower the rotor speed and power output of the turbine. If the instantaneous power is lower than the set value, then the controls pitch the blades in the direction that will increase the rotor speed and power output of the turbine.

7. FULL ASSEMBLY

7.1 Final Turbine Assembly

After subsystem testing was completed, the team worked collectively to integrate all of the components into a fully assembled turbine shown in Figure 17. The turntable driving the yaw system was implemented between two plates connecting the tower and nacelle. The nacelle base plate was connected to the turntable using bolts and served as a ground to secure the pillow blocks and pitching actuators. The rotor shaft was fit into the pillow blocks, secured with set screws, and attached to the motor using a flexible shaft coupler. The swash plate and the hub were then added to the shaft and fastened to the linear actuators. The blades were attached to the rotor using a shoulder bolt that attaches the blade bushing to the blade. The entire nacelle was then fastened to the tower using bolts. The structure team verified that the height adjustment piece fit in the upright tube of the foundation and was able to achieve the correct heights prior to testing. Once the foundation was securely connected to the height adjustment, the team attached the transition stub to the top of the height adjustment component. The tower was then attached to the top of the transition piece, with the nacelle already fastened, completing a full assembly for final testing.

Figure 17: Full Turbine Assembly

The team was divided into three subsections to make sure design, manufacturing, and testing of each subsystem was completed on time and with distinction. The three sub teams were structure, rotor, and electrical. These sub teams met biweekly while the entire team met once weekly to discuss updates and make sure the team fully agreed with design and testing decisions. The team emphasized respect and community this year as team dynamics played a significant role in fostering a positive work environment and increasing overall productivity. Weekly progress updates and feedback sessions proved to be extremely effective in creating a sense of community and group accomplishment.

7.2 Commissioning Checklist

In order to properly set up the wind turbine in the competition wind tunnel and ensure that it will work, a structured installation procedure with diagnostic checks must be followed. This will guide the team in setting-up for competition testing and in debugging any potential issues. The team divided the checklist into two parts: one for the installation of the turbine with the foundation and one for the controls testing to ensure that the turbine functions properly. Testing in the practice wind tunnel will be conducted to recalibrate sensors, run through control architecture, verify expected speed and power, troubleshoot electrical issues, and observe and remedy any problems that might arise during testing.

Installation:

- ❑ Install the foundation
    - ❑ Unscrew the three bolts on the foundation

    - ❑ Put the foundation in the water and push it all the way into the sand
    - ❑ Ensure that the foundation is level using a bubble level
    - ❑ Tighten the three bolts on the foundation using the extended socket wrench
- ❑ Place the cables in the slot in the top of the foundation
    - ❑ Make sure that there is sufficient length of cable on each side of the foundation
- ❑ Attach the height adjustment piece and adjust it if necessary
- ❑ Run the cable through the competition stub piece and attach the stub piece to the foundation
- ❑ Place pre-assembled turbine through wind tunnel turbine door and attach the cable connector pieces
- ❑ Tighten stub assembly wing nuts to secure turbine
- ❑ Align the yaw mechanism with the wind direction and tighten the set screws
- ❑ Attach cables to the PCBs outside of the tunnel
- ❑ Attach the required cables to the PCC
- ❑ Plug the load side into the wall power supply

Controls Testing:

- ❑ Ensure that the anemometer readings match the wind speed set by the competition
    - ❑ If they do not match, adjust the zero-wind speed in the code to recalibrate the sensor
- ❑ With the tunnel wind speed at 11 m/s, record the power output of the turbine and set this value in the control code so the code has an accurate value for the control of rated power portion of the testing
- ❑ With the wind tunnel at a high speed, test that the emergency stop mechanisms will actuate and slow the rotor speed sufficiently when the emergency stop button is pressed and when the load is disconnected

7.2 Testing

Testing of the four critical subsystems was completed as early and often as possible before integrating each subassembly into a full system. The four subsystems included the foundation, blades, rotor system, and power & controls. One of the largest challenges the team faced was not having access to a wind tunnel large enough to fit the rotor inside the testing chamber. To solve this issue, the team created a homemade wind tunnel by designing a diffuser to attach to the end of a leaf blower and adding a vinyl enclosure to the diffuser to act as a controlled testing chamber.

During the early stages of full system testing, the team determined what load resistance should be used at different generator shaft speeds. According to theoretical calculations, to maximize the power output at the PCC, the load resistance should be equivalent to the internal resistance of the generator windings. The motor spec sheet lists a constant value for this, meaning that the load resistance should be set to that value, but the team wanted to complete testing to ensure that this was the case. After testing the power outputs at different shaft speeds and load resistance values, the team determined that the best value for the load resistance was 0.45 Ω at all rotor speeds.

In addition to load resistance, the team also wanted to determine the pitch angles for different wind speeds. For states one, four, and five, the pitch angles determined through testing are coded in as set values. For states two and three, the code uses these pitch angles as starting pitch angles before beginning the MPPT and constant power output algorithms. The team determined the cut-in wind speed of the turbine to be 4.8 m/s at a pitch angle of 10 degrees. The optimal pitch at 11 m/s was determined to be 40 degrees since this is the angle at which power was maximized. The team is utilizing the few weeks until the competition to determine the optimal pitch angles at the rest of the wind speeds, which will yield the actual power curve of the turbine. Once final testing is completed, the actual power curve will be compared to the theoretical power, which was determined through running simulations in Qblade (Figure 18).

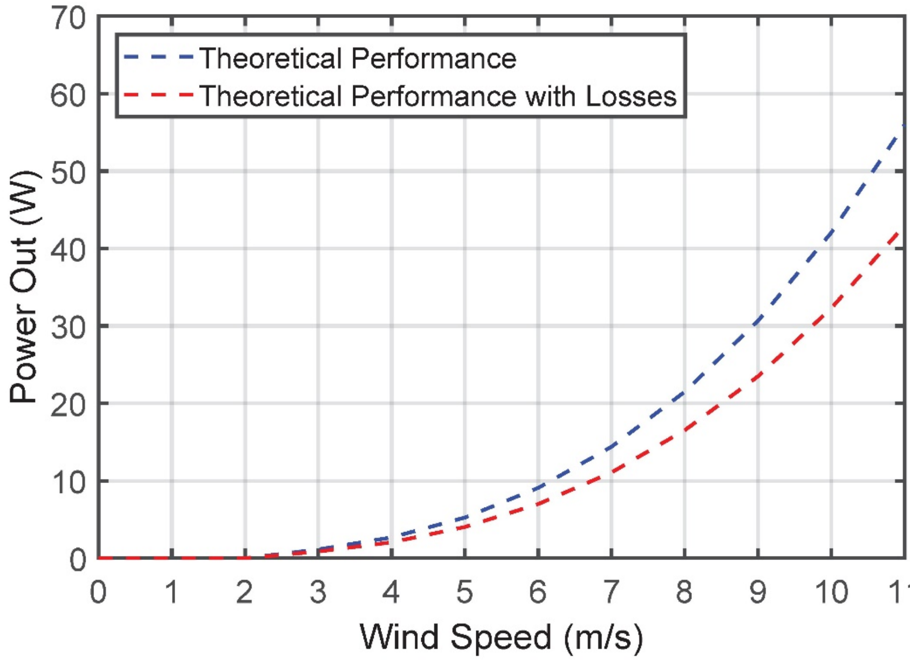


Figure 18: Theoretical power curve before and after theoretical losses (Prandtl tip losses, 3D correction, drag correction)

The team designed a system that would use active pitching, generator shorting, and a mechanical brake in conjunction to significantly reduce the rotor speed to the competition standards. Initial testing of the emergency stop system included pitching the blades at a negative angle in front of the homemade wind tunnel to observe the effectiveness of active pitching on rotor speed. Additionally, the team shorted each phase of the generator, and tested the back-drive force of the brake actuator. During wind tunnel testing, the team observed the most significant results from active pitching, as the hall effect sensors from the generator showed a dramatic decrease in RPMs. At a maximum wind speed of 22 m/s, pitching the blades brought the rotor to a complete stop within approximately five seconds of being engaged, proving to be very effective as the primary emergency stop mechanism (Figure 19). To test the generator shorting, the team used a motor driver to spin the motor and then shorted each phase while monitoring voltage output. During this test the team observed a voltage spike which could potentially exceed competition limits across the PCC. For this reason, the generator shorting will no longer be included in the emergency stop system. To test the efficiency of the mechanical brake, the team engaged the braking actuator, which has a neoprene brake pad mounted to it, against the rotor shaft while it was spinning at various speeds and measured the decrease in RPMs using the hall effect sensors. This test proved that the mechanical brake did not perform as effectively as the negative pitching at wind speeds over 10 m/s. For this reason, the decided to use negative pitching as the main mechanism for the emergency stop system and the mechanical brake as a secondary option.

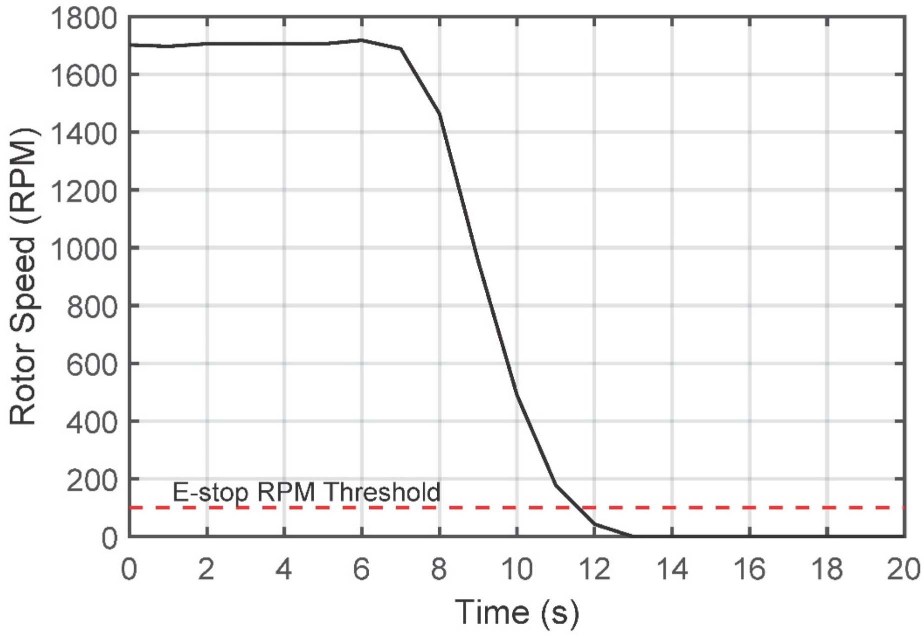


Figure 19: RPM vs Time for Emergency Stop

8. LOOKING FORWARD FOR FUTURE CU WIND TEAMS

Since CU is still relatively new to the CWC and the wind team competes as a single-year senior design team, there is a focus is to organize the team's data such that it's easily accessible for next year's team. The importance of clear documentation will make this transition seamless for the following years. Other ideas are being considered to make the team span across multiple years. The creation of a club has helped, but ways to hold members accountable and motivated need to be further clarified.

Furthermore, CU will dedicate an entire sub team next year to the development of a wind tunnel so proper testing can be conducted. This was one of the biggest challenges this year as a lack of consistent wind speeds required us to get creative to conduct full systems testing. Further development of testing capabilities would improve the team's turbine design significantly and help prioritize early testing and the optimization of the controls systems.

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