The Pennsylvania State University
Wind Energy Club
Technical Design Report

Submitted to

2019 Collegiate Wind Competition

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1.0 Executive Summary

In this document, the Pennsylvania State University Wind Energy Club analyzes and explains the technical components of the test turbine for the 2019 Department of Energy Collegiate Wind Competition (CWC). The CWC has tasked the club with building a small scale, functioning wind turbine according to specifications in the CWC rules and requirements manual[1]. The turbine must 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 tasks.

Section 2 details the design and analysis of the test turbine, shown below in Figure 1, with respect to the aerodynamics, generator, and electrical systems, as well as how these parts function together in the whole turbine system. The section begins by providing the design objectives and constraints of the turbine as stated by the competition. Then, the blade and tailfin design and analysis are provided along with their optimization and safety parameters to ensure they operate within system requirements for safety and overall operational efficiency. Next, the generator design, analysis, and testing is covered, which documents the process that results in a reliable generator that produces enough power for the electrical system to function and for the whole system to be competitive. Finally, the electrical system is detailed, which encompasses the design, analysis and testing of the control box as well as the load box, both of which function together to ensure the turbine is operating safely and optimized for the given competition task.

Section 3 covers the wind tunnel testing completed prior to competition to ensure that each individual turbine component as well as the system is not only functioning properly but also optimized to achieve the maximum score at the competition. The objective, procedure, and results of the tests are explained as well as how the results influenced changes in the system and individual components.

Section 4 concludes how the pre-competition testing results have shown that the turbine performs as designed, meets all the competition requirements, and will score well in the competition.

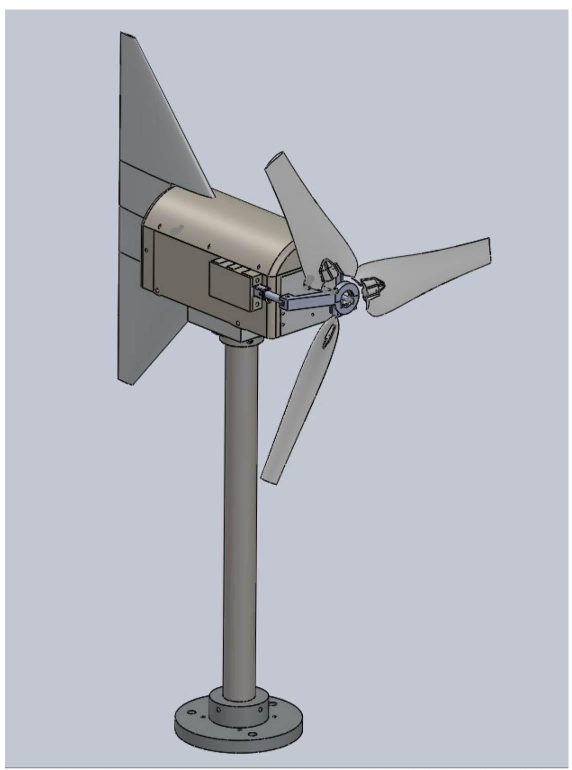

Figure 1: CAD Drawing of PSU Wind Energy Club 2019 Test Turbine

2.0 Technical Design

A wind turbine converts the wind's kinetic energy into electrical energy through three main subsystems; the blades, generator, and electrical systems. For the turbine system to maximize energy production, each subsystem has to be individually designed to optimize its performance in the expected operating conditions while the system as a whole also has to be optimized through testing so the components function together to achieve peak performance. Ideally, the subsystems would be optimized during design and the entire system would perform as expected, however for a turbine of this scale, it can be difficult to accurately predict the actual performance. This is especially true for the blade aerodynamics since the effects of low Reynolds number on the small blades can promptly degrade their performance. There is also an inadequate bridge between the theoretical and actual performance of the electrical system as many components are specified to work within a given operating condition, but their performance begins to decline before the limits of the operating range are reached. The difference between expected and actual performance in these subsystems demonstrates why their design must be meticulous and also why testing must be done to ensure they function together as expected. These differences are on the order of 5 to 10% for each subsystem so the whole system's actual performance can be significantly worse than predicted if these deviations are not accounted for. Each subsystem's discrepancy is discussed in its respective section.

2.1 Design Objective

The test turbine was designed with the goal of scoring as high as possible in the Collegiate Wind Competition. To score well, it is imperative that all the competition tasks be completed as described in the Rules and Requirements[1]. Each task requires the turbine system to function differently under varying operating conditions so there must be a high degree of control over each turbine subsystem. A variable electronic load and active blade pitch are the two means with which the turbine is controlled. The generator and rotor design are critical in giving 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 individually while also functioning together as one cohesive unit to achieve the intended results.

2.2 Blade Design Objective

Modeling was used to analyze and optimize the blade design. An Excel program implementing blade-element momentum theory was used to design the test turbine blades. PSU-XTurb[2], a wind turbine lifting-line theory aerodynamic analysis tool, was used to confirm the Excel program's predictions and provide data about the rotor performance to ensure that the torque produced by the blades would properly integrate with the torque required by the generator.

Over the course of the 2019 academic year, the aerodynamic team completed design and analysis of a blade that incorporated a different airfoil, the PSU 94-097. This blade design and analysis produced a chord distribution that was smaller than ones previously used in the CWC competition. The analysis of this new blade predicted improved performance compared to the blades design used in the 2018 competition. When tested in the wind tunnel, however, the 2019 blade design performed marginally worse compared to the 2018 blade performance in terms of power and operating range. This decrease in actual performance may be credited to the smaller chord, which lowered the Reynolds number and subsequently hindered the performance. Due to this, the 2018 blade design was used in the 2019 test turbine system. The following design and analysis sections, 2.2.1 through 2.3.2, describe the techniques used to produce both blades, but contain specifics on the 2018 blade design since that is the design used in the 2019 competition.

2.2.1 Aerodynamic Blade Design

This section provides an overview of the design process used to design the test turbine blades. The initial design is generated with an in-house blade-element momentum theory Excel program. The program discretizes a blade into a finite number of radial stations and then calculates the aerodynamic forces at each radial position along the length of the blade using the airfoil lift coefficient and drag coefficient data shown in Figures 2-3, respectively. The test turbine blade design has thirty-one equally spaced radial stations. The blade design is fully defined with three parameters versus the blade radius: airfoil, chord length, and twist. The airfoil selection, shown in Figure 4, was based on the operating conditions as well as the generator torque and speed requirements. Then the program optimizes the blade chord and twist to achieve the appropriate axial-induction factor. Since the program only optimizes a blade at one wind speed and RPM, an intermediate wind speed of 8 m/s was used to maximize the competition score. A design tip-speed-ratio (TSR) was selected based on the team's prior experience integrating past blade and generator designs, which determined the design RPM. For the test turbine, control of power and rotor speed is achieved through active pitch of the rotor blades. PSU-XTurb was also used alongside the Excel program to check the rotor power output as a function of tip-speed-ratio and wind speed. The XTurb design analysis will be further described in section 2.3. The important output parameters for the rotor design are the torque

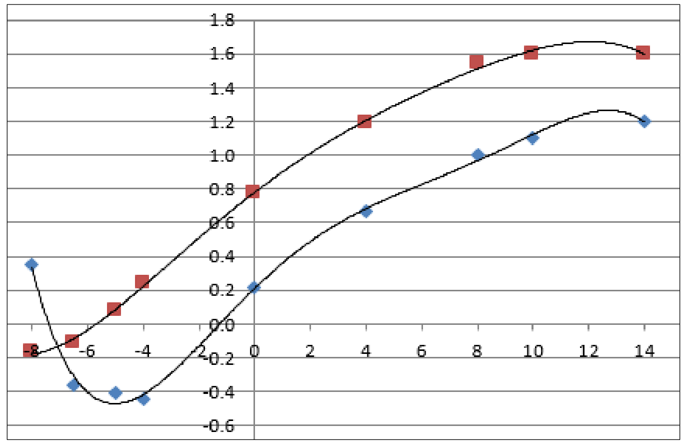

Figure 2: Airfoil Cl vs Angle-of-Attack for Re = 50k (Blue), Re = 100k (Red)

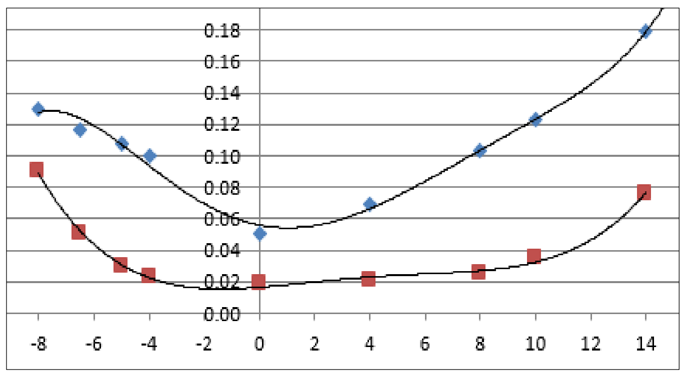

Figure 3: Airfoil Cd vs Angle-of-Attack for Re = 50k (Blue), Re = 100k (Red)

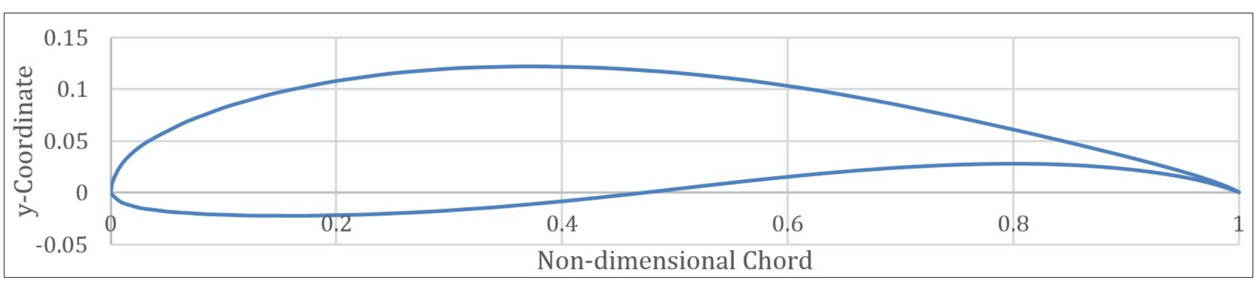

Figure 4: Wortmann FX 63-137 Airfoil

and power coefficient (C_p). Although increasing C_p is the focus, matching the torque produced by the blades to the torque required by the generator is vital for the system to function properly. The relationship governing the torque required to spin the generator at a given RPM and load resistance is determined through dynamometer testing, which is explained in Section 2.6.2. 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. An iterative process of adjusting various input parameters is performed until sufficient blade performance is obtained. Figure 5 shows the final chord and twist distributions.

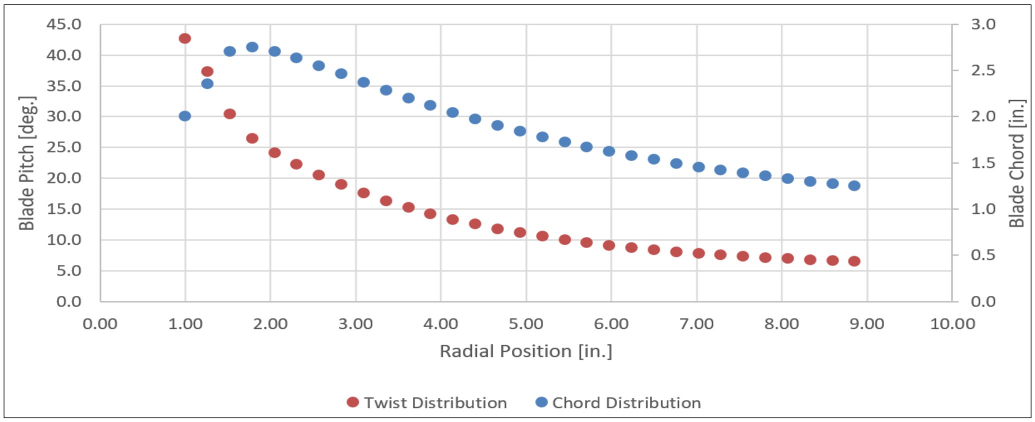

Figure 5: Blade Chord and Twist

2.3 Blade Analysis Objective

The goal of analyzing and testing the test turbine blades is to find the optimal collective pitch angles to maximize the amount of power the turbine generates at each wind speed. These maximum power values are then adjusted by the weighting specified in the competition scoring guidelines to arrive at the final power curve score.

2.3.1 Aerodynamic Blade Analysis

PSU-XTurb[2] is a blade-element momentum theory code, developed by Penn State Professor Dr. Sven Schmitz, which 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 polars, operating conditions, and wind speed. The blade geometry is defined by the chord and twist along the span. Airfoil polars are specified along the blade span based on the local Reynolds number. The code allows for 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.

The output files generated after running the code provide performance values, including rotor torque, C_p, C_L, 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 at low wind speeds to ensure the turbine will cut in before a wind speed of 2.5 m/s as given by the competition requirements. The generator team performed static torque testing to find the minimum torque required to cut in. The aerodynamic team then used this data to determine the optimal pitch to achieve the required start-up torque at a low wind speed, while still maintaining an adequate angle to drive

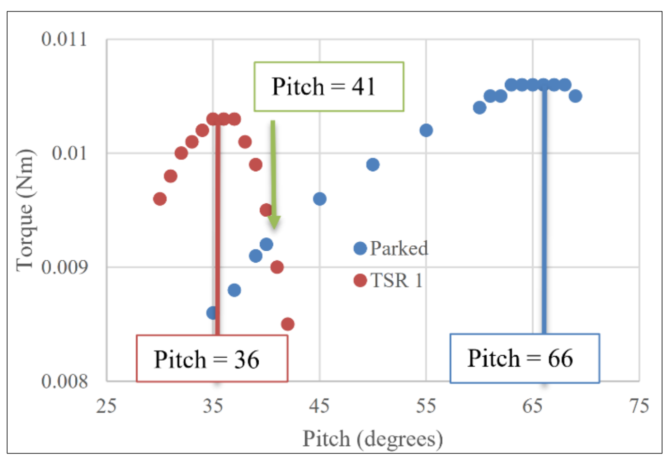

Figure 6: Torque produced vs pitch angle for parked and TSR 1 conditions

the rotor once it begins spinning. The C_P was then analyzed at higher wind speeds to assess how much power the blades could theoretically generate.

The blades are first put through X-Turb to analyze a parked blade case and a TSR 1 case. The results show that the pitch required to achieve the maximum torque output decreases as TSR increases. With each increase in wind speed, a decrease in pitch was needed to maintain an angle-of-attack that operates the rotor at C_L/C_D max, thus maximizing the torque. This data is shown in Figure 6.

The turbine system does not produce enough power to actively pitch the blades at wind speeds less than 5 m/s. Therefore, a startup angle must be selected that provides a low cut-in wind speed and allows for operation at low TSR until enough power is generated to pitch the blades. Therefore, the pitch angle between a TSR of 1 and the ideal startup pitch was selected.

2.3.2 Structural Blade Analysis

Nylon 12 was chosen to 3D print the blades through a selective laser sintering method. It is crucial for the blades to be sufficiently stiff to resist bending in high wind speeds, yet not so stiff that they become brittle. Also, the blades must have a relatively smooth surface finish. It was determined that this material and printing method was suitable for our application.

Using Finite Element Analysis (FEA) to analyze the blades was a crucial step in the structural analysis. SolidWorks was used to examine how the force of the wind on the blades' design would affect its structural integrity. The stress and deflection induced were the most critical parameters analyzed.

A CAD model of the blade was created in SolidWorks and a point force was applied at the center of mass of the blade to simulate the force of the wind. The formula used to calculate the point forces was $F = \frac{1}{2}\rho v^2 S$, with the air density, ρ, determined to be 0.96 kg/m^3 for the NREL competition location. The surface area, S, was determined through SolidWorks to be 0.0193 m^2. To simulate the competition wind speeds, analysis was run at five wind speeds: 6, 7, 10, 15, and 20 m/s. The subsequent forces applied to the blade were: 0.442, 0.601, 1.227, 2.761, and 4.908 N.

Nylon 12 material properties were used and a fixture was modeled at the blade root to simulate the hub attachment. After inputting the magnitude and location of the force the simulation was run. The program outputs the stress, displacement, and strain on the blade, with stress being the most significant parameter.

Figure 7 shows the stress on the blade for 0.442 N case with the blade deformation scaled for better visualization. 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. The greatest load, 4.908 N, corresponding to 20 m/s wind speed, had a maximum stress of 139.8 Pa. Nylon 12 yield strength is approximately 48 MPa. As determined by this small stress, it was concluded that the structure of the blade would withstand the stresses and deflections imparted by the incoming wind under normal operating conditions with little to no impact on the aerodynamic performance.

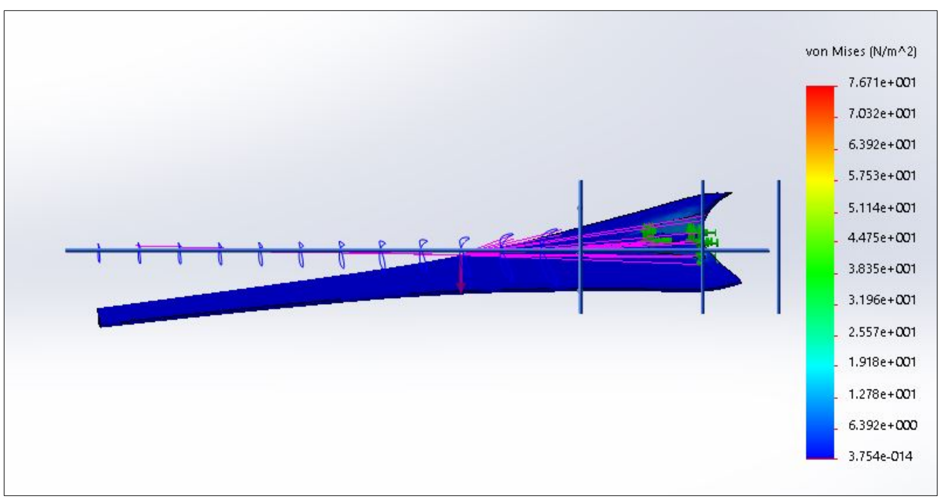

Figure 7: Stress results for 6 m/s FEA analysis

The blade was further analyzed through benchtop testing to determine the point of failure and factor of safety (FOS). As seen in Figure 8, the blade was clamped at the root to simulate the blade hub fixture while weights were hung from the center of mass of the blade. This figure shows roughly 17.3 N hanging from the blade with minimal deflection so it was determined that the blade would withstand the forces imparted by the wind speeds discussed earlier. The weight was slowly increased until failure occurred when 307 N were applied. As predicted by the FEA model and seen in Figure 9, the blade fractured at the location of highest stress near the blade root. Given that the highest load expected load under normal operating conditions is 4.9 N, the FOS of the blades is roughly 62. This is a very high FOS, so uncontrolled vibration or another factor that induces unexpected loading outside normal operating conditions would need to occur for this failure mode to happen.

Figure 8: Benchtop blade strength setup

Figure 9: Blade fracture from benchtop strength test

2.4 Tailfin Design and Analysis

The tailfin, shown in Figure 10, is an integral component of the turbine that ensures the turbine is positioned directly into the wind to maximize power production. As the wind direction changes, the vertical stabilizer produces a restoring moment on the nacelle bearing that returns the turbine to the optimal position into the wind. A NACA 0009 symmetric airfoil was incorporated into the tailfin, which increases the restoring force compared to a flat plate tailfin.

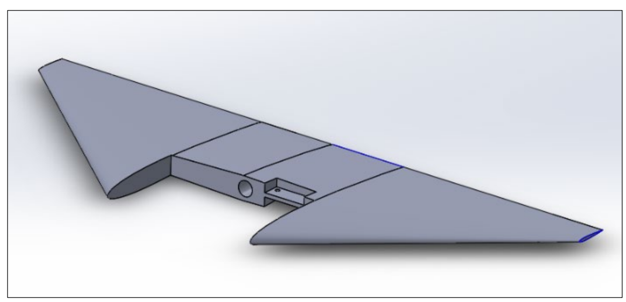

Figure 10: Tailfin with airfoil incorporated

2.5 Blade Hub and Servo Design

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. The blade hub, shown in Figure 11, is a repurposed RC helicopter rotor, the main benefit of which, is its ability to accurately 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.

A static strength test was performed to ensure the blade hub 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 12 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. The maximum force imparted by the blades spinning at 3000 RPM is roughly 70 lbs., giving the system a minimum factor of safety of 3.5. Although only one blade grip could be tested at a time, it is not believed that all three grips resisting 70 lbs. of force simultaneously would cause failure since each grip has its own structure independent of the other two.

Figure 11: Blade hub pitching mechanism

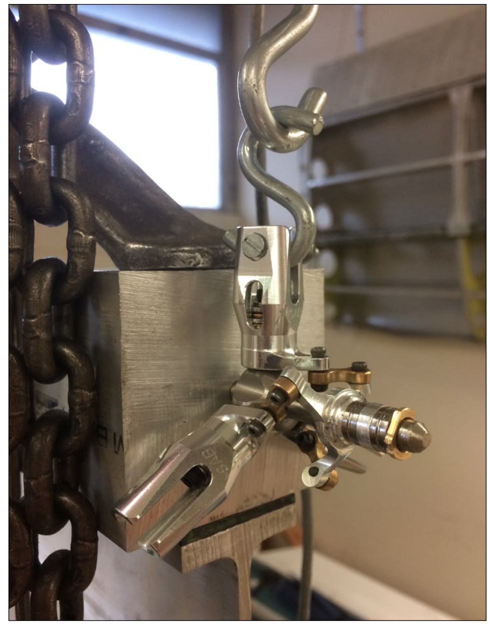

Figure 12: Blade hub strength test setup

2.6 Generator and Structure Design and Analysis

The generator and turbine structure are critical components of the turbine system as they produce electricity and support the physical components while absorbing the applied loads, respectively. The integration of the generator into the structure must be considered when designing and analyzing both subsystems since their connection and assembly process is crucial for the turbine's performance.

2.6.1 Generator Design

The generator transforms the rotational mechanical energy produced by the blades into electrical energy. It is crucial that the generator is designed in parallel with the blades and electrical system so it does not require more torque than the blades can produce and does not produce more power than the electrical system can handle. An in-house Excel code was used to design the generator stator and rotor. 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 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 can produce at every angular velocity, 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.

2.6.2 Generator Testing

Since the generator design code, described above, is not verified, it is essential to ensure a physical model of the proposed generator design performs as predicted by the code. This step is crucial since the generator is a key component of the turbine system and must perform well and furthermore, the final structural design followed the completion of the generator design. Also, testing the generator by itself works out any potential component level issues prior to testing the full system in the wind tunnel.

The generator was tested on a dynamometer, seen in Figure 13, where the RPM and electronic load resistance can be varied. The measured output parameters were torque, voltage, and current. From these parameters, the power input into the system, power produced, and efficiency were calculated. Many other important figures can be created including a power curve, C_P vs RPM, and torque vs RPM over a range resistances. All of this data was collected for one, two, and three generator stages, which demonstrated the value of additional power and increased efficiency with more stages.

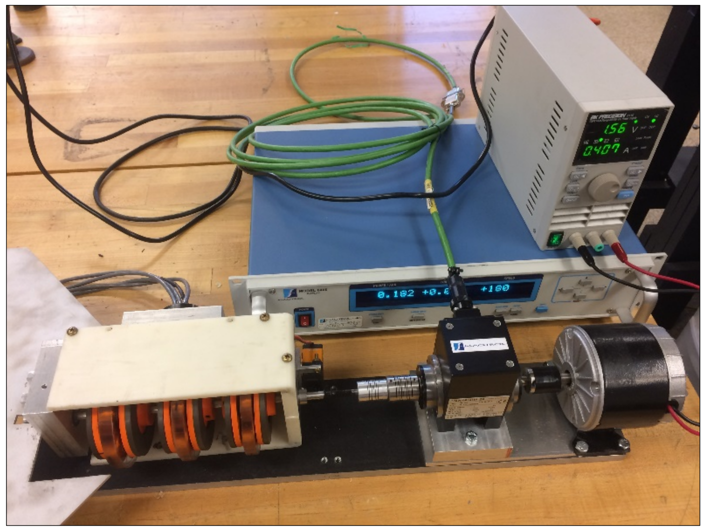

Figure 13: Dynamometer test setup

The data generated from the dynamometer test validated that the generator design would perform adequately in the system if the blades also performed as predicted. This data also characterizes the generator for all operating conditions and is essential when optimizing and automating the turbine control. See Figure 22 in Section 3.3 for the results from these tests.

2.6.3 Structure and Housing Design

With a verified generator design, the nacelle structure and housing can be designed to adequately support and encapsulate the generator. A structural failure would be more catastrophic compared to a housing failure, so the structure design is completed first. 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.

With the nacelle structure design completed, the housing must be designed to connect to the structure. The housing must shield the generator from all unwanted external substances including water and general detritus as well as 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.

2.6.4 Structure Analysis

Finite element analysis (FEA) was performed on the turbine structure to ensure it would not fail under the most extreme operating condition. This operating condition was determined to be during the durability task where the wind speed will reach 20 m/s with yaw as prescribed by the competition. The structure is designed such that the thrust force pushing against the blades is transmitted to the front face of the nacelle. This thrust creates a bending moment on the tower that must be counteracted by the baseplate's connection to the wind tunnel. If any of these structural components, the nacelle, tower, or baseplate, were to fail while testing, the blades and generator would certainly be damaged.

Abaqus was used to run the simulations and it was determined that the base of the tower experiences the greatest stress and lowest factor of safety of 531 psi and 75 FOS, respectively. Given that this factor of safety is much larger than what is necessary to prevent failure, the turbine structure should not be a point of failure under normal operating conditions. If this turbine were to be commercially manufactured, it would be financially beneficial to alter the design to have a lower FOS so each component would not be as expensive but would still perform adequately.

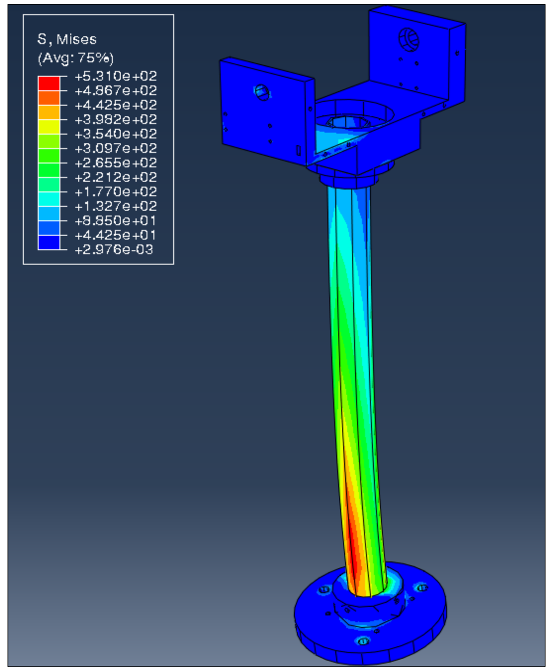

Figure 14: Turbine structure FEA results

2.6.5 Generator and Structure Construction

The turbine structure was constructed using traditional machining techniques, which produce high-strength aluminum and steel parts with relatively simple geometries. The tower baseplate, nacelle structure, shaft, and servo connector were made using this technique. The housing, and generator rotors however, have very complex geometries that are best constructed out of ABS plastic with fused deposition modeling 3D printing. This technique is very accurate but does not produce as strong a final product as traditional machining does with metals. For this reason, the plastic parts are designed to not be structural and to take minimal loads.

2.7 Electrical Design and Analysis

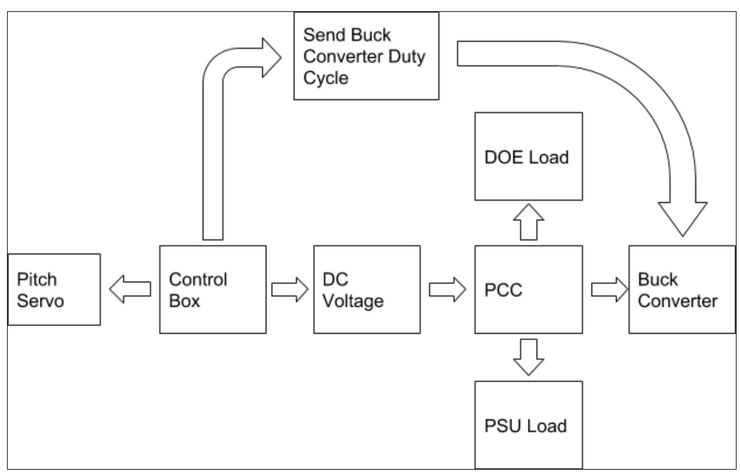

Figure 15: Electrical system control overview diagram

The blades convert the kinetic energy in the wind to rotational mechanical energy, which is input to the generator to produce AC electricity. The goal of the electrical system is to refine and regulate this power produced by the generator as well as optimize the entire system's energy production for any given competition task. To accomplish this, as shown in Figure 15, two parts of the electrical system work in tandem; the control box, which rectifies the AC power into DC power and optimizes blade pitch and the load box, which optimizes the system resistance for maximum power production for a given wind speed. There are two distinct operating modes with different algorithms for the two different testing conditions: power optimization and the durability task. The power optimization and control portion of the competition consists of a constant load resistance while the durability portion of the testing contains a variable load resistance utilizing the same control signals.

2.7.1 Control Box Design and Analysis

The turbine is controlled by an Arduino "micro" processor, which is powered by a DC regulated input voltage from the turbine power production. This control box Arduino controls pitching of the blades and the duty cycle input to the DC/DC converter. The system also continually monitors safety criteria and performs the operations necessary to brake the turbine. The first part of the control circuit, seen in Figure 16, consists of a Schottky diode bridge rectifier, which converts the three phase AC generator output into DC power. The DC power then proceeds through a buck converter, serving to maintain or optimize power production as determined through the control Arduino logic. The resultant signal then travels to the point of common coupling (PCC).

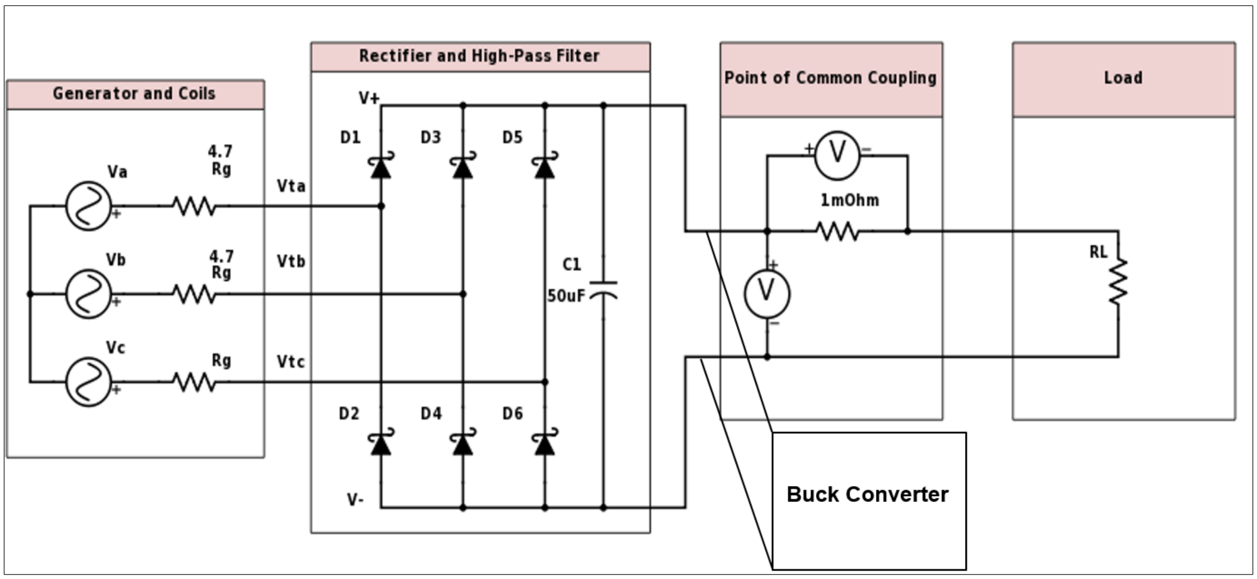

Figure 16: Control circuit and load diagram

In addition to duty cycle control, the control Arduino actuates a servo motor, which actively pitches the blades as a secondary method to optimize or control the power through the PCC. This dynamic pitch angle allows the blade orientation to be optimized both at startup and throughout power collection aspects of the competition. Tabulated data of the optimum pitch angle at a given wind speed that was collected during wind tunnel testing is hard coded into the control Arduino. The system infers the wind speed through programmed voltage relations by relating the current pitch angle and voltage output to a given wind speed to then set the corresponding blade pitch to the optimum tabulated value. Pitch optimizations are broken up into 2 m/s divisions of inferred wind speed to ensure the system pitches incrementally, as opposed to constantly, as the microprocessor continually updates the estimated speed. For wind speeds higher than the competition prescribed 11 m/s required for 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.

2.7.2 Load Box Design and Analysis

The main objective of the load box is to optimize the system resistance, and thus power production, of the turbine. This section of the electrical system is also responsible for supplying power back to the control box during the safety task. The load box is comprised of a fixed 50 ohm resistor which, when in conjunction with the buck converter's control logic, serves to alter the effective system resistance to its optimal value. The fixed 50 ohm resistor in the load box was selected for compromising between optimizing for start-up power production and power optimization at higher wind speeds. The team selected this resistance as it produced the most power at wind speeds greater than 5 m/s, while still allowing the turbine to start-up below 2.5 m/s.

The load box also serves as a power source for the control Arduino when the turbine brakes during the safety task. A nine-volt battery powers the load Arduino for the duration of testing. This load Arduino receives a boolean signal from the microprocessor in the control box to open or close an electrical switch, sending power back to the control box as mentioned previously in the safety procedures.

2.7.3 Buck Converter Design and Analysis

In addition to pitch control from the servo, a buck converter, diagramed in Figure 17, is used to maintain or further maximize power, depending on the given task. The buck converter relations allow the effective system resistance to be modified and increase power production by chopping down the turbine input voltage to the optimal value. Furthermore, in cases where the turbine produces more than the competition's 48V voltage limit, the buck converter steps down the voltage to a predetermined value. This is especially useful in the durability task, where 5V needs to be maintained across the competition provided variable load.

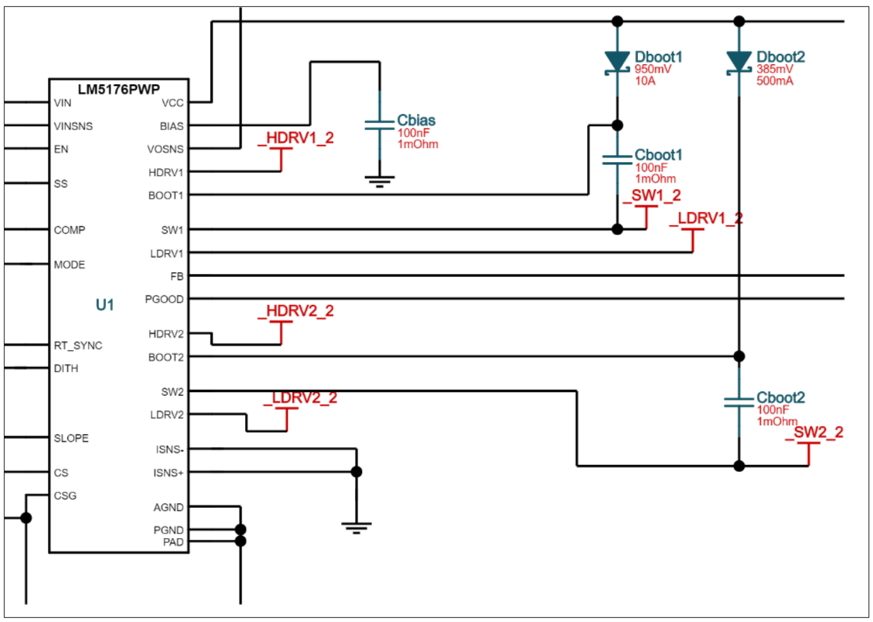

Figure 17: System-level buck converter diagram

The voltage drop is directly related to the duty cycle of the buck converter's switch. To regulate the voltage, the buck converter switching frequency is altered from an external Arduino pulse width modulation (PWM) signal from the control Arduino into a gate driver. The gate driver, included in the LM5176-44 IC in Figure 17, receives the signal from the control Arduino via an infrared diode and based on the received switching frequency, the buck converter will determine how much the voltage will drop before entering the remainder of the circuit. For the durability task, the system calculates the duty cycle of the PWM control Arduino signal required to regulate output to 5V.

2.7.4 Control Logic

The main goal of the control logic is to optimize the implemented hardware for power output within the 5 to 11 m/s wind speed range and to control the electrical output to desired values for the durability task (5V) and rated power and RPM task, where the wind speed can reach 20 m/s. To achieve these objectives, the system utilizes the control Arduino microprocessor to send signals that control blade pitch and switching frequency of the buck converter.

Before competition testing begins, the blades are pitched to an ideal startup angle determined in wind tunnel testing. Once generating five volts, the turbine powers the control Arduino, which initiates the switching frequency portion of the control system. Once producing eight volts, the servo is powered and able to change the blade pitch. At this voltage, which is reached at a wind speed less than 5 m/s by using an optimal load resistance and blade pitch combination, the control system becomes fully functional.

To optimize the power output by the system, both the blade pitch and buck converter switching frequency are modified, as shown in Figure 18. The pitch angles are determined based on a correlation to estimated wind speed. Voltage input data from the turbine is read into the microprocessor, which then uses tabulated values correlating input voltage and estimated wind speed. The system then looks through a table of the experimentally determined optimal pitch angles at this given wind speed and sends this information to the servo to alter the blade pitch to the specified angle. These experimentally determined values are based on State College conditions but will be updated at the competition to account for the different air properties. This process repeats until the voltage reaches a critical level of 45V, giving a small buffer for the 48V competition limit, signaling the buck converter duty cycle to regulate the output voltage. Given an input voltage, the necessary duty cycle is calculated and corresponding PWM pulse sent from the control Arduino to the Mosfet. This stabilizes output voltage at the threshold and prevents incremental increases in the voltage past competition limitations.

During the durability task, new code is implemented, the logic of which is shown in Figure 19. The voltage is regulated via the same method described above of using the buck converter and PWM. However, the maximum allowable voltage is restricted to 5V to refrain from frying the ultracapacitor and to regulate the voltage drop across the load. A significant portion of the ultracapacitor is not charged so it can act as an additional sink given the case of excess power output in the remainder of the durability test. After the charging portion of the durability task is finished, the buck converter steps down the input voltage to a consistent five volts using the equation $5 = V_{in} * d$, where V_{in} is the DC input voltage produced from the rectifiers and d is the duty cycle of the PWM signal sent from the microprocessor. If the turbine does not produce enough power for this five volt requirement at the given wind speed, the ultracapacitor discharges and supplements the power input. If too much power is produced, the system begins to pitch the blades out of the wind to prevent the ultracapacitor from overcharging with the excess power.

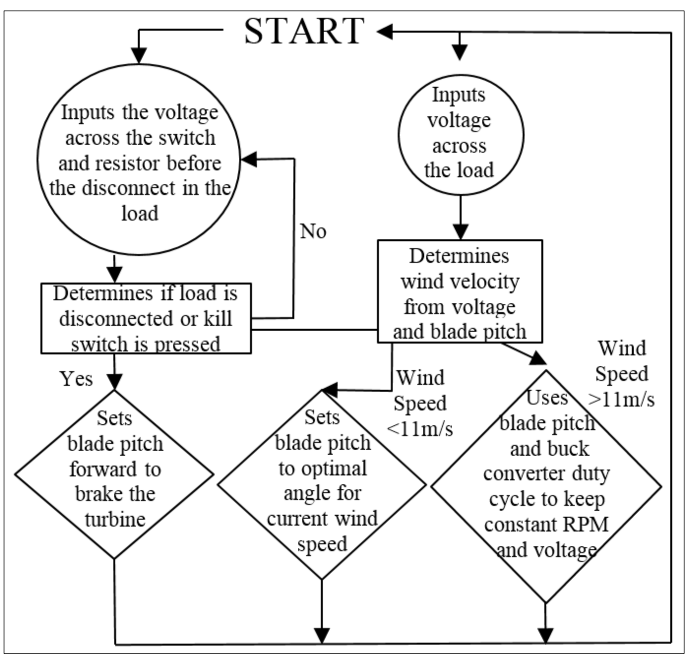

Figure 18: Normal operation control flow chart

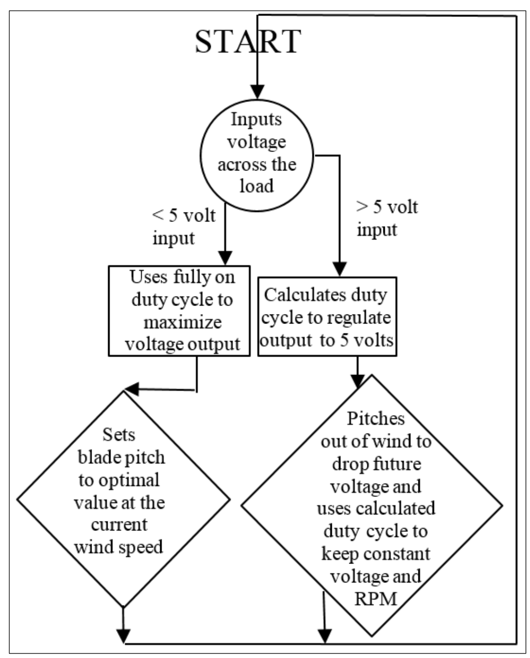

Figure 19: Durability task control flow

2.7.5 Safety Tasks

The system is tasked with braking and restarting the turbine under either a PCC disconnect or the triggering of a kill switch. Two main procedures have been implemented to stop the turbine in response to these signals. The first, a kill switch, signals the control Arduino to pitch the blades out of the wind to prevent further power production. At this pitch angle, the lift force produced acts in the opposite direction as normal operation. A one-way clutch bearing prevents the blades from spinning in this direction and stops power production. The system still reads the voltage drop across the load and if the control Arduino senses this to be zero, it deduces that there must be no current running through it. This indicates a disconnect, causing the servo to pitch the blades to the brake pitch subsequently stopping the turbine.

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 output ceases. The control Arduino then continually monitors the aforementioned brake cases. When the braking condition is changed, being the kill switch flipped back or the PCC reconnected, the 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.

3.0 Wind Tunnel Testing

Throughout the year, wind tunnel tests were run to gather data on the current performance of the turbine, which gave insight into how the turbine design could be improved as well as how the turbine's performance could currently be optimized. The wind tunnel used on campus provided a few challenges when predicting the turbine's performance at competition. The first of these is the blockage effects caused by the small tunnel cross-section, which makes the measured wind speed higher than the actual wind speed. The blockage effects were combated by calibrating the wind tunnel and adjusting the measured wind speed to better match the actual wind speed in the data. The second challenge was predicting performance in Colorado while testing in Pennsylvania, where the air is much denser. This was accounted for by scaling down the wind speeds so there was less power in the wind, as if it was less dense for the same wind speed.

3.1 Wind Tunnel Testing Objective

The ultimate objective of the wind tunnel testing was to document how the turbine performed under every operating condition so optimization algorithms could be produced to control the turbine at competition. The turbine performance was quantified by measuring the current, voltage, and RPM at every operating condition, which constitutes variable wind speed, blade pitch angle, and electronic load resistance. Table 1, which shows the turbine inputs required for each competition task, was used to ensure the turbine system could complete each task and to run wind tunnel tests that demonstrate each task will be completed.

Table 1: Turbine inputs and expected outputs for competition tasks

	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	<20	N/A	0	0
Control of rated power & rotor speed	Yes	Yes	12-20	Variable based on wind speed and blade pitch	11m/s power performance	11m/s power performance
Durability	Yes	No	6-20	.625 - ~∞	Variable based on wind speed and load value	5

3.2 Wind Tunnel Testing Procedure

The wind tunnel testing objective required that six data points be collected for every operating condition tested; three input conditions, wind speed, blade pitch angle, and load resistance, as well as three output variables, current produced, voltage produced, and RPM.

To simulate the power production task and make the power curve shown in Figure 20, four wind speeds of 5, 7, 9, and 11 m/s were tested and maintained constant by the wind tunnel's control system. Six to eight blade pitch angles were tested, depending on the wind speed, that ranged from steeply pitched into the wind, horizontal blade tip, to almost pitched out of the wind, vertical blade tip. This angle was recorded as Arduino pitching angle in the control code and does not have any relation to aerodynamic angle. As many as ten load resistances were tested ranging from 100 to 8 ohms on an electronic load. Since a given wind speed and blade pitch angle produces a fixed amount of torque, some low resistance values required too much torque to spin at lower wind speeds, so they were not viable operating conditions and therefore no data was collected.

The voltage and current produced were both measured on an electronic load while the angular velocity was measured with a strobe light. This data collected during testing was used to calculate the power produced, power in the wind, C_p, and tip speed ratio (TSR). This data provides insight into the turbine system characteristics that can be programmed into the control logic to optimize power, voltage, and RPM for each competition task.

With a Weibull distribution and the power curve determined from wind tunnel testing, the annual energy production was estimated for the turbine in locations with annual average wind speed between 3 and 8 m/s, as shown in Figure 21. The Weibull distribution was calculated using a shape factor of 2 (Rayleigh) and a scale factor which is correlated to the annual average wind speed, $\bar{u}$, by $\lambda = \frac{\bar{u}}{\left(\frac{\sqrt{\pi}}{2}\right)}$. To get the weighted energy, the Weibull distribution values were multiplied by the power curve wattage and the number of hours in a year. The annual energy for each average wind speed is then the sum of all the weighted energies. The following graphs display the power curve of the specified turbine and the average annual energy production curve produced for each given average wind speed.

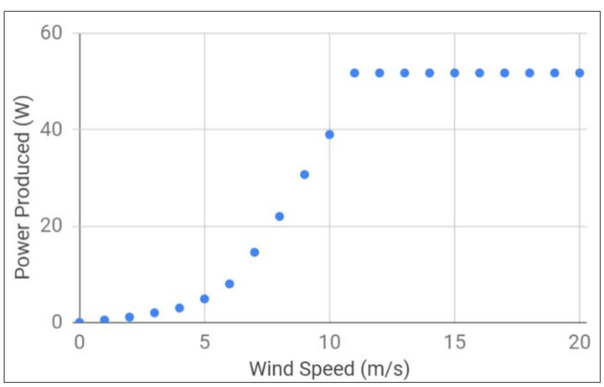

Figure 20: Power curve in State College, PA

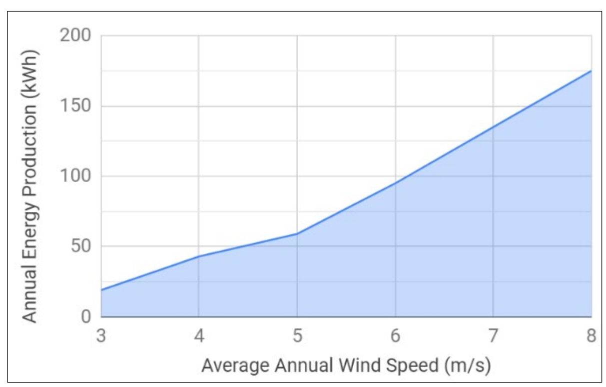

Figure 21: Test turbine annual energy production

3.3 Wind Tunnel Testing Results

Figure 22 is the final product of the dynamometer and wind tunnel testing. It shows the power curves produced in the dynamometer testing discussed in section 2.6.2 overlaid with the maximum Betz and actual power determined through wind tunnel testing. This figure is crucial to visualize the turbine's operating range and the relation between electronic load value and power produced. This data is programmed into the control logic, in some capacity, for each task to optimize power production, voltage production and/or RPM. See Figures 23 and 24 in the Appendix for the full results from these tests.

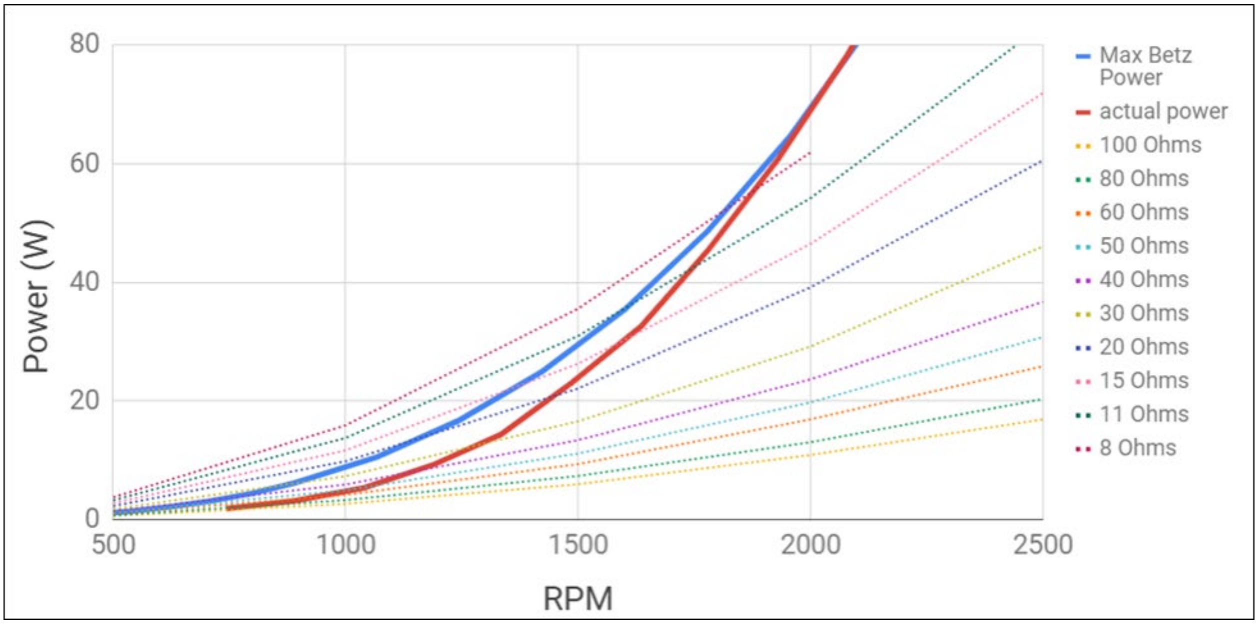

Figure 22: Dynamometer and wind tunnel data for power vs RPM

4.0 Conclusion

Table 2 shows a summary of the wind tunnel testing completed prior to competition, which indicates that the turbine, as a system, should perform as intended for all competition tasks when the electrical system uses the reference voltage, blade pitch, and wind speed data to produce the optimal output for a given task. Testing at 6000' elevation in Colorado poses energy production challenges but the team is prepared to solve any remaining issues during the practice testing sessions. Given this, the team expects to produce a competitive score at competition.

Table 2: Pre-competition wind tunnel testing results summary

Task	Pre-Test	Comments
Cut-in wind speed	~ 1.75 m/s	Cut-in in Colorado will be greater than 1.75 m/s but less than 2.5 m/s
Power curve performance	Average total C_p of 0.122	Power produced will be lower in Colorado
Safety	Functions as expected	
Control of rated power & rotor speed	Power w/in 20% of 11m/s power RPM w/in 15% of 11m/s Rpm;	Power not tested in wind tunnel but expected to perform identically
Durability	Voltage within 30% of 5V Yawing works as intended	Only yawing tested in wind tunnel but expected to perform identically

5.0 Appendix

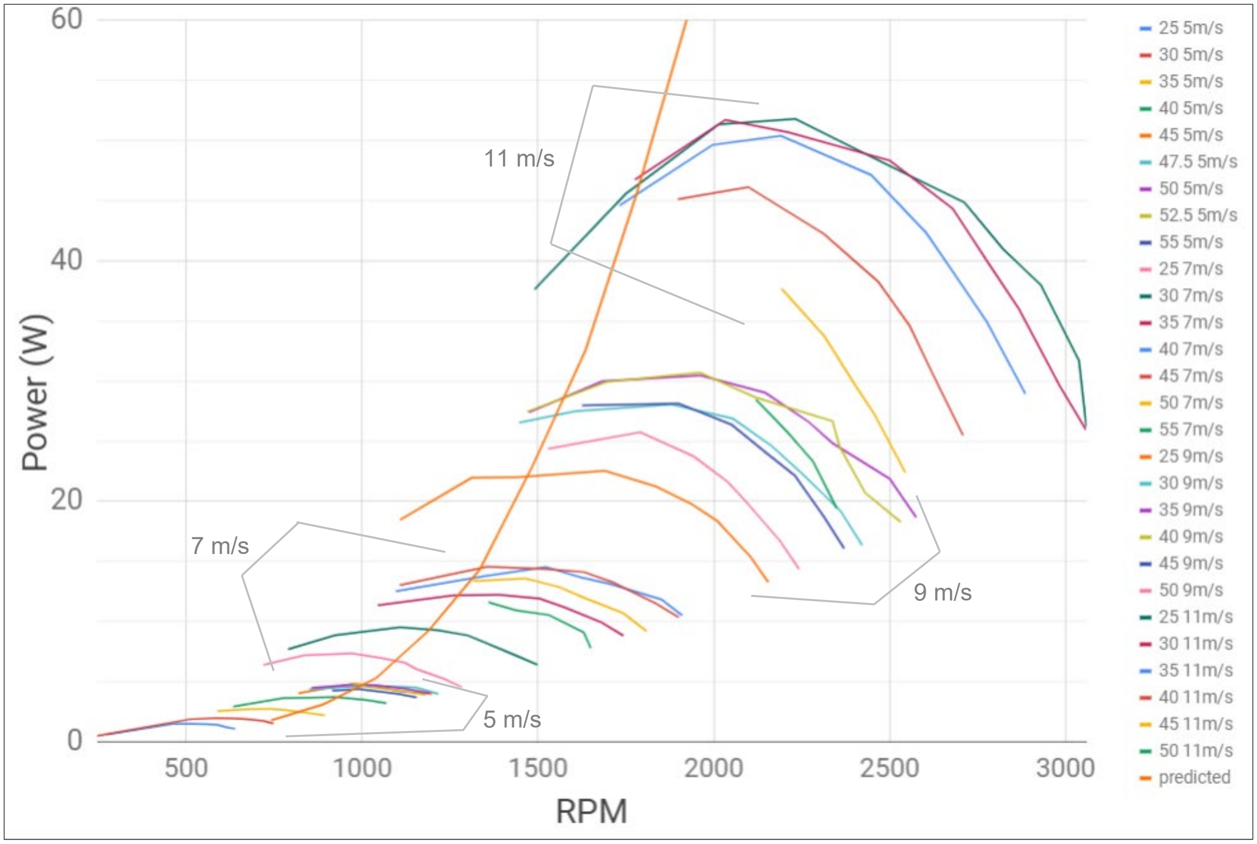

Figure 23: Power produced vs RPM for wind tunnel testing

In Figure 23, every continuous data plot is showing the power produced at the recorded RPM with blade pitch angle and wind speed held constant. Each individual arc was produced by holding blade pitch and wind speed constant while varying the electronic resistance. The legend indicates the blade pitch angle and wind speed. A data set of “35 9m/s” would have an Arduino code blade pitch angle of 35 at a wind speed of 9m/s. The orange exponential plot shows the predicted power produced given the power in the wind, the generator efficiency from the dynamometer testing (Section 2.6.2), and the blades’ C_p.

This data is used to characterize the entire turbine system and evaluate how well it performs under varying operating conditions. This allows the team to make changes to the subsystems to improve performance and provides insight into how the turbine should be controlled during competition testing to produce the highest score possible.

This figure shows that the turbine is not producing as much power as predicted at higher wind speeds and RPMs. One cause of this was that the radial servo motor used to pitch the blades was drawing a large amount of power. Also, inaccurate wind speeds due to blockage effects incurred from testing in the wind tunnel could also be a cause for the difference in actual and predicted values.

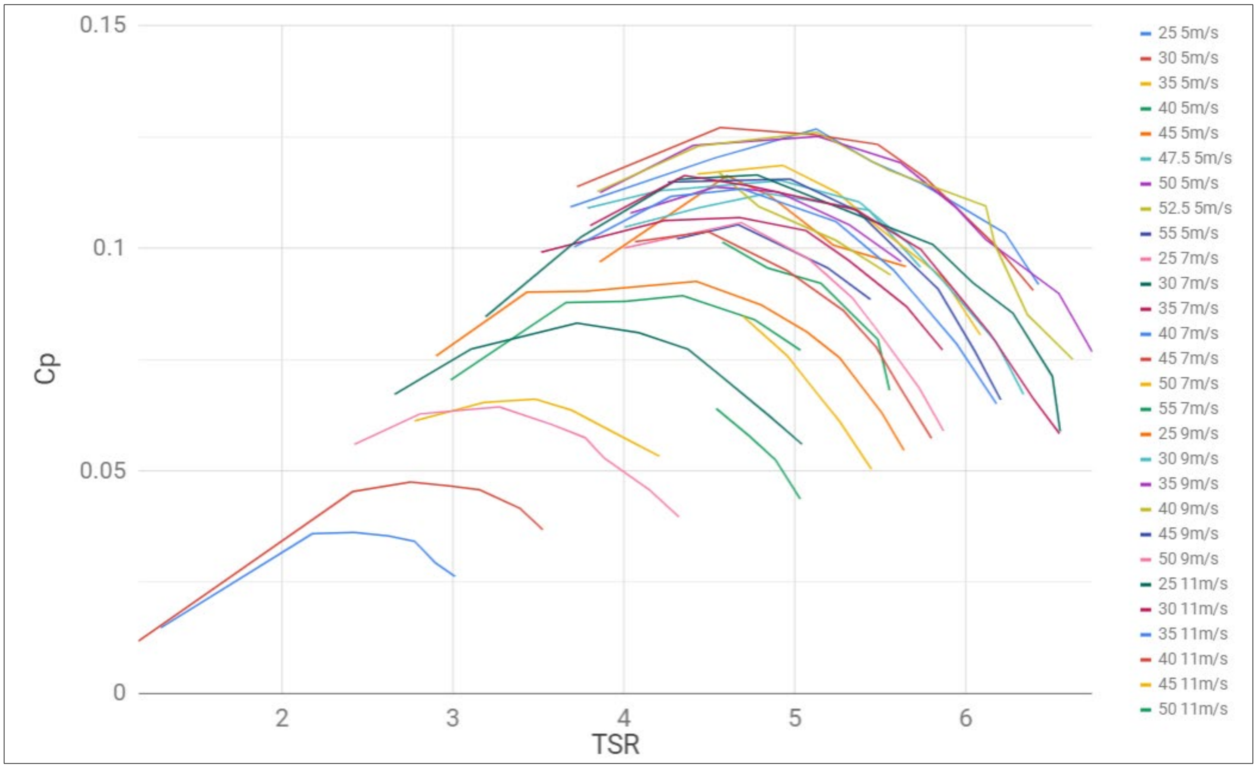

Figure 24. Cp vs TSR for 2018 test turbine configuration.

Figure 24 shows the same data displayed in Figure 23 that was collected during wind tunnel testing except further processed to show the turbine's overall C_p and tip speed ratio (TSR). Each individual data set shows the data collected for a constant wind speed and blade pitch angle. The legend differentiates between the data sets with the Arduino pitch angle and wind speed. "35 7m/s" means the blade pitch was an Arduino code angle of 35 at a wind speed of 7m/s. Each individual arc is created by varying the electrical load resistance for the constant pitch angle and wind speed.

This data shows the optimal operating range for the turbine is between 4.5 and 5.25 TSR values, producing maximum C_p values of about 0.125. Although this data is more difficult to decipher compared to the data provided in Figure 23, it is still valuable as it provides insight into how the turbine and its subsystems operate and interact with each other. Knowledge of the most favorable operating range allows the team to further analyze the blades in this region and to design new blades that can perform better over a larger region. Similarly, the team can also analyze the current generator and design a new generator in parallel with the blades that will maximize the C_p values for a large TSR range.

```
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 25: Code to pitch to optimal angle for a given wind speed

Figure 25 is an excerpt of code that is 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.

```
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 26: Code to brake turbine and signal braked condition

Figure 26 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

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[1] Department of Energy, 2019 Collegiate Wind Competition Rules & Requirements, https://www.energy.gov/sites/prod/files/2019/01/f58/CWC%202019%20Rules%20and%20Requirements%20Manual_20190104_0.pdf Accessed 4/21/2019.

[2] Schmitz, S. XTURB-PSU: A wind turbine design and analysis tool, http://www.aero.psu.edu/Faculty_Staff/schmitz/XTurb/XTurb.html 2012.