Pennsylvania State University Wind Energy Club

Technical Design Report

April 18, 2024

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EXECUTIVE SUMMARY

The following report describes the offshore wind turbine designed and built by the Penn State University Wind Energy Club for the 2023-2024 season. While the team found great success last year, this year there was much to improve. While we retained the two-blade design, the airfoil and chord/twist distribution of the turbine blades have been redone to optimize power at low speeds. A new generator was picked to complement the aero team's goal of optimizing power at low speeds, using the generator's low cogging torque and high efficiency. The electrical system follows the conventional design where a rectifier circuit inside the nacelle converts the three stage AC phase of the generator to DC before transmitting the DC power across a variable load through the Point of Common Coupling (PCC). While maintaining all functionalities present last year, the electrical circuit has been greatly simplified by replacing all 12V components with 5V. Software is used to unite all the sub teams with the safety tasks. Additionally, new feedback systems have been developed this year to enhance power production. Finally, the foundation team removed the screws from the design while maintaining similar strength reducing its overall weight, and the overall structure was better sized to the competition's regulations. Zinc galvanized plates were chosen to resist rust during testing in water.

INTRODUCTION

The PSU WEC's wind turbine design will fulfill five tasks: (1) produce stable power between 5 m/s and 11 m/s, (2) control the rated power and rotor speed, (3) shut down and restart automatically, (4) perform at wind speeds up to 22 m/s, and (5) withstand wind speeds up to 22 m/s, while securely anchored in sand by a lightweight foundation. The overall turbine concept is an upwind, horizontal axis, and two-bladed design. Five sections—aerodynamics, generator, electrical, software, and foundation—will detail the design, fabrication, assembly, and testing of the turbine prototype.

REPEATED DESIGN ELEMENTS & JUSTIFICATION

1. **Linear Actuators**: This year's linear actuators are the same make and model as last year's due to the part's reliability. There is also little difference between off-the-shelf linear actuators. Due to the voltage requirement needed to power the system and load required, the 6V linear actuators are best for this year's design because they need to handle a larger load.
2. **Rotor Hub:** The team is using the same rotor hub component (Align 700 from RC Tail Rotor) that secures the blades. However, a new rotor hub was purchased for this year's design and was eventually modified as described in the Pitching Mechanism subsection. The rotor hub was repurchased because off-the-shelf, small-sized rotor hubs with the ability to pitch are limited. Manufacturing a completely custom rotor hub was also not feasible due to limited machining tools.
3. **Tower & Base Plates:** The team is reusing last year's tower design (the steel rod that connects between the turbine and foundation) and base plate. Because the design requirements for both pieces are explicitly stated in the competition's rules & requirements, the team felt that redesigning the piece was unnecessary.
4. **Foundation Design:** The team is reusing a similar design for the foundation due to its favorable testing results, portability, and success in competition.
5. **45 V Buck Circuit:** The team is reusing the same 45 V buck design. A new PCB was redesigned and rebuilt for this competition.
6. **5 V Buck Circuit:** The team is reusing the same 5 V buck design. A new PCB was redesigned and rebuilt for this competition.

AERODYNAMIC DESIGN

The Aerodynamics sub-team identified several design objectives to optimize turbine performance. Since a two-bladed rotor design with a larger average chord reaches higher Reynolds (Re) numbers than a three-bladed design with a smaller average chord, the team improved the two-bladed design from previous years by refining the airfoil selection. First, designing blades capable of generating power at 5 m/s wind speeds was prioritized. Second, extending the range of possible pitch angles during operation was crucial to reach the turbine's ideal operating condition. Last, the nacelle was redesigned to house the new generator, minimize drag, and accommodate all necessary electrical components.

BLADE DESIGN, MANUFACTURING, AND ANALYSIS

To improve the blade performance in low Re number conditions (i.e. low wind speeds), designing blades that output power at 5 m/s wind speeds was the team's primary objective. First, last year's blade airfoil, the Ma-409, was compared to alternative airfoils. Considering parameters like maximum generator RPM (4000), blade radius (19.5cm), air density/viscosity, and the Re number as shown in equation (1), the team calculated

$$Re = \frac{\rho\left(\frac{RPM \cdot 2\pi R}{60}\right)c}{\mu} \tag{1}$$

That the rotor's ideal operating range is at Re numbers between 50,000 and 500,000. With this information, the team analyzed airfoils using the XFOIL program to find the optimal airfoil that would operate in this range. The FX-60100 was selected. A comparison of its performance to the MA 409 airfoil is shown in Figure 1.

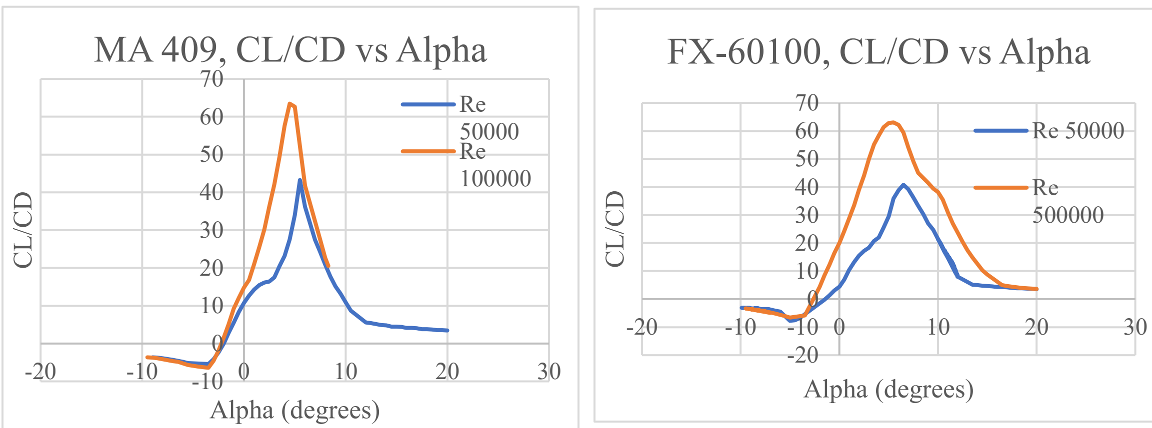

FIGURE 1: AIRFOIL COMPARATIVE ANALYSIS OF MA409 (LEFT) VS FX60100 (RIGHT)

Figure 1 shows that the MA-409 exhibits a steeper peak at its maximum CL/CD compared to the FX-60100, indicating a narrower operating range before the blades stall. Additionally, XFOIL could not converge for Re numbers above 100,000, suggesting that the MA-409 is an unsuitable choice at high wind speeds and high RPM. Figure 1 also shows that the FX-60100 airfoil has a smoother peak at its maximum CL/CD, allowing for a wider range of pitch angles before stalling. The FX-60100 was chosen because the team prioritized stability and a lower risk of stalling, which can enable blade rotation and power generation at lower wind speeds.

In the next phase of blade design, the team focused on optimizing the chord and twist distribution along the blade radius for a designated tip speed ratio (TSR). To accomplish this, the team used two programs: QBlade and Penn State's XTURB developed by Dr. Sven Schmitz, which generates and analyzes chord/twist data. First, the team analyzed three different tip speed ratio optimization designs in QBlade. Second, the chord/twist data was input into XTURB to observe its predicted performance under competition wind speeds.

Figure 2 displays XTURB's coefficient of power against TSR predictions for each of the three blade designs.

In Figure 2, different pitch angles were tested over a range of TSRs to determine the blade design that produces the largest power coefficient. A TSR of 4 performed the best with a peak power coefficient of over 0.35. This TSR thus became the final value for QBlade's chord/twist design optimization. Figure 3 displays the finalized blade design with a TSR of 4.

Like last year, the team decided to continue manufacturing the blades with Rigid 10K material through the Penn State Applied Research Laboratory (ARL) due to the material's stiffness and ability to withstand significant loads without bending. The stiffness of the blade is important as blade deformation can lead to unstable power output [1].

To determine the ultimate strength of the blades during operation, the team performed a rotor strength test by increasing the wind tunnel speed with an unloaded turbine through 11 m/s, changing the pitch angle, and gradually increasing the turbine RPM until the centrifugal force caused the blades to fail. With a weight of 94 grams, the blades were able to withstand forces up to 4,000 RPM until they broke at the hub of the blade (R = 1.9 cm). Using equation 2, the blades can withstand to be around 313 Newtons (70 lbs).

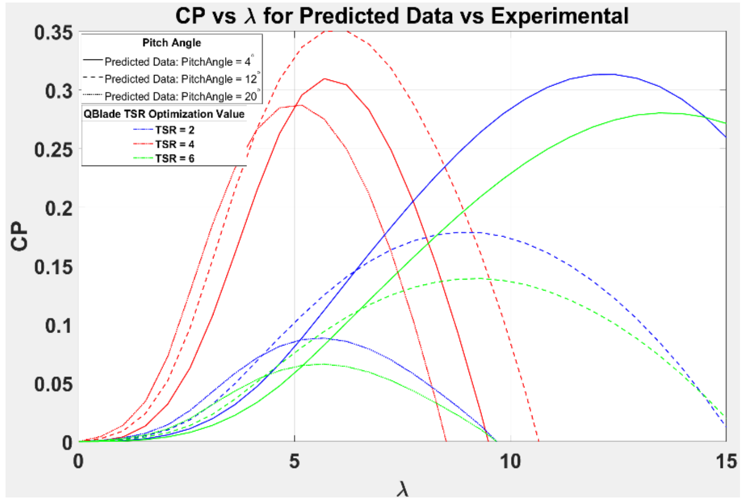

FIGURE 2: CP VS LAMBDA ANALYSIS FOR DIFFERENT QBLADE TSR OPTIMIZATIONS

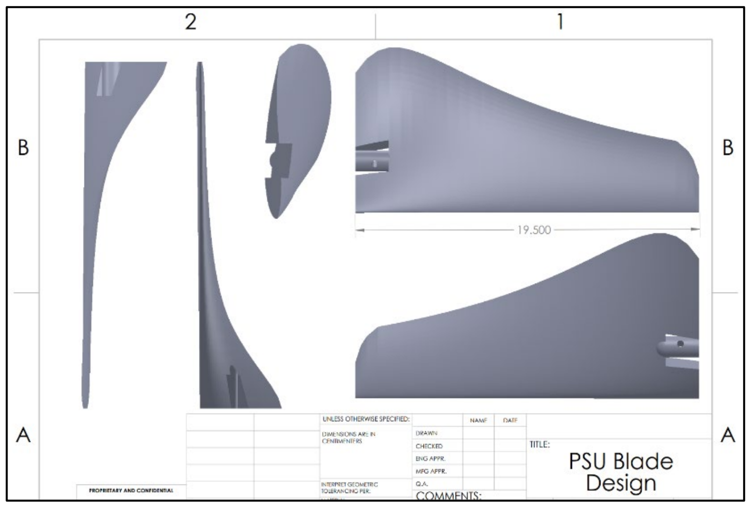

FIGURE 3: PSU BLADE DESIGN

$$Centrifugal\ Force = \frac{m\left(\frac{RPM \cdot 2\pi R}{60}\right)^2}{R} \tag{2}$$

The failure point on the blade, seen in Figure 4, verified a SolidWorks FEA simulation prediction. The point of highest strain was at the blade's connection point to the rotor hub, as displayed as in the red region of the 3D model.

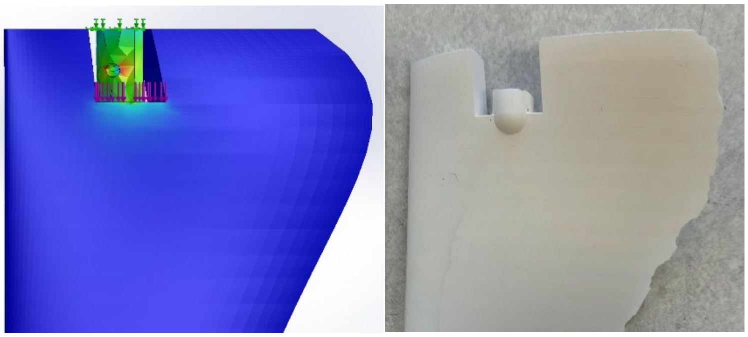

FIGURE 4: FEA FOR BLADE OPERATING CONDITION (LEFT), ACTUAL RESULTS (RIGHT)

Additionally, further finite element analysis (FEA) was conducted within SolidWorks to ensure that the blades can withstand 22 m/s wind speeds at parked conditions. First, a flow simulation was completed at 22 m/s to understand the blades' behavior under these conditions. Then, the results were imported to a static loading scenario to assess the von Mises stress values on the blade, utilizing the Rigid 10K material properties. The highest stress observed in the parked rotor condition while under 22 m/s wind speed was found to be 2.34 MPa, which can be seen in the red region on the blade in the left picture of Figure 5. This is significantly below the maximum yield stress of 126 MPa for Rigid 10K [2], therefore there is a large factor of safety with this material. Furthermore, to evaluate if blade deformation affects power output stability at these conditions, FEA was employed to predict blade deformation. The analysis revealed a maximum displacement of 0.256 mm at the tip, as shown in Figure 5 on the right. This minimal deformation is predicted to have a negligible impact on the stability of power generation.

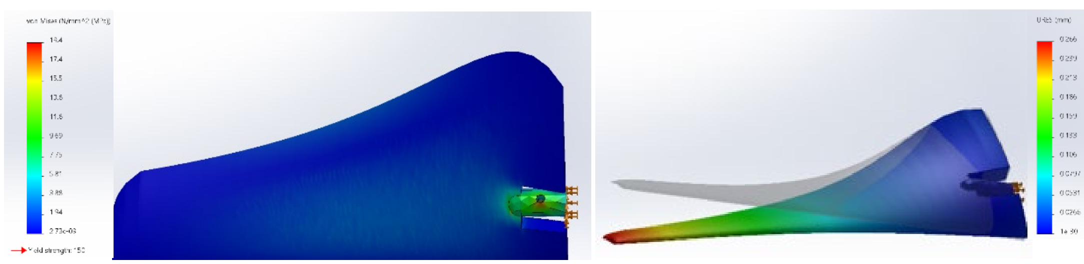

FIGURE 5: PREDICTED STRESS (LEFT) AND DISPLACEMENT (RIGHT) AT PARKED CONDITIONS

NACELLE DESIGN, MANUFACTURING, AND ANALYSIS

The nacelle design aims to be as compact as possible to minimize drag (therefore decreasing the moment generated on the foundation) and design a new plate, connecting the nacelle to the tower.

Drawing inspiration from last year's nacelle concept, the aerodynamics team opted for a bullet shaped design as shown in Figure 6. The bullet shape is known to have a low drag coefficient of around 0.295 [3]. The nacelle's internal volume is larger than initially expected because of the new generator design, the generator's mounting requirements, and ease of access for electrical debugging. A larger volume also made internal component failures easier to address during wind tunnel testing.

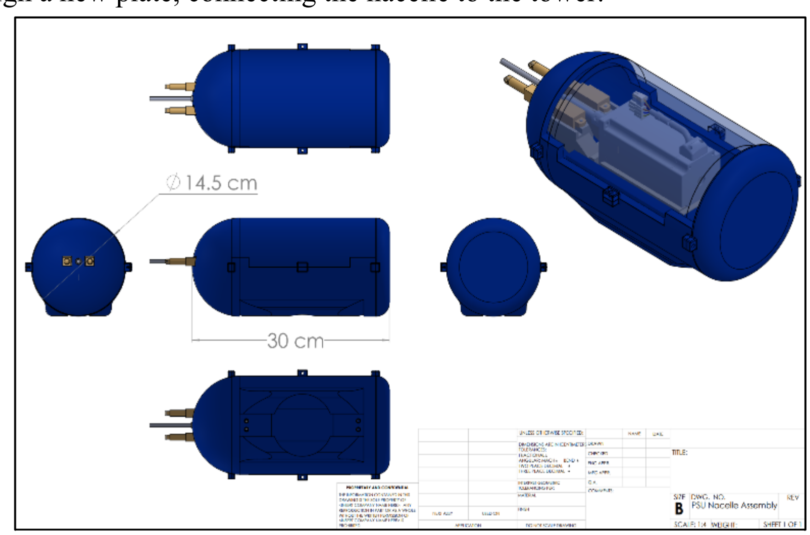

FIGURE 6: PSU NACELLE ASSEMBLY

In compliance with the no re-use rule, the yaw plate was redesigned to be a fixed piece, eliminating the need for a tailfin and further reducing the turbine drag. Figure 7 shows the fixed yaw plate which was designed in SolidWorks and 3D-printed with ABS material for high stiffness. Two screws connect the plate and the tower.

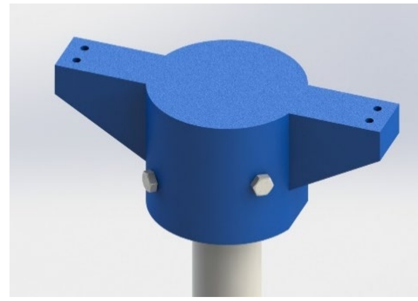

FIGURE 7: FIXED YAW PLATE DESIGN

Pitching Mechanism

For the past several years, the team repurposed an RC Helicopter Tail rotor (Align 700) for the blade hub and pitching mechanism. This year, the aerodynamics team decided to repurchase the same rotor for the final design. This decision was discussed in the Repeated Design Elements & Justification section. Using two linear actuators, the team implemented this tail rotor system to adjust the blade pitch angles during wind tunnel operation. While the device accurately pitches the blades to different angles and maintains them during operation, its operating range is limited because it would jam, requiring manual intervention. This limitation posed major challenges during wind tunnel testing, particularly in the rotor control and safety tasks. With the current configuration, there was no way to pitch the blades toward the wind to create a negative angle of attack, which is needed to stop the turbine.

To address this challenge, the team re-engineered the RC Helicopter Tail rotor, extending the mechanism's pivoting arms to achieve a broader range of pitch angles. This redesign is shown in Figure 8. The arms were designed in SolidWorks and 3D printed using ABS material for optimum strength. Extending the arms successfully expanded the pitch angle range from 48 degrees to nearly 100 degrees.

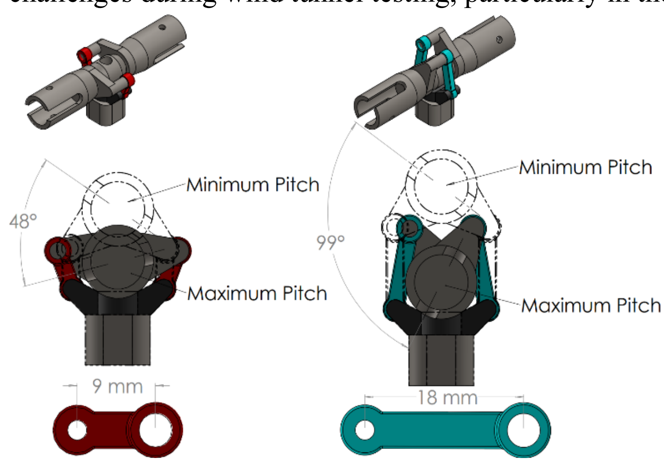

FIGURE 8: OLD PITCHING MECHANISM (LEFT), NEW PITCHING MECHANISM (RIGHT)

Generator Design

The generator and mechanical sub-team identified several design objectives aimed to enhance the viability of the turbine. The first objective was to choose a new generator. Because of the no-reuse rule, the team was forced to cease using the homemade axial flux generator that was used for years. The second objective was to integrate a new generator into the turbine system, requiring a mechanical system able to maintain stability at high rotation speeds. With a new generator, the team prepared for wind tunnel testing by performing preliminary testing and computational analysis.

Generator Choice

The team had to first decide whether to purchase an off-the-shelf generator or remake the previous year's generator with modifications. Although the old generator design was effective, the team decided that manufacturing a new generator would be too time consuming. Buying a generator allows for more time to test the generator and overall performance of the system.

The team chose the Lin Engineering BL23E48-02 motor, which is a brushless DC motor with a rated voltage of 48V and a rated speed of 4000 rpm. The main parameters considered during selection were the torque constant and back EMF constant. These are motor constants that specify a theoretical output torque and rotational speed for an input voltage and current, respectively. Since the blades were to be designed for the chosen generator, it was difficult to find an input torque and rotational speed that would be accurate to this year's competition. Torque and speed values from previous years were used as estimates. Around seven motors of different sizes were considered with the estimated torque and rotation speed values and before the Lin Engineering BL23048-02 was chosen. The motor was favored in part because of its internal hall effect sensor. Last year, the team struggled to manually install a hall effect sensor. A reliable sensor allows the team to gather real-time RPM data, increasing the accuracy of the optimal pitches and load resistances at different wind speeds.

PREDICTIVE MECHANICAL SYSTEM ANALYSIS

The generator team investigated how the new generator would affect the mechanical system. This analysis was crucial because it informed the aerodynamic and electrical design teams as prototyping progressed.

The team began testing the generator on a dynamometer to fully understand the generator's efficiency at different speeds and resistances. The resulting power curve is shown in Figure 9. It was understood that the efficiency of the generator, and thus the slope of the power curve, would continue to increase until it reaches its rated power. Thus, the system's ideal operating range is 3000-4000 RPM.

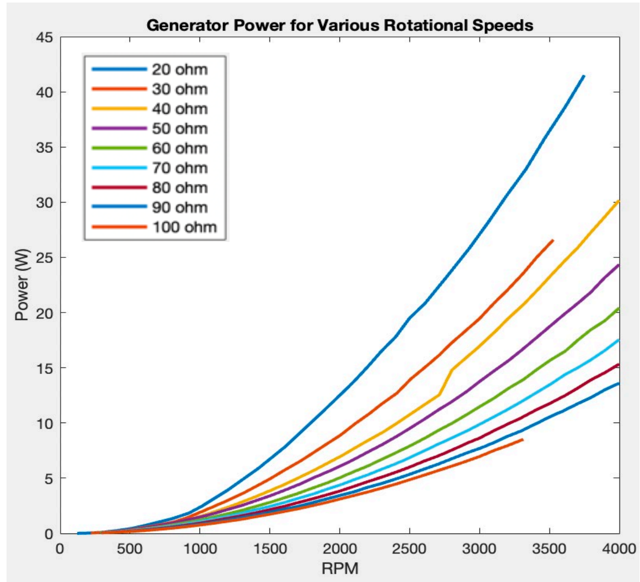

FIGURE 9: GENERATOR DYNAMOMETER DATA

In addition to the power testing, an experimental analysis of the generator's cogging torque was done, as shown in Figure 10. Cogging torque is the interaction between the permanent magnets of the rotor and the various coils in the stator. It is a mechanically resistive force that is present during start up and at low wind speeds. The team tested the required torque for the dynamometer to begin turning the generator and determined that the cogging torque is constant and does not depend on electrical resistance. This determined the generator's mechanical cut-in speed.

While the dynamometer tests revealed the behavior of the power at different rotational speeds and load resistance, they did not reveal the behavior of the rotational speeds at different wind speeds. Therefore, it was unknown whether the generator could produce power at 5 m/s. A combined analysis of the Cp-λ plots generated by XTurb and the generator power curves were used to predict this startup position as well as

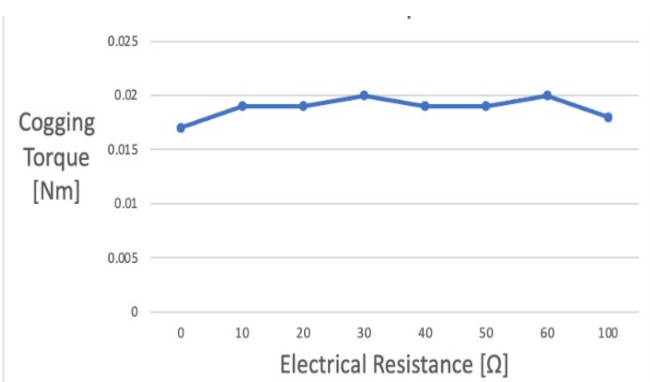

FIGURE 10: GENERATOR COGGING TORQUE EXPERIMENTAL ANALYSIS

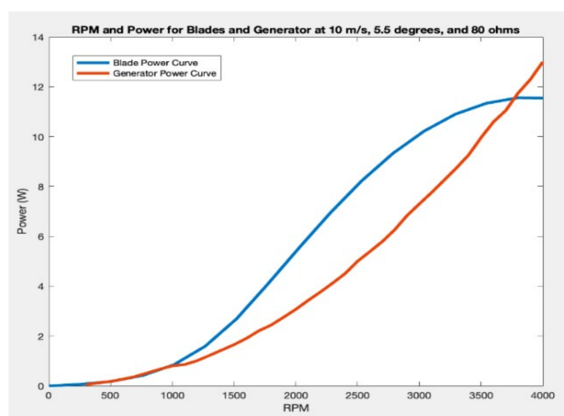

FIGURE 11: GENERATOR AND BLADE DIMENSIONALIZED POWER PREDICTIONS FOR OPTIMAL PARAMETERS AT 10 M/S WINDSPEED.

optimal pitch and load resistance values for the entire range. A script was written in MatLab to redimensionalize and plot graphs for a specified load resistance, wind speed, and pitch angle. These plots were predictive and used to inform wind tunnel testing. An example of the predicted optimal configuration for 10 m/s windspeed can be seen in Figure 11.

In addition to the C_p-λ plots, C_τ- λ plots were also analyzed. These were used to predict the mechanical cut in of the blades and ensure that they could overcome the cogging torque. Using the XTurb data, torques for each wind speed and pitch angle were calculated for the condition of 0 rotational speed. This data is seen in Figure 12. The relation between torque and windspeed was plotted for various pitch angles. The experimentally found cogging torque was also plotted as a horizontal line. The data predicted the pitches to have near identical torques at low windspeeds. Mechanical cut in was predicted to occur when the blade torque curve crosses the cogging torque line—around 3 m/s. However, because of mechanical friction, the turbine was ultimately expected to begin movement between 3 m/s and 4 m/s.

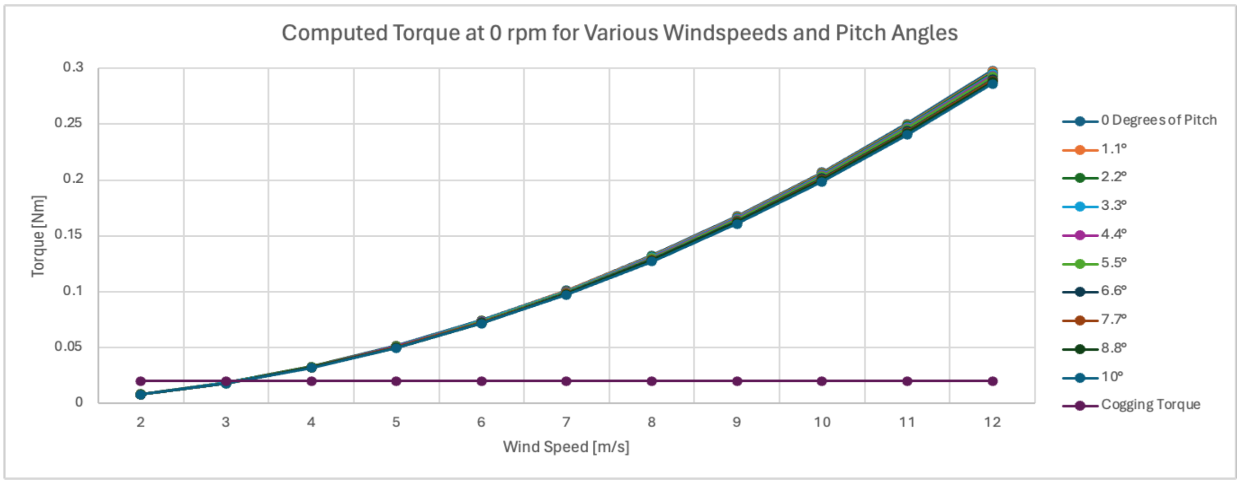

FIGURE 12: TORQUE FROM BLADE STAND-STILL AT VARIOUS WINDSPEEDS AND PITCH ANGLES VERSUS EXPERIMENTAL COGGING TORQUE

ELECTRICAL DESIGN

The electronics sub team focuses on delivering the power generated by the turbine to a usable and measurable DC power at maximum efficiency and safety. The team establishes proper communication between the controller and the rest of the turbine design which controls parts of the circuit including the variable load, PCC disconnect, and the transition from start up to a stable power generation stage.

CIRCUIT COMPONENTS

The circuit consists of four major parts: Rectification, 45V Buck Converter, 5V Buck Converter, and Variable Load. The generator outputs a 3 phase signal due to the brushless DC architecture of winding which is converted to DC power ranging from 5V to 60V through the rectifier. Under normal operation, power bypasses the 45V Buck Converter. When the generated voltage exceeds 48V, the 45V Buck Converter is turned on via relay, ensuring the safety of the rest of the electrical system. In the rare case of generated voltage exceeding 60V, the system should shut off. The 5V Buck Converter provides a stable 5V DC source for the electrical components to function properly.

To complete the control system, several voltages such as generator voltage, PCC voltage, and load voltages are measured by the controller. Because the controller can only read voltages ranging between 0V to 3.3V, the design incorporates voltage dividers for each of the signals. Resistor values are selected to drop a maximum of 60V down to 3.3V.

The Variable Load is built upon a composition of four fixed resistors of resistance 10Ω, 20Ω, 40Ω, and 80Ω, with an additional10Ω resistor to prevent a short circuit. Four relays are connected in parallel with the first four fixed resistors, allowing the system to adjust the load resistance every 10Ω between 10Ω and 160Ω with each relay-resistor pair operating independently. The turbine power generation is determined by the load voltage and the load resistance.

Optimizing the PCBs

The electronics team greatly improved the design from previous years with a focus on simplicity and functionality. After some careful parts selection, the team eliminated all electrical components that required a 12V DC source, eliminating a major part of the previous year's circuit design—the 12V Boost Converter. The elimination of an extra IC component reduces the power consumption of the circuit and improves the efficiency of the electrical system.

The team also realized the complexity and difficulty in assembling the final product due to the number of signals needed in the control system. Instead of wiring the controller separately through several terminals, the new design incorporates the controller as part of the load circuit. With this update, the design was able to remove all the free wires coming out from the controller, making the connection more stable and consistent. The new, simplified PCB's can be seen in Figure 14.

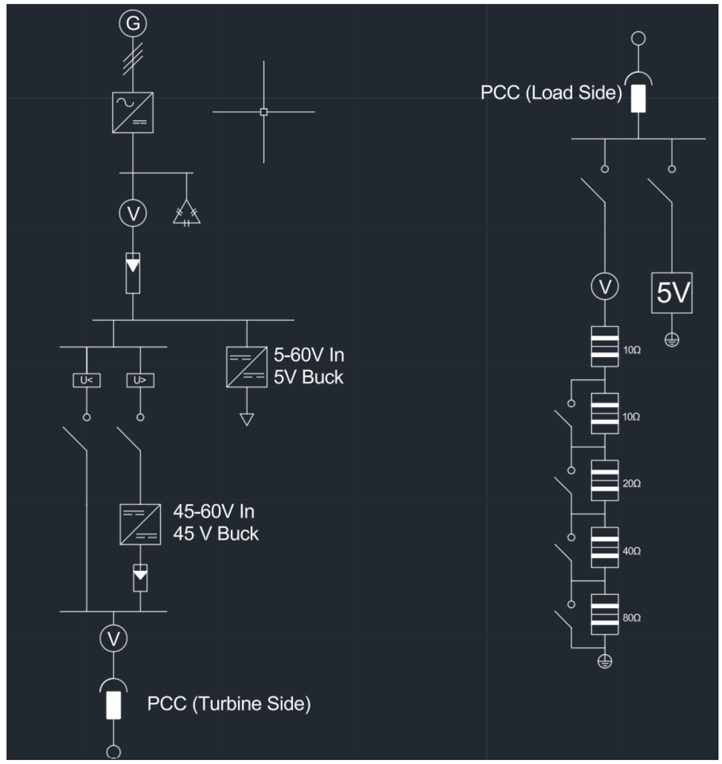

FIGURE 13: SINGLE LINE DIAGRAM

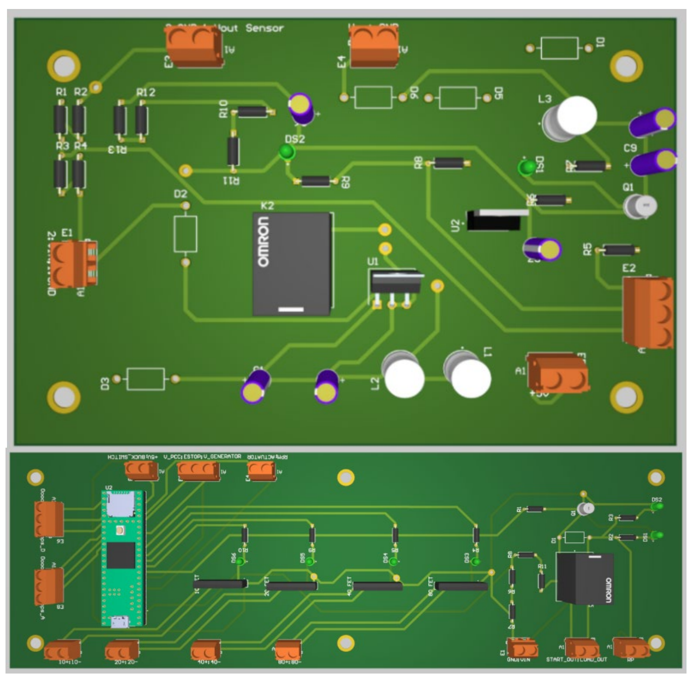

FIGURE 14: CONTROL (TOP) AND LOAD (BOTTOM) PCBS

Software Development

The software maintains wind turbine safety and augments the performance of the turbine by optimizing the turbine's pitch angle and load during operation. Each electrical component was defined as a software module and prototype using a breadboard while constructing the electrical PCB. Representing each hardware component as a separate module, interactions between the different modules were prevented, creating a more user-friendly and maintainable codebase. Individual models also allowed the team to work on multiple parts of the program at once which sped up the development process. The team used git and GitHub to collaborate on software development.

Hardware And Code Architecture

The Teensy 4.1 supported the Arduino libraries that the team normally uses, saving time on development. The Teensy 4.1 is a simple board; however, it accomplishes the required tasks extremely well. Boards like the STM Nucleo have more advanced features such as hardware timers, but they also introduce an extra layer of complexity for very little gain. With the microcontroller decided, the team decided to stay with our state machine architecture due to its simplicity and efficiency. State machines have a much lower memory usage compared to multithreading. State machines can also avoid the overhead of thread management, which requires significantly more resources for memory and processing power.

Each hardware component of the turbine is as a software module with each module designed to execute specific tasks corresponding to the turbine's different operational states: startup, looping, and stop. The turbine's state is determined based on sensor data. The independence of each module The whole turbine is then represented as a state machine where the states are initialized, startup, power curve, rotor speed, durability, and stop.

Deep Dive into States

Figure 15 visualizes the turbine states. The states are described in detail below.

Initialize: This section of the code will only run once during the turbine's runtime. This state is responsible for configuring all the ports on the microcontroller and initializing variables. Immediately after the code in this state runs, it will transition to the startup state.

Start Up: This section of the code runs continuously while the wind turbine cannot produce more than 5V—the needed voltage to turn on all electronics. Here, the turbine will use wall power and pitch the blades to the optimal angle and optimal load. PCC disconnect and emergency stop detection also runs. If either is detected, the turbine will transition to the stop state. Once 5V is detected, the turbine will transition to the power curve state.

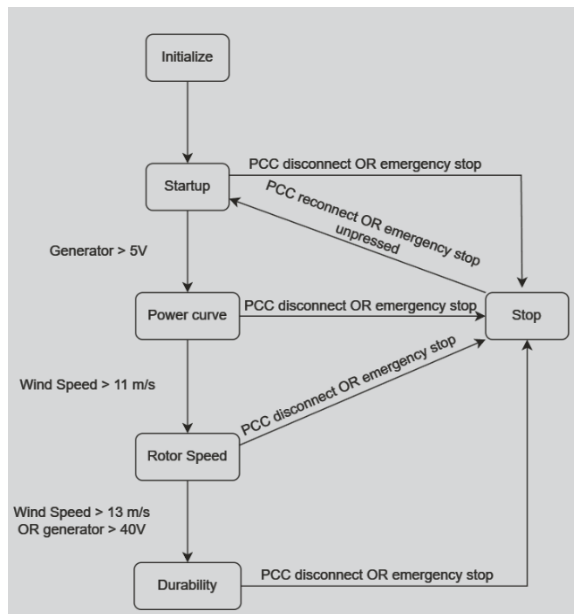

FIGURE 15: STATE DIAGRAM

Power Curve: This section of the code will run if the wind speed is detected to be 5-11 m/s. We determine wind speed by our RPM sensor. Pitching angle and load are adjusted to optimize power production. From testing, the team found the optimal pitch angle and load at every wind speed. From here, a cubic spline interpolation is generated, as shown in Figure 16. The load is only changed at every m/s change of wind speed (5,6, etc), where the pitch angle keeps changing as a function of RPM. The code continuously finds the RPM and inputs the RPM value into the cubic spline to calculate the optimal pitch angle.

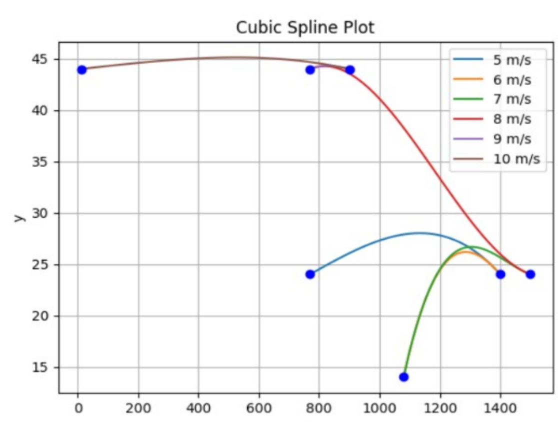

FIGURE 16: CUBIC SPLINE PLOT

Rotor Speed: At a wind speed of 11 m/s, the RPM will be continuously recorded once rotor speed starts. The pitch angle and load are set to its optimal point at each wind speed; however, variation can still occur that causes changes in RPM or power production. A proportional integral derivative controller is used to maintain the target RPM. By inputting the current RPM, the turbine will make corrections to match the target RPM found at the 11 m/s RPM.

Durability: Once the turbine enters rotor speed and the generator is making more than 40V, the turbine enters durability. From here, generator voltage is set between 10V-15V for sustainability. Using predetermined load and pitch angles, the pitch angle can be adjusted if the generated voltage falls below 10V or rises above 15V. The blades are kept close to the stopping pitch angle to minimize damage.

Stop State: The turbine transitions into stop state if the emergency stop has been pressed or if there is a significant voltage difference between the load and the generator (PCC disconnect). If the stop state was triggered by the emergency stop, it will wait until the button is unpressed before moving back to the startup state. If it was a PCC disconnect, the program waits for the PCC voltage to rise above a determined threshold before moving back to the startup state.

Data Collection

Data was collected during development and testing through an internally made tool called Houston. Starting last year, Houston displays, graphs, and saves data transmitted from the turbine. Houston also allows a user to change turbine values like pitch angle without reuploading the code. Houston has been rewritten this year to improve user experience. One of the main goals of Houston is to allow non-software sub-teams to control the turbine, test, and acquire data without needing extensive programming experience.

Foundation Design

The Foundation sub-team's design objective was to create a lightweight foundation that is feasible to manufacture and achieves little deflection under load. The team decided to renew last year's box-shaped design because the shape best operates within the competition's sizing requirements. The team identified the successful components and removed extraneous components to reduce weight. Finally, the team tested the foundation to ensure a safety factor under the calculated maximum stress with conditions like the competition scenario.

Foundation Construction

The team decided to continue with the successful egg crate design but determined the sand screws added an insignificant amount of security compared to their weight. Overall, the design philosophy was to implement several small changes during reconstruction of a similar design to lower the weight while maintaining a safety factor of 1.7-2. To achieve this, 8 zinc galvanized mild steel plates were used for their corrosion resistance and machinability, as seen in Figure 17. Inlets were cut into the plates, so they could interlock into two concentric boxes. The angle brackets and flange were remade to connect the system components. The new base plate is mounted onto this egg crate structure through bolted angle brackets. The improved design was determined to maximize surface area parallel with the turbine to generate as much friction as possible.

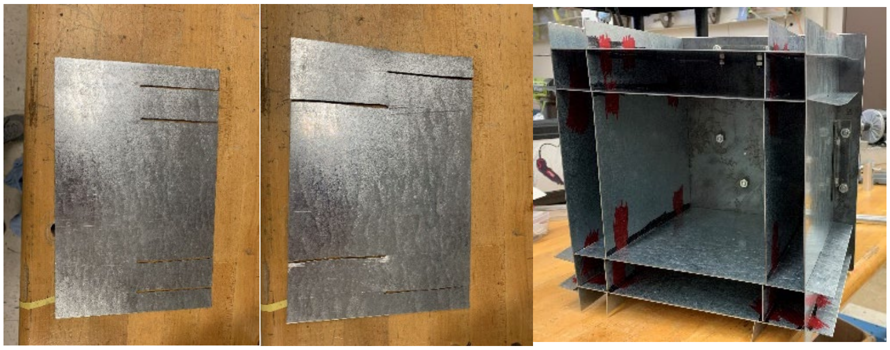

FIGURE 17: FOUNDATION CONSTRUCTION

Foundation Testing

The foundation was tested, as shown in Figure 18 as close to competition conditions as possible. It was measured to fit within the 30 by 30 by 20 cm competition requirement and weighs 6.17 kg. Multiple installations were completed. The average installation time was just under 12 minutes. Once installed, the strength of the foundation was tested via applying a moment to the tower. Weights were added to a pulley that applied a moment to the foundation, as seen in Figure 18. We calculated the maximum thrust force on the turbine to be ~35N. Using the estimated distance between the centerline of the wind tunnel and the top of the sand as 95 cm, the maximum predicted moment was 33.22 N-m. Failure was determined when the tower shifted over 2.5 cm. During testing, the foundation sustained well over the predicted max moment, and testing was stopped at a moment of 94.91 N-m due to testing equipment concerns netting at least a safety factor of 2.85 for the final foundation.

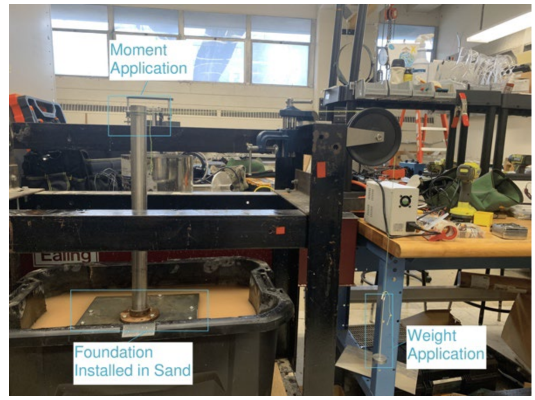

FIGURE 18: FOUNDATION TESTING

Commissioning Checklist

TABLE 1: TURBINE TESTING COMMISIONING CHECKLIST

Turbine Testing Verification Procedure	Team Lead #1 Certification	Team Lead #2 Certification
Aerodynamic Subsystem Verification Steps		
Check linear actuator connections		
Calibrate linear actuators		
Make sure all screws in nacelle have nuts/hex screws		
Place set screws into yaw plate/foundation		
Make sure blades are facing correct direction for clockwise rotation		
Generator Subsystem Verification Steps		
Make sure generator is secured to generator seat		
Place set screws in coupler and axel		
Make sure bearing piece is in place		
Electronics Subsystem Verification Steps		
Check continuity of signal wires and GND wires		
Test actuators		
Check connections inside the Nacelle		
Check voltage at +5V and make sure it is 5V		
Test Teensy sensors		
Foundations Subsystem Verification Steps		
Make sure all nuts are fully tightened to bolts		
Ensure electrical connections are above water level		
Make sure top foundation plate is leveled with sand		
Make sure tower attachment is tightened fully with set screws		
Make sure tower is within 10 cm center diameter		

Final Design

The following subsections details complete turbine assembly instructions and a commissioning checklist to ensure wind tunnel readiness. To successfully design and manufacture the turbine, five sub-teams were created: aerodynamics, generator, electrical, software, and foundation. Each team was responsible for the design, manufacturing, and assembly of their associated turbine components.

Turbine Assembly

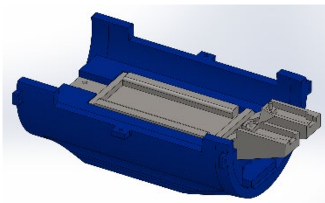

FIGURE 19

Step 1: Insert the electrical cable through the bottom of the nacelle to internal circuit board is.

Step 2: Insert the generator seat into the designated slot of the nacelle, with two zip ties placed underneath the generator seat before placing into the slot, shown in Figure 19.

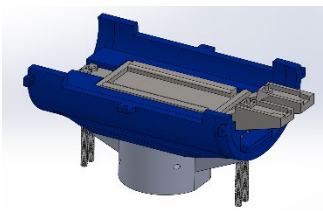

FIGURE 20

Step 3: Place the current nacelle state onto the yaw plate, and screw in all designated screws for the four holes on the generator seat. Make sure a hex nut is placed on the bottom of each screw, as displayed in Figure 20.

Step 4: Place generator and linear actuators onto the generator seat, tying the zip ties around the generator for increased stability, shown in Figure 21.

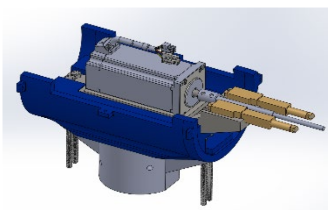

FIGURE 21

Step 5: Connect all wires from electrical cable, linear actuators, and generator to the circuit board attached to the back of the nacelle.

Step 6: Confirm connections are good (Linear actuators work, power can be read, etc.)

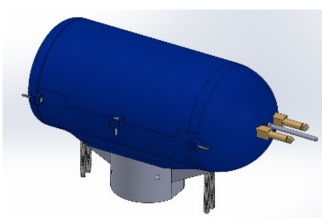

FIGURE 22

Step 7: Put nacelle front, back, and lid onto the nacelle. Make sure all designated screws are tight and each has a hex nut, shown in Figure 22.

Step 8: Attach pitching mechanism and blades.

Step 9: Place tower into yaw plate, and place in set screws.

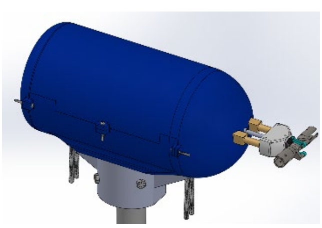

FIGURE 23

Step 10: Place on Foundation

Step 11: Ready for testing

EXPERIMENTAL RESULTS

As shown in Figure 24, early turbine testing suggested that more power was generated than what was initially predicted from the PSU XTURB program. After testing at low wind speeds and a load of 90 Ω, the team needed to decrease the turbine RPM by decreasing the load because the blades experienced a structural failure at 4000 RPM during free spin. To mitigate the risk of failure during testing, it was essential to maintain the low RPMs. Knowing the challenges of determining the attachment of airflow to low Re number airfoils, the team opted to operate the turbine at approximately 75% of the failure limit, providing a buffer time for intervention and preventing continued acceleration. After doing this, the team decided to retest the lower wind speeds at a lower load and found that similar RPMs were obtained, and the turbine produced even more power. This gave the team high confidence in the turbine's capabilities to produce power at all wind speeds tested during the competition.

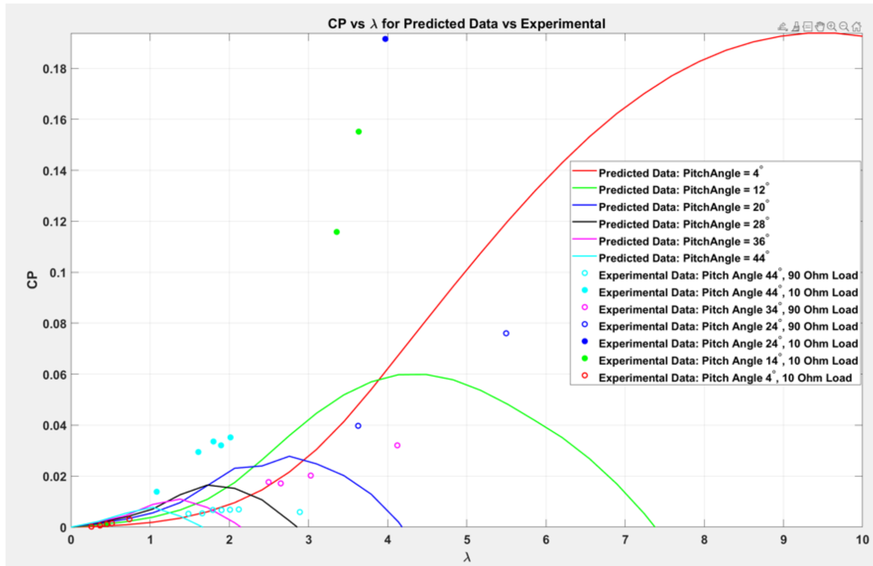

FIGURE 24: EXPERIMENTAL VS PREDICTED RESULTS

ANNUAL ENERGY PRODUCTION

To calculate the annual energy production of the turbine, first simulated data from PSU XTURB was used to estimate the power generated by the turbine between 3 m/s to 25 m/s, as displayed in Figure 25 on the left. After this, using a shape factor of 2, a Weibull distribution for each average wind speed from 3 m/s to 9 m/s was generated, and the annual energy was calculated. Displayed in Figure 18 on the right is the annual energy production in units of kilowatt hours for each annual average wind speed.

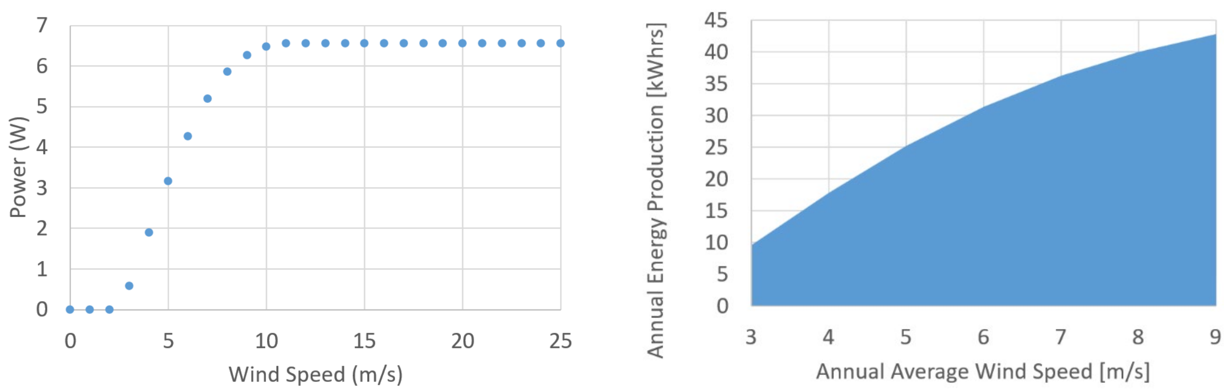

FIGURE 25: TURBINE POWER CURVE (LEFT), ANNUAL ENERGY PRODUCTION (RIGHT)

References

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