Technical Design Report

Submitted to

2020 Collegiate Wind Competition

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1.0 Executive Summary

In this 2020 Technical Design report, the Pennsylvania State University Wind Energy Club details the design of the test turbine developed for the 2020 Department of Energy Collegiate Wind Competition (CWC). For the 2020 CWC, as altered by the COVID19 pandemic, the Penn State Wind Energy Club has been tasked with designing a small scale, functioning wind turbine which meets specifications outlined in the CWC 2020 Rules and Requirements[i]. The turbine has been designed to complete a set of defined tasks, which include cut-in wind speed, power curve performance, safety, control of rated power and rotor speed, and durability and cut-out wind speed. The test turbine is shown in Figure 1.

Section 2 of this report, Technical Design, walks through the Penn State team's approach to the constraints and design objectives outlined by the CWC 2020 competition. This section then goes on to cover the specific design considerations used in the aerodynamics, generator, and electrical systems, respectively, and how these systems work together. The aerodynamics section then walks through the design and analysis of the turbine's rotor blades and tailfin as well as the structural considerations in ensuring their safe operation. The rotor blade hub and rotor strength test deliverable is also discussed. Next, the generator design is covered, including an overview of the generator, the structural design of the turbine nacelle, and the implementation of linear servos. Finally, the electrical system is detailed, which includes the summary of the control and load boxes as well as descriptions detailing the control logic, variable load design, and power quality considerations. Section 3 covers the wind tunnel testing already completed, as well as wind tunnel testing that was planned prior to the COVID19 pandemic. The objectives of the wind tunnel tests are explained as well as how the results would be used to improve the turbine design. Section 4 concludes the technical report, recapping some important details and considerations for this year's turbine design.

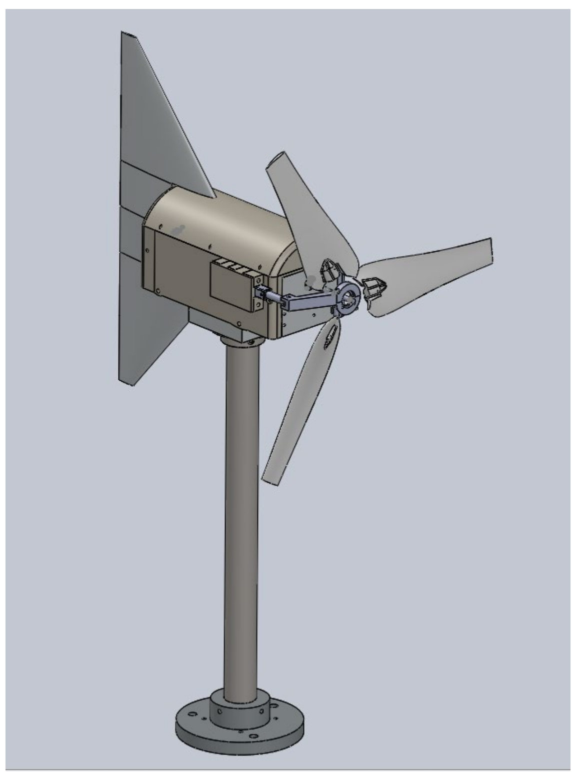

Figure 1 CAD Drawing of the 2019 - 2020 prototype PSU Wind Energy Club Test Turbine.

2.0 Technical Design

A wind turbine is composed of several main subsystems which serves to convert the power in the wind into electrical energy. In particular, the blades, the generator and the electrical systems must each be designed to work well in any given operating conditions and they must also function optimally as a system. In this application, the test turbine and its subsystems must be designed and optimized to best complete competition tasks.

For a turbine of the scale required for the competition, blade aerodynamics and component synergy can be quite tricky. A particular challenge in subsystem optimization is that the differences between theoretical and actual performance of the electrical system can yield poor or highly unexpected results. Oftentimes, this is because components are operating in non-ideal conditions or at the limits of their operating ranges. The subsequent difference between expected and actual performance in these subsystems demonstrates why their design must be well developed and also why testing must be done to ensure they function together as expected. The circumstances surrounding this year's competition make ensuring proper function of the turbine design almost impossible, however an effort has been made in earnest to develop an effective and functional design.

2.1 System Design Objective

The objective of design for the test turbine of the competition is to achieve the highest possible score in the Collegiate Wind Competition according to the tasks outlined in the Rules and Requirements[1]. For 2020, in light of limitations brought by the outbreak of COVID19, test turbine construction and testing tasks were not able to be completed. The systems and elements in the turbine, however, were still designed in preparation for a physical competition. These test turbine systems and elements were designed to fulfill the tasks, as detailed by the Rules and Requirements, and also with consideration for the wide range of operating conditions expected in the competition.

The turbine is controlled by two means, a variable resistance load and active blade pitching. The design of both the generator and the rotor provide the system the physical capabilities for this control, while the electrical system executes the commands to achieve the desired output for a given task. These subsystems must perform well individually while also functioning together as one cohesive unit to achieve the intended results. Additionally, the structure of the system must be robust, able to withstand the forces anticipated during test operation at wind speeds up to 25 m/s.

2.2 Blade Design Objective

Computer analysis was used to reassess and refine the blade design for the 2020 CWC competition. An in-house Excel program uses blade-element momentum theory for blade design, and it allows us to analyze some key characteristics for the blade. XTurb-PSU[2], a wind turbine lifting-line theory aerodynamic analysis tool, was used to analyze the designed blades by generating data about the rotor performance and efficiency. Using the tools mentioned, the team designed blades that integrate with the generator by producing more torque than what is required by the generator to start.

For the 2020 CWC, the aerodynamics team reassessed the strength and performance of the previous design based on the Wortmann FX 63-137 airfoil. Through previous research with alternative airfoils, the Wortmann FX 63-137 has proven to achieve superior performance for the test turbine scale, even in high wind speed conditions. The following sections on design and analysis, 2.2.1 through 2.2.3, describe the general techniques used to produce the blade and also detail the exploration into high wind speed blade performance and stability.

2.2.1 Aerodynamic Blade Design

This section will discuss the process used to design and select the test turbine blades. The design is done so using the aforementioned, in-house Excel blade design code. It uses blade-element momentum theory to calculate the aerodynamic forces by discretizing a projected turbine blade into thirty-one radial points. The program then uses known data about the airfoil, specifically the lift and drag coefficients (C_L and C_D) which are obtained through MIT's XFoil[ii]. The generated blade design from this program can be done with three variable parameters for a given blade radius: choice of airfoil, chord distribution, and twist distribution.

The Wortmann FX 63-137 airfoil, as shown in Figure 2, was selected based on previous operating conditions and torque requirements for the generator. The program can use a specified radius for the blade and the desired airfoil, which then optimizes the chord and twist distributions to obtain the optimum axial-induction factor. To optimize the score for the performance aspect of this test turbine, the design process maintained a constant wind speed of 8 m/s for our blades. In years past, the team has gone through different test turbine design iterations that define the design tip-speed-ratio (TSR). The TSR then dictates the design RPM. For the test turbine, the control system is achieved through an active pitch of the rotor blades. By changing the pitch of the blades, the turbine is in control of the power and rotor speed.

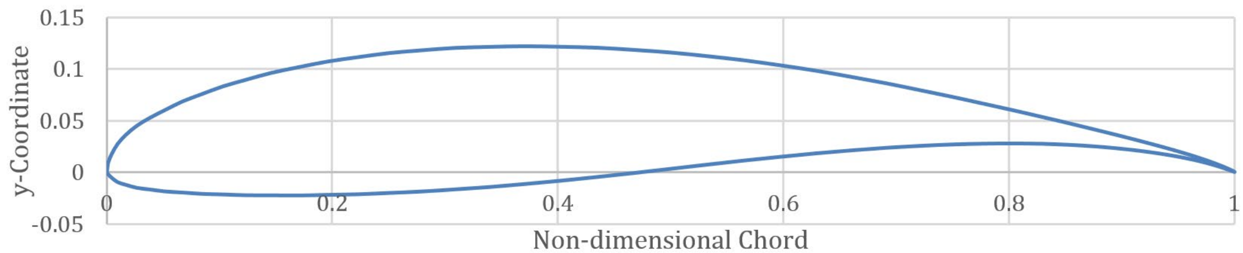

Figure 2 Wortmann FX 63-137 Airfoil.

In addition to the in-house Excel code, XTurb-PSU was also used to calculate the rotor power output as a function of TSR and wind speed. The XTurb design analysis will be further described in section 2.3. Important output parameters for the rotor design include the torque and power coefficient (C_p). Although increasing C_p is the focus, matching the torque produced by the blades to that required by the generator is vital for the system to function effectively. The relationship governing the torque required to spin the generator at a given RPM as well as load resistance was determined through dynamometer testing. Once it has been verified that the rotor will produce sufficient torque to drive the generator, the effectiveness of the blade design is assessed by the C_p value. The design process becomes an iterative procedure to achieve sufficient blade performance. Figure 3 shows the final chord and twist distributions for the blade design.

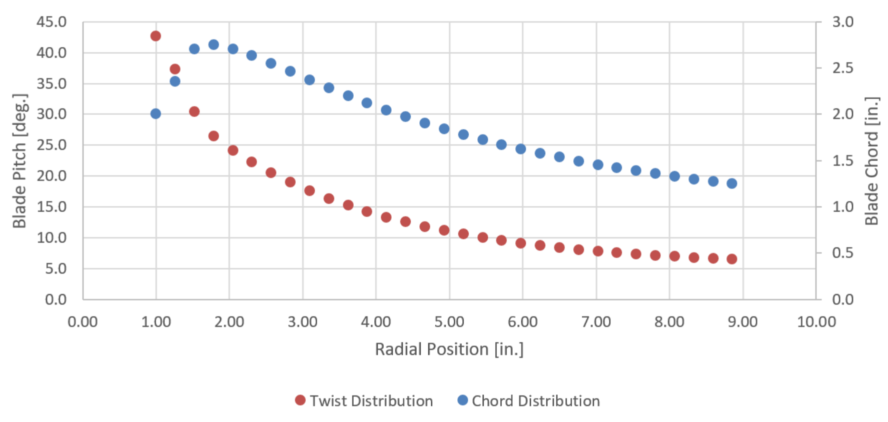

Figure 3 Blade chord and twist distributions.

2.2.2 Aerodynamic Blade Analysis

The goal of analyzing and testing the wind turbine blades is to find the optimal pitch angles that maximize the amount of power the turbine generates at each wind speed. XTurb-PSU[iii] was used to perform this analysis. The software runs a specified blade geometry for a set of input conditions and outputs the blade performance characteristics. The input file requires different sets of data that include the blade geometry, airfoil performance, operating conditions, and wind speed. The blade geometry is defined by the chord and twist distributions along the span of the blade. Airfoil performance is specified along the blade span based on the local Reynolds number. The code allows the pitch to be set thus allowing for analysis through a sweep of pitch angles. This process is used to determine the ideal aerodynamic pitch angle at each wind speed.

Upon running the XTurb code, output files are generated which provide performance values, including rotor torque, C_p, C_L, C_D, and Reynolds number, for each operating condition. These values are used to fine tune the input airfoil performance tables. The main values of interest, in terms of performance, are C_p and torque.

The blade was analyzed to ensure cut-in before a wind speed of 2.5 m/s, below which no additional points are awarded as per the rules. The turbine does not produce enough power to actively pitch the blades at cut-in wind speeds. The generator team performed static torque testing to find the minimum torque required to cut-in. The aerodynamics team then used this data to determine the optimal pitch to achieve the required start-up torque at a low wind speed. The turbine is set at that optimal angle of attack for startup, such that it provides a low cut-in wind speed and can operate at a low TSR long enough to power the pitch activation for the blades. The blades have been analyzed in XTurb for two separate cases, a case where the blades are spinning just as fast as the incoming wind, and a case for the parked blade, where the blades are not yet spinning. By investigating the torque output in these two cases, the optimal starting pitch was determined to be 41°. At this pitch, the blades can operate for startup and while producing the torque required to power the generator.

Given the increased wind speeds of up to 25 m/s, the C_P was then analyzed for the wind turbine runaway conditions. The team must determine the projected TSR for a runaway condition to occur. In the case of a runaway turbine, the generator load is lost, and the blades are left to spin on their own. XTurb was used to identify the optimal pitch for the system immediately before losing the active pitch control. This is done under the assumption that the generator will actively pitch the blades until runaway. Given that the runaway conditions will occur at a high wind speed, the blades were analyzed at 25 m/s for the pitch where C_p is maximized. The blade pitch was found to be 10.5°. This pitch was then held constant as the team ran an iterated process to determine the max C_p at every relevant TSR as shown in Figure 4. It can be observed that from our C_p-λ curve, our turbine approaches runaway conditions past a TSR of 7.5. The team considered methods of determining the characteristics of the turbine for the given TSR, but without concrete assumptions, it was difficult to ascertain an ideal RPM for the given runaway conditions. Still, the runaway TSR can then be used to anticipate runaway conditions in a wind tunnel test environment as described in Section 3.2.

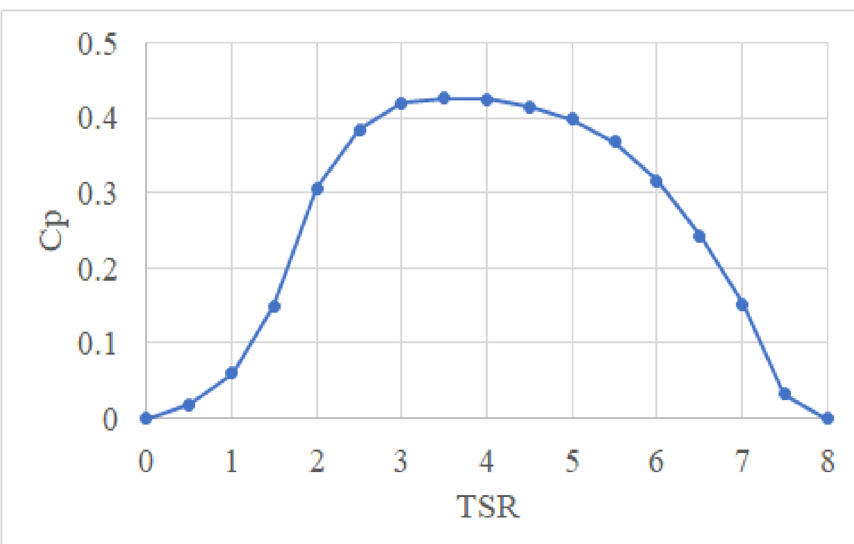

Figure 4 Cp vs TSR curve generated by XTurb

2.2.3 Structural Blade Analysis

The blade shape and material must be strong enough to resist bending in high wind speeds, yet not so stiff that they become brittle. The blades must also have a relatively smooth surface finish. For these reasons, the blades were constructed using Nylon 12 through a selective laser sintering method.

Using Finite Element Analysis (FEA) to analyze the strength of the blades was a crucial step in understanding their structural performance. SolidWorks was used to examine how the force of the wind on the blades would affect its structural integrity. The stress and deflection induced were the most critical parameters analyzed. The program outputs the stress, displacement, and strain on the blade, with stress being the most significant parameter.

A CAD model of the blade was used to simulate potential forces the test turbine blades may face at higher wind speeds. From previous years' simulations, the blades were projected to experience forces less than 5 N for wind speeds less than or equal to 20 m/s. This analysis was expanded to include a wind speed of 25 m/s. Using the formula $F = \frac{1}{2}\rho v^2 S C_l$, where ρ is the air density, 0.96 kg/m^3 at what was supposed to be the CWC location, Denver, Colorado, v is the absolute local speed of the radial position, which takes into account the incoming wind speed and tangential speed along the span of the blade. S is the surface area of the blade obtained through SolidWorks, 0.021 m^2, and C_l is the lift coefficient for the blade, which is approximately 1.6. The projected force at maximum wind speed was 61.6 N.

The highest stresses in each loading case occurred near the blade root, adjacent to the attachment point, while the rest of the blade was largely unaffected, as shown in Figure 5. The greatest load, 61.6 N had a maximum stress of 19 MPa. Nylon 12 yield strength is approximately 43 MPa. Comparing the maximum stress with the yield strength, the team concluded that the structure of the blade can withstand the onset stress from the incoming wind operating at 25 m/s. As determined by this structural analysis, it was concluded that the structure of the blade would withstand the stresses and deflections imparted by the incoming wind under normal operating conditions.

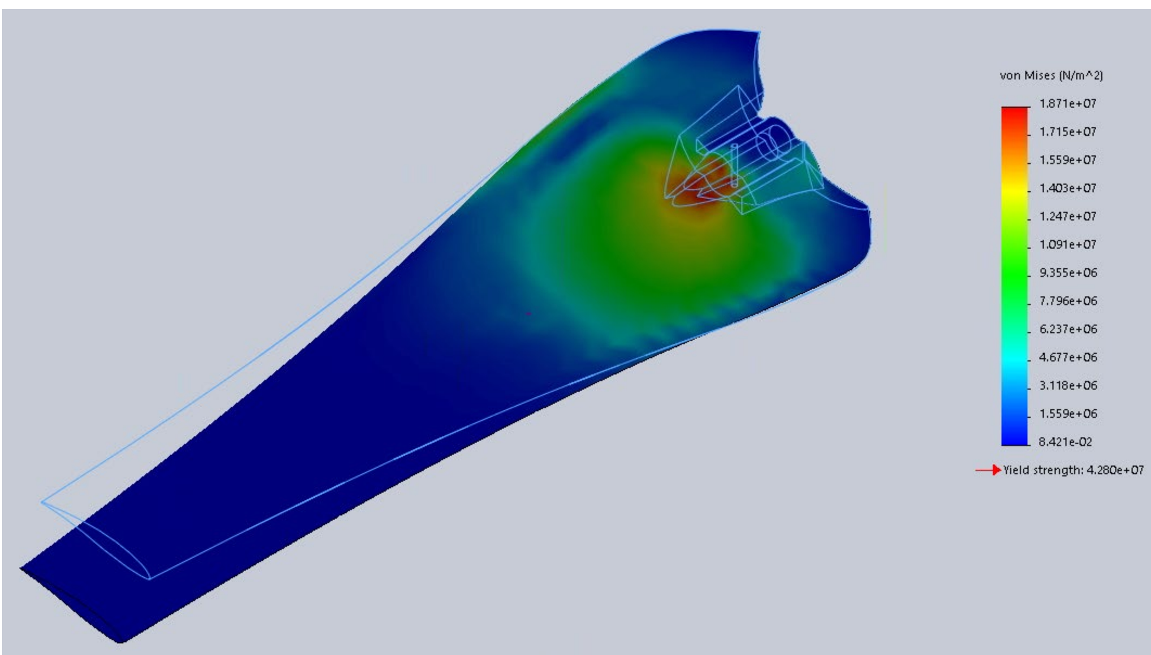

Figure 5 Stress Results for 25 m/s FEA analysis

The Nylon 12 blades have gone through benchtop testing to determine the point of failure and factor of safety (FOS). The blade was clamped at the root to simulate the rotor hub while weights were hung from the center of mass of the blade. As shown in Figure 6, the blade is carrying a 17.3 N load with minimal deflection. The hanging masses were then slowly added until failure at a 307 N load. As predicted by the FEA model and seen in Figure 7, the blade fractured at the location of highest stress near the blade root. Given that the highest expected load under normal operating conditions is 61.6 N, the FOS of the blades is approximately 5. This is an acceptable FOS. Uncontrolled vibration or another factor that induces unexpected loading outside normal operating conditions would need to be present to reach this critical failure.

Figure 6 Benchtop Test for Nylon 12 Blade

Figure 7 Critical failure at max load

2.3 Tailfin Design and Analysis

The turbine must be designed to stay oriented into the wind under yaw conditions. A tailfin is used for this purpose. The tailfin, or vertical stabilizer, is a simple mechanism that applies a restoring moment on the nacelle bearing, such that it returns the turbine into the optimal position, facing directly into the wind. This ensures that the turbine is always oriented to produce the maximum amount of power.

The current design, as shown in Figure 8, is a computer-generated model of the test turbine's tailfin. The tailfin design uses the NACA 0009 symmetric airfoil, which increases the restoring force compared to a flat plate tailfin, which has been used in the past.

The considerations for this year's tailfin design had been focused around optimizing the weight. The test turbine tailfin is currently a steel flat plate core with a 3D printed jacket that makes up the desired airfoil shape. The team looked into researching methods on producing a tailfin with the same airfoil with the intentions of removing the weight carried by the flat plate. Some research was made into 3D printing with Nylon 12, but no concrete design was completed before the COVID19 pandemic.

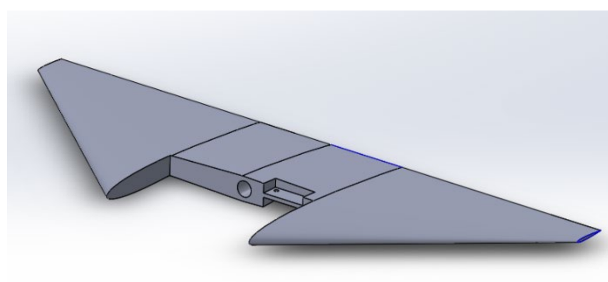

Figure 8 Tailfin CAD model

2.4 Blade Hub and Servo Design

The hub pitching mechanism, shown in Figure 9, is a repurposed RC helicopter rotor. This device is able to precisely pitch the blades to a wide range of angles that can be held constant for the cut-in, power production, and rated power tasks. For the safety task, the blades are pitched to a negative angle of attack, which produces torque in the opposite direction from typical operation. A one-way clutch bearing prevents the turbine from spinning backwards, so the rotor simply comes to a stop.

The optimal pitch angles for each wind speed, determined through wind tunnel testing, are stored in the Arduino control code described in Section 2.7.4. The Arduino infers the wind speed and then relays the signal to a servo motor that adjusts the blade hub position, resulting in the blades pitching to the specified angle.

Figure 9 Repurposed rotor hub for turbine blades

The servo motor used for pitching the blades in previous years was a radial servo. However, when a pitch angle is set the servo is constantly self-correcting and slightly oscillates around the intended pitch angle. With the added competition element for smooth power, this problem was investigated. It was determined that a linear servo would hold truer as it rotates a screw drive to extend the actuator and then sits steady at the desired length. Before the COVID19 pandemic, our team was investigating possible designs to change the servo type, and it was determined that most likely two linear servos would need to be used on either side to create the proper force for pitching the blades without creating a bending moment on the shaft around the nacelle. It was determined that two servos in parallel draw relatively equal power compared to a single servo, and therefore a two-servo design was plausible. Unfortunately, no design was ever finalized with the disruption of the semester by COVID19.

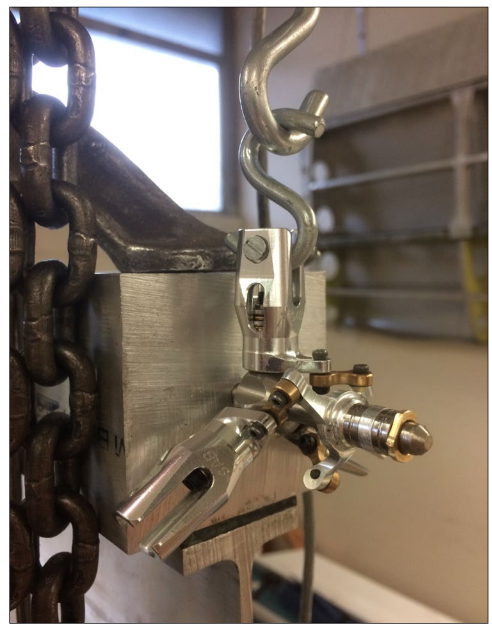

Figure 10 Blade hub undergoing static strength test

As the hub pitching mechanism holds the blades in place via small bolts, a static strength test was performed to ensure that this mechanism would not fail under normal operating conditions by simulating the force imparted on the grip by the centripetal force of the spinning blade. The hooks shown in Figure 10 were attached to a load cell, which measured the applied load, and a crane, which applied the desired force . The maximum force applied to the hub was 247 lbs. The test was stopped at this point due to the testing rig's limitations. The hub had not failed at this point and still appeared structurally sound. Applying this information to the CWC, the maximum expected radial force, expected at 3750 RPM, is around ~110 lbs., giving the rotor hub an FOS of 2.45. Although only one blade grip could be tested at a time, it is not believed that all three grips resisting 110 lbs. of force simultaneously would cause failure since each grip has its own structure independent of the other two.

During the rotor strength deliverable, the single point of failure of the turbine was in the set screw for the rotor hub. While no component yielded or underwent catastrophic failure, at the worst-case aerodynamic loads, the set screw slipped along the turbine shaft and caused uncontrollable pitching of the turbine blades. To correct this, the design team intended to add a secondary securing bolt behind the set screw to ensure no slippage would occur during competition. In conjunction with the presence of a significant electrical load, this measure was assumed to be an adequate solution to ensure no failure at runaway.

2.5 Generator and Structure Design and Analysis

The generator and overall turbine structure are critical design elements of the overall turbine system. The generator is the heart of the system, producing electricity and allowing for operation across a wide range of wind speeds. The turbine structure supports the physical components of the system and must withstand high loads. It is important that the generator is well integrated into the structure when designing and analyzing both subsystems, since their connection and assembly process is crucial for the turbine's performance.

2.5.1 Generator Design

The generator must be designed in parallel with the blades and electrical system so that it does not require more torque than the blades can produce and at the same time does not produce more power than the electrical system can handle. A three-stage axial-flux generator design, developed by the PSU Wind Energy Club team over several years, is used for the test turbine. In an axial-flux generator, rotors and stators can be made out of non-magnetic materials, which reduce the amount of cogging torque that must be overcome. This allows for the turbine to begin producing power at lower wind speeds. Another in-house Excel code was used to design the generator's stators and rotors. This code uses basic electromagnetic theory to calculate the voltage and current produced at different RPMs. The variable parameters input into the code are the magnet and coil dimensions, magnet strength, and wire gauge. These parameters were adjusted from previous years' designs so that the generator would produce a similar amount of power compared to what the blades produce at a given RPM. If the blades produce slightly more power than the generator requires at every angular velocity, then the turbine will be able to spin for any given operating condition. The variable electrical load and blade pitch can then optimize the system's power production by matching the generator and blade torque more closely.

2.5.2 Generator Testing

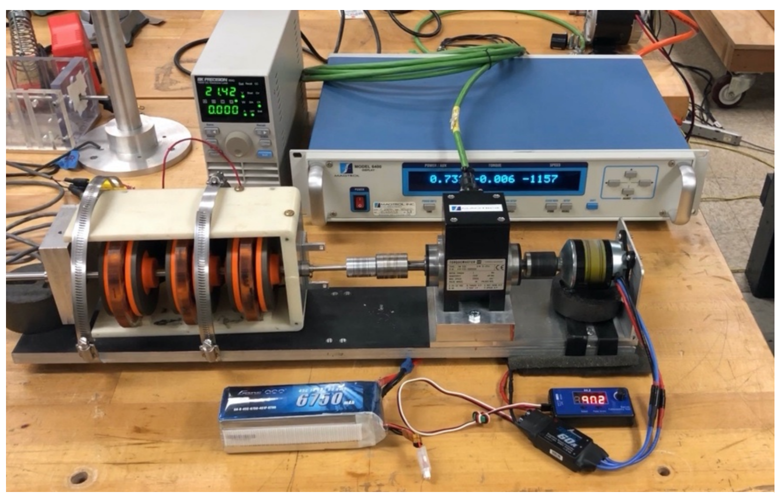

Figure 11 An image from the dynamometer deliverable testing.

The generator is typically tested on a dynamometer, seen in Figure 11, where the RPM and electronic load resistance can be varied. The measured output parameters are torque, voltage, and current. From these parameters, the power input into the system, power produced, and efficiency can be calculated. Many other important figures can be created including a power curve, C_P vs RPM, and torque vs RPM over a range of resistances. The data generated from the dynamometer test typically validates the generator design to perform adequately in the system, so long as the blades also perform as predicted. This data also characterizes the generator for all operating conditions and is essential when optimizing and automating the turbine control. Unfortunately, this data was not collected for the 2020 CWC outside of zero load testing for the dynamometer deliverable.

2.5.3 Structure and Housing Design

The nacelle structure and housing are designed to support and encapsulate the generator. The structure must be able to support the static load of the generator, tail fin, and blade assembly as well as absorb any vibrational energy generated by rotational imbalance. The structure must also be as compact as possible, so its cross-section imposes the smallest blockage effects and also allows for the largest tail fin within the 45cm box prescribed by the competition.

The housing must be designed to connect to the structure, must shield the generator from all unwanted external substances including water and general debris, and must securely hold the stators and allow for easy generator assembly. The structure and housing are designed such that rotors can be slid on the shaft and into place from the back of the nacelle, while the stators are secured into slots in the housing.

One intended change that was not able to be completed due to COVID19 was the fabrication of a new nacelle housing. Over time several small cracks developed around some of the bolt holes in the existing housing. These areas were planned to be bolstered by adding additional material to prevent cracking.

Another intended adjustment to the housing that was not able to be completed is the implementation of two linear servo housings integrated into the housing on the left and right sides of the overall generator housing. The current radial servo used in the team's current design exhibits undesirable oscillatory behavior past 12 m/s, where the servo constantly slips and corrects itself. Because this oscillatory behavior is applied to the swash plate pitching mechanism, it can also create significant electrical noise in the generator output power. Supplying power to the radial servo for these continuous corrections is also not efficient, thus the team intended to implement two linear servos that can better hold blade pitch. The plan was to use two linear servos, one on each side of the nacelle housing with arms extending from each connecting them to the rotor. This servo implementation can be seen partially in Figure 1 on the side of the turbine nacelle. An image of the Actuonix L12, the model of linear servo intended to be used, can be seen in Figure 12.

Figure 12 Actuonix L12 linear actuator planned to be implemented.

2.5.4 Structural Analysis

The turbine's structure has been designed so that the thrust force on the blades is transmitted to the front face of the nacelle. This thrust force on the nacelle then creates a bending moment on the tower which is counteracted by the baseplate's connection to the wind tunnel. In preparation for the 2019 CWC, finite element analysis (FEA) was performed on the turbine structure (nacelle, tower and base plate) to ensure it would be able to withstand the forces experienced by a 20 m/s wind speed, expected to be the extreme load condition for 2019 competition. The results of the FEA analysis, conducted in Abaqus, determined that the base of the tower experienced the greatest stress of 531 psi and a FOS of 75. This simulation was going to be repeated for the 25 m/s condition expected in the 2020 competition to confirm that the values would still be with a reasonable factor of safety, however due the pandemic and loss of access to the necessary software, the team did not accomplish this task. In all likelihood, the tower design is still very safe. In fact, with such a large factor of safety, the design could likely be altered to reduce the use materials, and thus cost, as would be necessary in a commercial product.

2.5.5 Generator and Structure Fabrication

The tower baseplate, nacelle structure, shaft, and servo connector were to be constructed using traditional machining techniques, which produce high-strength aluminum and steel parts with relatively simple geometries. The previously constructed housing, and generator rotors are made out of ABS plastic with fused deposition additive manufacturing. This technique is very accurate and can produce the complex geometries needed for the rotors but does not produce as strong of a final product as traditional machining does with metals. For this reason, the plastic parts are designed to not be structural and take minimal loads.

2.6 Electrical Design and Analysis

The goal of the electrical system is to regulate the power produced by the generator and to optimize the entire system's energy production for the CWC. To do this, two parts of the electrical system work in tandem: the control box, which rectifies the AC power from the generator into DC and optimizes blade pitch, and the load box, which optimizes the system resistance for maximum power production for a given wind speed.

These two boxes are designed to function in the two main operating conditions that the electrical system will encounter during competition. First is the power optimization and control portion of the competition, and second is the durability and cut-out wind speed portion of the competition. For the power optimization and control portion of the competition, the electrical system focuses on optimizing power using pre-collected data (see code in Figure 19, appendix), while in the durability and cut-out wind speed portion of the competition, the electrical system focuses on controlling the turbine RPM and limiting output power.

2.6.1 Control Box Design and Analysis

The turbine is controlled chiefly by the control Arduino (an Arduino Uno), which is powered via a regulated DC power produced by the test turbine. The control Arduino, which is located in the control box, manages the pitching of the blades, the variable resistance load, as well as the on/off control of a DC step down converter. The control Arduino also monitors input voltage from the generator and voltage at the point of common coupling (PCC), and also brakes the turbine under certain safety criteria. The first part of the control circuit, seen in Figure 13, consists of a Schottky diode bridge rectifier, which converts the three phase AC generator output into DC power. The rectified DC power from the generator then passes through an unseen voltage regulator specifically for powering the control Arduino, and then through a safety DC step down converter. The DC step down converter, which can be turned on or off by the control Arduino depending on the voltage, limits the voltage going through the point of common coupling (PCC). After passing through all these portions of the electrical control box, this regulated and filtered power then passes through the PCC to the load box.

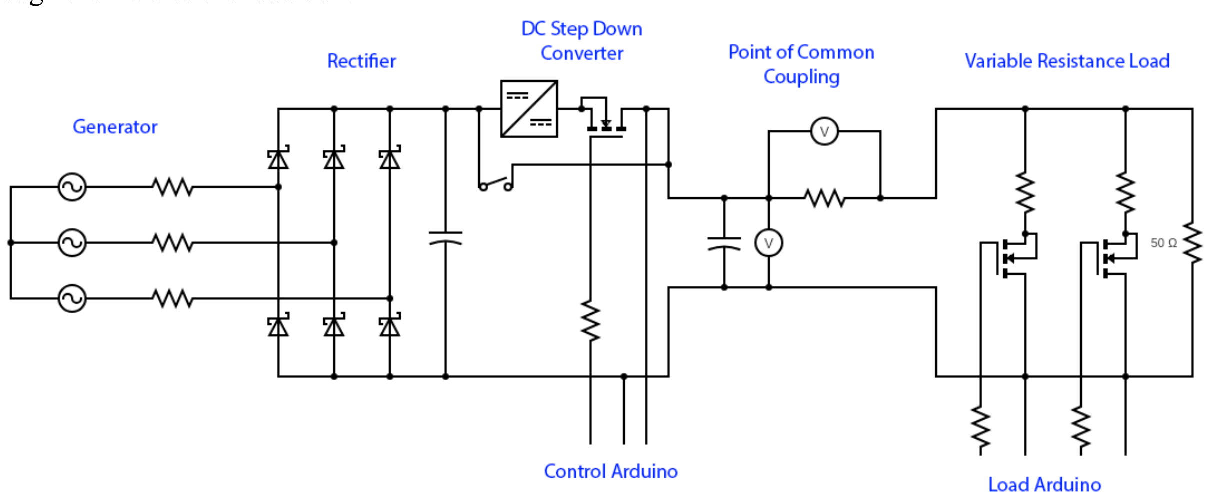

Figure 13 Basic control circuit and load diagram.

In addition to load resistance and power optimization, the control Arduino actuates a servo motor, which pitches the rotor blades as a secondary method to optimize or control the power through the PCC. The control Arduino dynamically adjusts pitch angle in order to optimize blade orientation both at startup and throughout the power collection aspects of the competition. The optimal pitch angle at any given competition wind speed would have been determined through wind tunnel testing and hard coded into the control Arduino prior to competition. Wind speed is able to be inferred through a relationship between output voltage, current, and pitch angle. The control Arduino is able to sense the output voltage from the generator via a shunt resistor, infer a wind speed, and set the corresponding optimal blade pitch. Pitch optimizations are incremented with respect to wind speed in 2 m/s steps, as opposed to constantly, to avoid any unintentional stepping of pitch control. For wind speeds higher than the prescribed 11 m/s required for the power optimization task, the servo is programmed to pitch the blades to an angle that maintains rated power and blade RPM for a given wind speed. For the higher wind speed portions of the competition — mainly the durability and cut-out wind speed tasks — the Arduino-controlled DC step down converter implemented before the PCC ensures the voltage across the PCC never exceeds 45V.

2.6.2 Load Box Design and Analysis

The main objective of the load box is to optimize the system resistance and subsequent power production of the turbine. During the safety task, the load box is also responsible for supplying power back to the control box. The load box consists of a fixed 50 Ohm resistor and several supplementary resistors, which serve to optimize the effective system resistance. The fixed 50 Ohm resistance value was selected because, based upon previously collected data, it produced reasonable power at wind speeds greater than 5 m/s, while still allowing the turbine to start-up below 2.5 m/s.

When the turbine brakes for the safety task, the generator is no longer able to power the control Arduino. During this competition task, the load box also serves as a power source for the control Arduino via a nine-volt battery which also powers a separate load Arduino (also an Arduino Uno). This load Arduino receives a preprogrammed Boolean signal from the control Arduino to open or close an electrical switch, sending power back to the control box as mentioned previously in the safety procedures.

2.6.3 Intended Variable Resistance Load Design

A primary option being explored prior to the COVID19 pandemic, was the implementation of a new variable resistance load design. The variable resistance load design would work together with the dynamic pitching of rotor blades to regulate and optimize turbine output power for any competition task. In previous years, variable resistance was accomplished using a buck-boost converter, however, this implementation never worked properly. This new variable resistance load would consist of a number of constant resistance resistors in the load box: one permanently affixed 50 Ohm resistor, in addition to one or two supplementary resistors. These supplementary resistors would be controlled by the load Arduino via N-channel mosfet switches, which could be opened or closed to alter the system resistance, increasing or decreasing turbine output power. A basic, tentative version this variable load design can be seen in Figure 13 above.

The load Arduino would open or close these switches when signaled by the control Arduino. The control Arduino constantly monitors the power across the PCC and under certain criteria, would signal the load Arduino to change the system resistance. The optimal resistance values as a function of pitch angle and wind speed are determined experimentally and are preprogrammed into the control Arduino.

2.6.4 Control Logic

The main goal of the control logic is to make best use of the selected hardware for each competition task. The control logic is critical for optimizing power output within the 5 to 11 m/s wind speed range, holding rated power, controlling the electrical output to desired values for the durability task, and controlling turbine RPM during cut-out, where the wind speed can reach 25 m/s. The control logic is implemented in the control Arduino which sends signals that control blade pitch, change system resistance, and turn on/off the DC step down converter. A control flow chart is shown in Figure 14.

Before competition testing begins, the blades are pitched to the ideal startup angle that was determined in prior wind tunnel testing. Once the wind turbine produces five volts, the turbine is able to power the control Arduino, and once producing eight volts, the servo is powered and able to pitch the turbine blades. Eight volts is typically reached at a wind speed of less than 5 m/s and an ideal load resistance and blade pitch angle. At eight volts, the control system would become fully functional.

To optimize the power output by the system, both the blade pitch and the variable load are adjusted dynamically. The optimal pitch angles are determined based on an experimentally derived correlation to estimated wind speed. In order to infer this wind speed, voltage input data from the turbine is read into the control Arduino, which then uses tabulated values correlating input voltage and estimated wind speed. The Arduino matches optimal pitch angle and wind speed from a table of the experimentally determined values and then commands the servo to pitch the blades accordingly. These experimentally determined values are based on State College conditions but are updated at the competition to account for the different air properties. This output power is continuously optimized until the voltage reaches a critical level of 45 V, signaling the control Arduino to turn on a DC step down converter at the PCC to regulate the output voltage. This DC step down converter can turn on automatically at any point during the competition to ensure that the voltage across the PCC does not exceed the competition limit of 48 V.

For the durability and cut-out wind speed tasks specifically, this DC step down converter is expected to be turned on at all times. Since specific voltage power production is not a concern outside of producing negative power, turbine control during these tasks is done mainly through pitch control of the turbine blades. For the free yaw durability task, the control logic is unchanged from the control of rated power task. For the cut-out wind speed task, the control logic shifts to manage the RPM of the turbine. Using experimentally obtained data on wind speed, the control Arduino is able to sense the cut-out wind speed. Once the cut-out wind speed is detected, the control Arduino pitches the blades and/or changes the system resistance to experimentally derived combinations to reduce turbine RPM. Ten percent RPM reduction pitch angles and load resistances are obtained for wind speeds ranging from 19 to 26 m/s to ensure margin for the control logic.

2.6.5 Safety Tasks

For the safety task, the electrical system is tasked with braking and restarting the turbine upon either the triggering of a kill switch or a PCC disconnect. The primary mechanism used to brake the turbine is control of blade pitch in conjunction with a one-way clutch bearing. In either braking condition, when the safety criteria are met, the control Arduino signals the servo to pitch the blades out of the wind. At this out of the wind pitch angle, the resultant force produced acts in the opposite direction as normal operation. A one-way clutch bearing then prevents the blades from spinning in this opposite direction, thus braking the turbine and stopping power production.

When a kill switch is triggered, the control Arduino is signaled directly to initiate braking. When the electrical system is disconnected at the PCC, the control Arduino will detect the disconnect, as it constantly reads the voltage drop across the load. If the control Arduino senses this to be zero, then there must be no current running through it, indicating a disconnect. The control Arduino similarly pitches the blades to brake the turbine. An excerpt of code for this portion of the competition can be seen in Figure 20, in the appendix.

In either braking condition, before the control Arduino brakes the turbine, it sends a signal to the load Arduino indicating the braked condition. The load Arduino then opens up a switch sending 5 V back through the PCC. This voltage powers the control Arduino once the turbine power output ceases. The control Arduino is able to then continue to monitor the aforementioned brake cases. When the braking condition is changed, when the kill switch is flipped back or the PCC is reconnected, the braking process reverses. The blades are pitched back to the optimal startup angle and a signal to the load Arduino closes the switch sending power back to the PCC thus resuming normal operation.

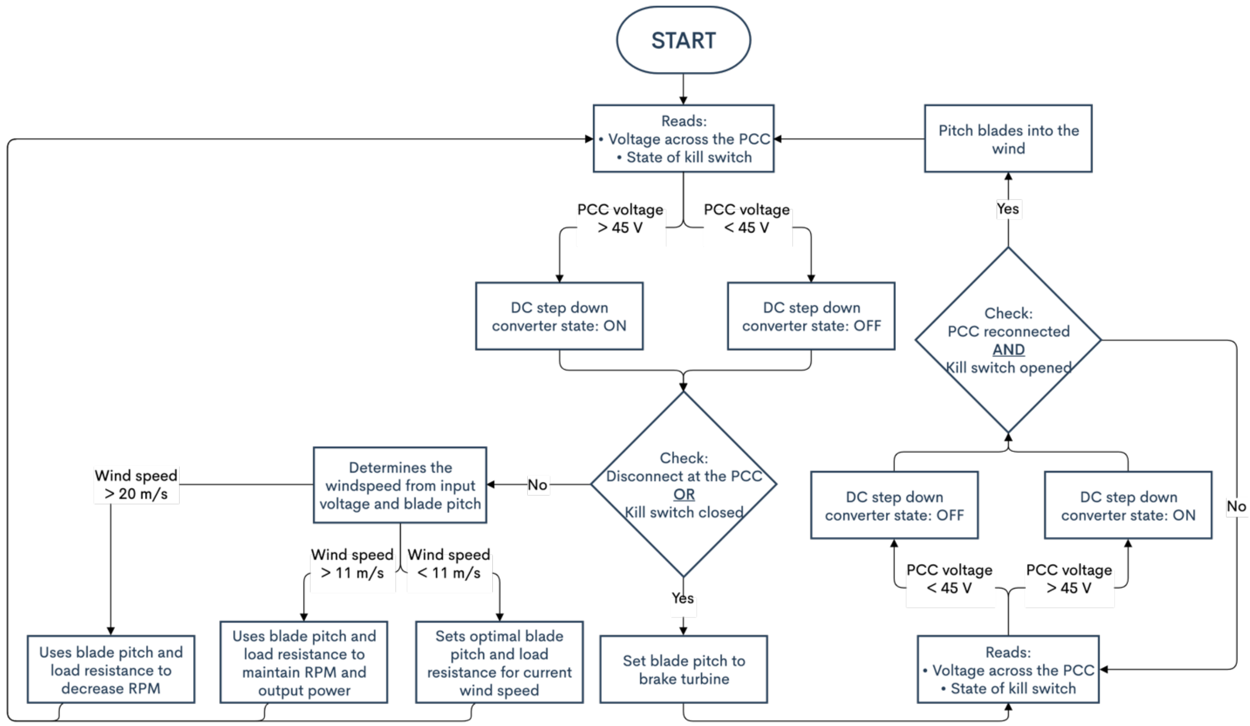

Figure 14 Turbine control logic flow chart

2.6.6 Power Quality

A design choice for the power quality deliverable was made before the COVID19 pandemic, smoothing capacitors were intended to have been implemented in various locations within the system circuit. The purpose of the smoothing capacitor was to dampen the amplitude of the output waveform by absorbing voltage at positive peaks and by releasing voltage at negative valleys. Smoothing capacitors after the rectifier as well as before the PCC were intended to doubly smooth the output voltage.

In addition to smoothing capacitors, prefabricated, high power LC filters were considered as an alternative or additional measure to smooth the output waveform at the PCC. Deciding between either option would have depended on results from breadboard testing, benchtop dynamometer testing, and wind tunnel testing. An oscilloscope was planned to be used at the 50 kHz and 200 Hz settings to evaluate performance of the separate solutions or smoothing circuit as a whole. Unfortunately, this was ultimately not possible, regardless non-specific capacitors have still been included in the circuit design.

3.0 Wind Tunnel Testing

Wind tunnel tests are normally run to gather real world performance data on the test turbine, giving insights on how well the turbine might perform competition tasks as well as improvements that can be made. An on-campus closed loop wind tunnel has historically been used to test the performance of the test turbine, however due to the COVID19 pandemic, the majority of wind tunnel testing has not been able to be conducted for this year's competition. Regardless, two primary challenges have still been considered for would-be wind tunnel testing. First are the blockage effects caused by the small cross-section of the wind tunnel test section, which cause the measured wind speed to be higher than the true wind speed. A calibration factor is typically implemented to account for these blockage effects and achieve a more accurate wind speed measurement. Second is adapting the performance data obtained in Pennsylvania to match testing conditions in Colorado. Using previous competitions as a precedent, wind tunnel testing data is adjusted to account for the lower air density and lower subsequent energy in the wind.

3.1 Wind Tunnel Testing Objective

The main objective of pre-competition wind tunnel testing is to observe and document how the test turbine will perform under operating conditions similar to those expected during the CWC. The performance of the turbine is quantified by the current, voltage, and RPM measured at different wind speeds, blade pitch angles, and load resistances. These values are tabulated, and variables such as optimal blade pitch values and optimal resistances can be backed out for certain operating conditions. Turbine control algorithms can also then be developed and refined from these wind tunnel results.

Unfortunately, due to the COVID19 pandemic, substantial wind tunnel testing data was unable to be collected for this year's turbine design, however, preliminary data for the rotor blade strength deliverable was gathered. Planned wind tunnel testing included collecting six data points under every operating condition tested: three input conditions, wind speed, blade pitch angle, and load resistance, and three output variables, current produced, voltage produced, and RPM. Table 1, which tabulates these variables with respect to CWC tasks, was intended to be used to evaluate turbine readiness, with wind tunnel testing methodology based around the prescribed tasks.

Table 1 Evaluation criteria and variables used in wind tunnel testing.

	Blade Pitch required ?	**Specific RPM required?**	**Wind Speed (m/s)**	**Load Impedance (Ohms)**	**Expected Current (A)**	**Expected Voltage (V)**
Cut-in wind speed	No	No	< 2.5	50	Measurable	Measurable
Power curve performance	Yes	No	5-11	50	Optimal for max power	Optimal for max power
Safety	Yes	Yes	< 25	N/A	0	0
Control of rated power & rotor speed	Yes	Yes	12-25	Variable based on wind speed	11m/s power performance	11m/s power performance
Durability	Yes	No	6 - 18	Variable based on wind speed	Positive power	Positive power
Cut-out part 1	Yes	< 90% of max power curve RPM	6 - 22	Variable based on wind speed	Positive power	Positive power
Cut-out part 2	Yes	< 90% of max power curve RPM	22 - 25	Variable based on wind speed	Positive power	Positive power

In previous years, the power production was simulated at 2 m/s incremented wind speeds from 5 to 11 m/s. At these wind speeds, different pitch angles and load resistances (using an electronic load) were tested. With these input variables, output voltage and current could be monitored via the electronic load and turbine RPM could be measured with a stroboscope. For the 2020 CWC, wind speeds ranging from 2 – 25 m/s were also planned to be tested, with the goal to collect extensive data for the cut-out wind speed portion of the competition. Ultimately, wind tunnel testing was not possible during the quarantine.

From the recorded values, the power produced and tip speed ratio (TSR or λ) can then all be calculated. This data can be used to validate theoretical or benchtop testing and can provide insight into specific turbine characteristics that can then be accounted for in the Arduino control logic. As an example, last year's power curve can be seen in Figure 15 below. In previous years, the annual energy production of the test turbine was also estimated using a Weibull distribution and the power curve determined from wind tunnel testing. Unfortunately, this analysis was also unable to be done in preparation for the 2020 CWC.

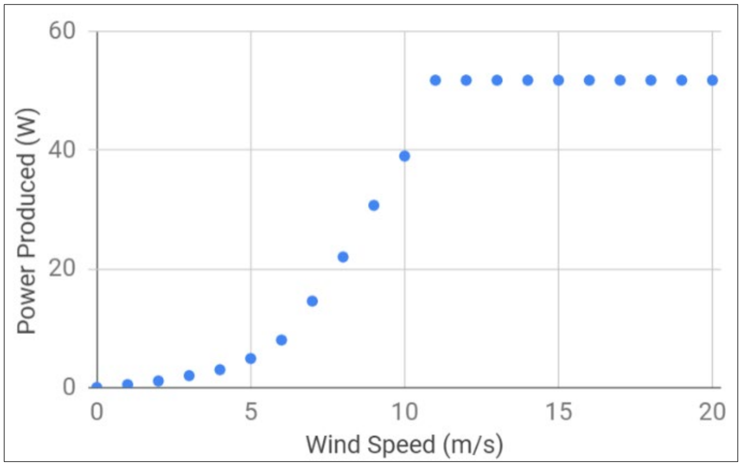

Figure 15 Power production vs wind speed for the 2019 test turbine.

3.2 Wind Tunnel Testing Results

The results of the limited wind tunnel testing done for the 2020 CWC can be seen in Figure 16 below, which shows the turbine TSR as a function of wind speed. During wind tunnel testing for the rotor strength deliverable, RPM and wind speed measurements were taken using a stroboscope and calibrated pressure transducer. TSR was then able to be calculated and was plotted against wind speed. The purpose of collecting this data was to validate the theoretical runaway TSR, predicted to be between 7.5 and 8. The multiple test runs were staggered as both a safety precaution as well as to examine the behavior of the turbine under the testing conditions.

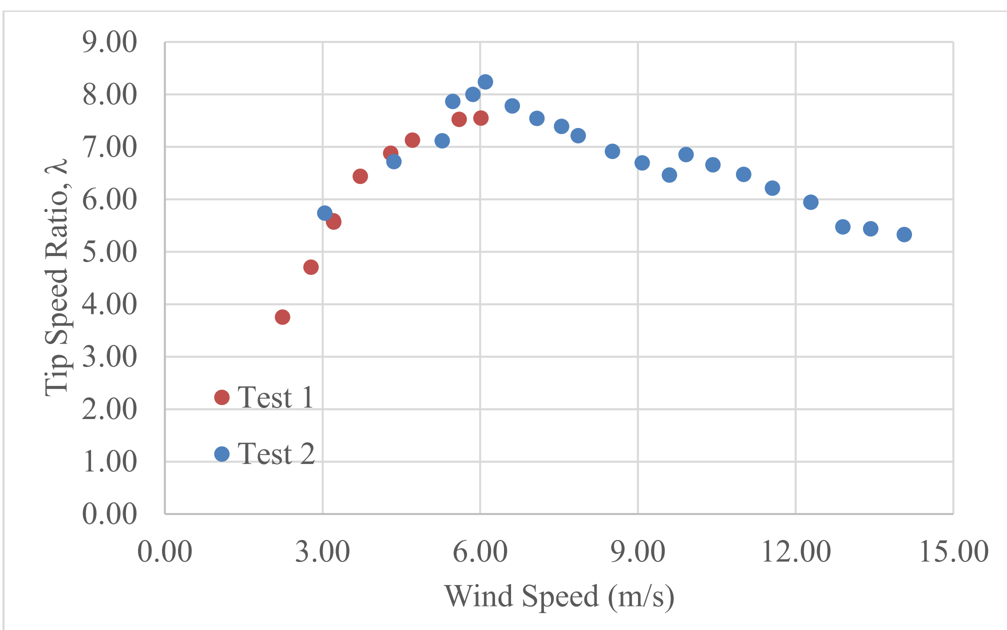

Figure 16 Tip speed ratio vs wind speed for the worst-case runaway conditions.

4.0 Conclusion

The test turbine design for the 2020 CWC was mainly focused on making incremental improvements in the aerodynamics and generator portions of the turbine design, while improving the reliability and reducing the complexity of the electrical system. Aerodynamic structural analysis was performed for the new expected wind speeds, a new linear servo design was devised to account for structural concerns, and a new variable resistance load was planned for the electrical system. It is unfortunate that many of these intended changes could not be fully realized as the outbreak of COVID19 barred student organizations from entering labs and accessing valuable resources, however, designs still progressed and efforts were made to create the most would-be competition ready turbine design for the 2020 CWC. The product of these efforts has been presented in this report.

5.0 Appendix

Figure 17 - 18 show the C_L vs Angle of Attack and C_D vs Angle of Attack for a Re = 50,000 (Blue) and Re = 100,000 (Red), respectively. These figures plot data acquired through MIT's X-Foil's analysis of the Wortmann FX 63-137 airfoil. This allows the team to analyze the lift/drag characteristics of the designed blades including the Cl/Cd.

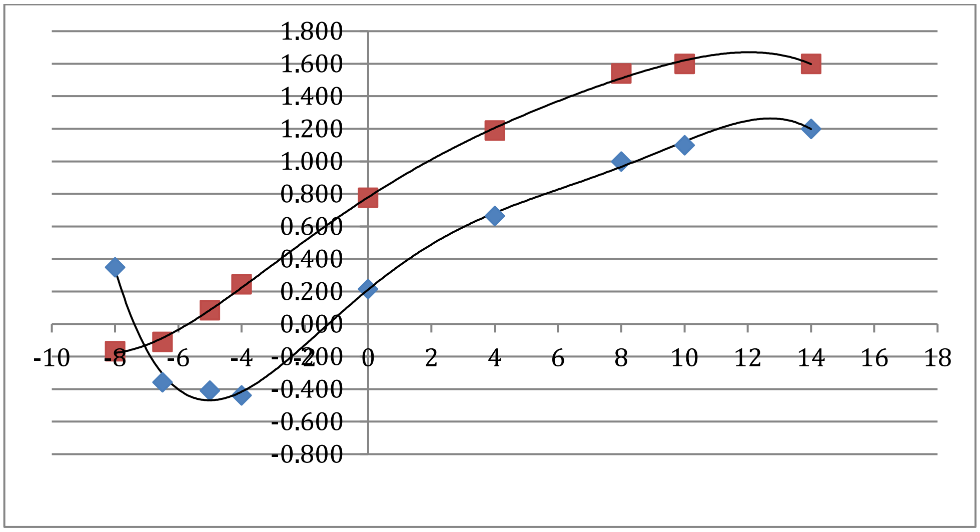

Figure 17 C_L vs α curves for Re = 50,000 (Blue) and Re = 100,000 (Red)

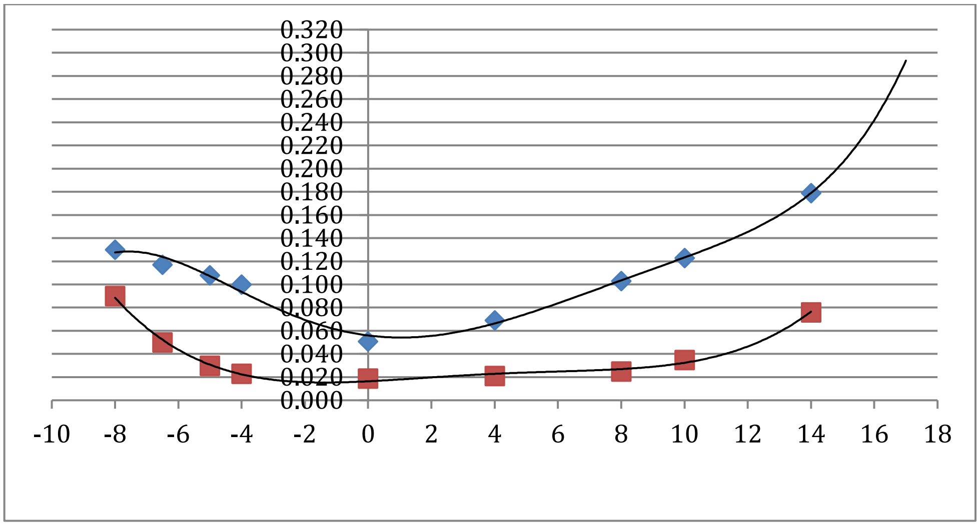

Figure 18 C_L vs C_D curves for Re = 50,000 (Blue) and Re = 100,000 (Red)

```
void pitchToPitchAngleBucket(double windSpeed){
  if(windSpeed > 5 && windSpeed < 7){
    pitch.write(FIVE_TO_SEVEN_PITCH_ANGLE);
    currentPitch = FIVE_TO_SEVEN_PITCH_ANGLE;
  }
  else if(windSpeed>=7 && windSpeed < 10){
    pitch.write(SEVEN_TO_TEN_PITCH_ANGLE);
    currentPitch = SEVEN_TO_TEN_PITCH_ANGLE;
  }
  else if(windSpeed > 10){
    pitch.write(TEN_PLUS_INITIAL_PITCH_ANGLE);
    currentPitch = TEN_PLUS_INITIAL_PITCH_ANGLE;
  }

}
```

Figure 19 Test turbine power performance curve code.

Figure 19 is an excerpt of code that would be used during the power performance task to pitch the blades to the optimal blade angle to maximize power production for a given wind speed between 5 and 11 m/s. This code itself has not changed from the previous year, however the optimal pitch value would change based upon newly acquired values from wind tunnel testing.

```
void processDisconnectedState(boolean disconnected){
  if(disconnected){
    Serial.println("Braking the turbine!");
    breakedInCompetition = true;
    EEPROM.write(0,breakedInCompetition);
    EEPROM.write(0+1,currentPitch);
    digitalWrite(LOAD_ARDUINO_PIN, LOW);
    pitch.write(BRAKE_PITCH);
  }
  else{
    breakedInCompetition = false;
    digitalWrite(LOAD_ARDUINO_PIN, HIGH);
    EEPROM.write(0,breakedInCompetition);
  }
  delay(10000);
  return;
}
```

Figure 20 Test turbine safety task braking code.

Figure 20 is an excerpt of code that is used to brake the turbine during the safety task by pitching the blades out of the wind. This code also signals to load the braked condition to prepare to restart the turbine on command.

6.0 References

[i] Department of Energy, 2020 Collegiate Wind Competition Rules & Requirements, https://www.energy.gov/sites/prod/files/2020/04/f73/cwc-2020-rules-requirements-1.pdf Accessed 5.18/2020.

[ii] Drela, M., XFOIL: Subsonic Airfoil Design System. https://web.mit.edu/drela/Public/web/xfoil/

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