BOISE STATE UNIVERSITY

VENTO: Wind Power Generator Design Portfolio

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Boise State University

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Mechanical Engineers

Michael Sansom - Mechanical engineering senior Michael Sansom took on the role of project manager for the majority of the development process. He had previous project management experience through an internship, so coordinating was a natural fit. During the initial design phase, he supported the team with research and selection of building materials. Michael was responsible for ordering the turbine parts and creating an engineering change order after the initial prototype's catastrophic failure. Michael also had previous SolidWorks experience, including FEA (finite element analysis), and was able to help test the redesign before production.

Luke Weaver - Utilized blade element momentum theory to design blades. Determined blade forces and aerodynamics, which allowed for power curve prediction. Determined optimal operation tip speed ratio. Optimized, modeled, tested, and revised blade design. Oversaw blade manufacturing and nacelle design, as well as analyzing full system aerodynamics.

Cody McConkey – Performed dynamic analysis and braking calculations. Assisted with airfoil redesign and performed FEA using SolidWorks. Worked with Electrical Engineers to optimize electrical system for maximum power output. Instrumental in developing the business model.

Calvin Brown -- With a strong background using Solidworks, Calvin was well suited for modeling the turbine during the initial design as well as for all FEA. His experience working with machinists also made him the primary candidate to machine the parts. He produced most of the dimensioned drawings for the assembly as well.

Electrical Engineers

Stephen Stauts – Wrote control algorithms and software for the microcontroller. Designed and implemented embedded circuitry for logical functions, braking system, and interfacing the microcontroller with the power electronics. Oversaw electrical system integration with the turbine, as well as the implementation of the controllable-motor system for testing and debugging the electrical system in a laboratory environment. Analyzed system testing results to refine control algorithms and microcontroller functionality.

Adrian Reyes - Worked on wind turbine modeling and hardware. Modeled wind turbine by integrating mechanical interface model and electrical interface model. Implemented 3-phase rectifier circuit for AC-DC signal conversion. Implemented DC-DC boost converter circuit based on microcontroller capabilities. Assisted in wind turbine testing in laboratory environment. Assisted in system analysis for performance improvement and modification.

Brian Dambi – Worked on design conception, research, implementation, and testing. Performed project management tasks. Collaboratively modeled electrical system from generator input to load for design verification. Assisted in 3-phase rectifier and DC-DC Boost Converter circuitry implementation. Assisted in electrical subcomponent testing, electrical system testing, and integrated mechanical and electrical testing. Designed and implemented final PCB board layout.

Firas Almasyabi – Helped to design and analyze the three-phase diode bridge rectifier and boost converter. Performed system simulations in LTspice and MATLAB Simulink, as well as calculating component values by hand and MATLAB code. Developed power curves for data gathered during various system tests involving the turbine integration.

Haitian Xu – Assisted in designing the diode-bridge rectifier and boost converter. Used LTspice and MATLAB Simulink to simulate various modules and integrate them properly into the electrical system. Researched calculated components and their necessary values for correct functionality in the system. Gathered and analyzed data from the turbine integration testing.

Design Objectives

***1.)* Increase interest in engineering and renewable energy through hands-on learning activities and demonstrations.**

In the classroom, students are rarely given opportunities to work hands-on with new and relevant technologies. By creating these opportunities, the wind turbine can improve the quality of the learning experience for students of all ages while raising awareness about renewable energy and engineering as a career.

The basic concepts of the turbine can be introduced to students at a very young age through demonstrations. Older students will have opportunities to touch and make adjustments to the turbine's components, while observing the effects that those adjustments had on the operation. Observing these cause and effect relationships lead students to ask why, and opens the door for discussion and critical thinking. For higher education students, the turbine can be used to verify calculations and test circuits by harvesting energy from the wind. By creating a memorable, engaging and hands-on learning experience using the wind turbine students will become more interested in engineering and renewable energy.

2.) Create interesting hands-on learning opportunities that relate classroom learning to real world applications.

The goal of this design is to create as many learning opportunities as possible with a single device while achieving all the performance requirements of Collegiate Wind Competition. By creating hands-on learning opportunities, students will get a better understanding how their classroom learning applies in the real world. Many components of the turbine were designed to be easily adjustable so students can make alterations to systems and then observe any changes in operation. The following subjects were identified as possible learning opportunities, and specific features were designed to maximize learning potential in each subject,

A.) *Mechanics*. The nacelle was intentionally designed to have no side walls so that all mechanical components could be seen and heard by students, and adjustments could be made easily. Being able to quickly adjust components like the gearbox is essential when learning, so that estimations can be verified and any changes in operation can be observed and documented.

B.) *Aerodynamics.* Changes in the shape or alignment of an airfoil have significant effects on its aerodynamic properties. To demonstrate these effects, the turbine was designed with removable airfoils that can be swapped out for other airfoil shapes, or simple drag-based blades that will be offered.

C.) *Power Systems*. The 3 phase AC generator selected to be used with the wind turbine outputs power that is similar to that seen with large scale generators. This type of generator will give students the opportunities to learn about the differences between multi-phase alternating current (AC) and direct current (DC) and grid integration.

D.) *Circuits*. The generator will produce outputs that vary in frequency, voltage, and current, all of which are affected by the external load that is present. All the electronics needed to operate the system and record data are included, but students will also be able to build their own circuits and test them using the wind turbine. Advanced students should eventually be able to build circuits that can charge batteries or provide other useful services.

3.) Meet all of the performance requirements for the Collegiate Wind Competition.

Although important to the scoring during the competition, some of the performance requirements established by the Collegiate Wind Competition were not essential to the marketability of this turbine. In order to create the most realistic experience possible for students, it was decided that the performance of the prototype turbine should meet or exceed all of the requirements outlined for the CWC. Special considerations had to be made when designing the drivetrain and electrical systems to ensure that all the required output conditions are met. Some of the systems required to regulate the voltage are only essential for the competition and may actually take away from the educational value the turbine.

In order to meet these performance requirements while maintaining the educational value of the turbine some components from the prototype will be removed or altered for the market version. Since there is no specific load requirement for the market turbine, a potentiometer will be added to the system so the effects of the external load can be observed in real time. Adding the potentiometer has little effect of the performance of the turbine and further increases its educational value.

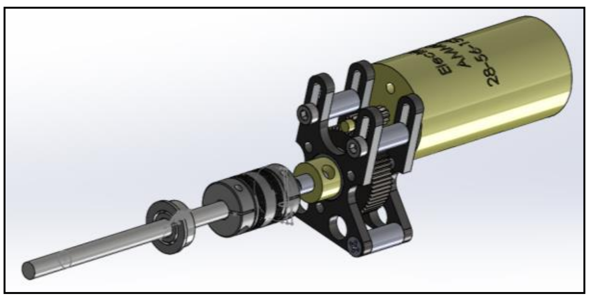
Design Overview

The overall design of the wind power system involved the integration of a mechanical turbine, power electronics, and microcontroller to provide regulated power over a range of wind speeds. The following sections outline each module of the mechanical and electrical systems and how they are integrated with one another to create a single, functional system.

Rotor

The rotor consists of three blades with cylindrical pins at the root that insert into the hub and attach using a single 5mm shoulder screw. It is responsible for converting the power from the wind into shaft rotation. To do this, the blade was designed to create a pressure difference on between the top and bottom of the airfoil that causes the turbine to spin. The blades utilize Betz optimized twist and chord distribution and contain a combination of profiles from NREL's S833, S834, and S835 airfoils.[1] For the prototype, all these components were 3D printed using Somos 14120 plastic.

Drivetrain



The rotational movement developed by the rotor is transferred to a small steel shaft that is connected to the gearbox with a flexible helical coupler. The coupler is essential to the safe operation of the wind turbine because it absorbs the vibrations and external forces from the rotor before they reach the gearbox or generator. This will increase the lifetime of these components while effectively transferring power to the generator.

The gearbox used for the turbine increases the rotational speed of the rotor by 2.5 times in order to output the proper voltage from the generator. An additional benefit of this gearbox is the adjustability that gives users the opportunity to try four different gear ratios which increases the educational potential of the product. Additionally, this entire subsystem is composed of off the shelf parts that can be purchased directly.

Generator

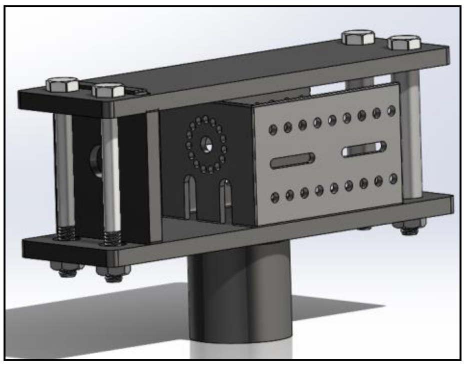
The type of generator used for the turbine is the Electrifly 450 Watt motor. The motor has a low kV rating of 1530 kV, meaning it will produce 1 Volt at 1530 RPM and is capable of reaching rotational speeds of 15,000 RPM. The motor was also selected because it produces enough torque to safely

[1] http://wind.nrel.gov/airfoils/Documents/S833,S834,S835_Design.pdf

shutdown the turbine using dynamic braking. Using dynamic braking also reduces the cost of the turbine because no braking system needs to be purchased or maintained.

This 3-phase brushless AC motor is important to the learning value of the product because the 3-phase output of the generator is similar to that of large scale wind turbines and will give students a realistic view of the actual output of large scale generators. It also gives students the opportunity to learn about grid integration while building circuits that convert the AC output into usable DC capable of charging small batteries or electronic devices. The generator is another off-the-shelf part.

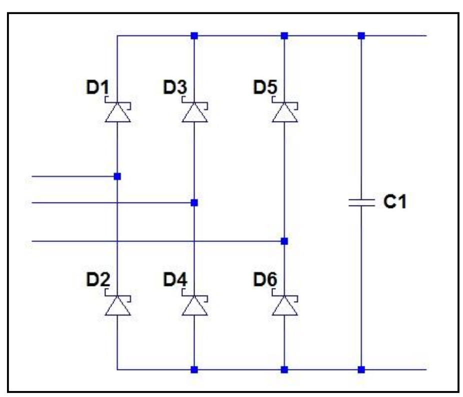
Nacelle



The nacelle was specifically designed to have no side walls and consists of a machined aluminum bearing mount plate in the front and bushings in the rear that are sandwiched between two plates and held together using four bolts. The top and bottom plates were machined from aluminum and have grooves that allow for the bearing plate to be adjusted horizontally and the bottom plate was machined so that it can be set on top of a pole. The generator and gearbox are mounted inside the nacelle using an off-the-shelf mounting bracket that is supplied by the same company that produces the generator.

The open nacelle design allows students to see and hear the inner workings of the turbine during operation. The open design also allows the user to make adjustments quickly and easily, without having to disassemble the entire turbine. Using no side walls also reduces the production costs associated with the nacelle, while remaining fully functional.

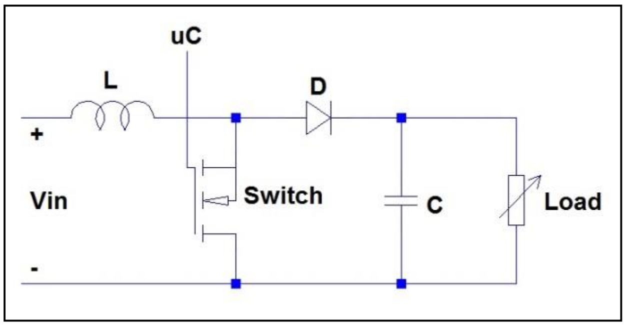
Three-Phase Rectifier



The three-phase rectifier takes the three-phase AC power from the generator and converts it into single-phase DC power. This is accomplished through the use of six diodes that work in harmony to pass current in specific directions. Since single-phase DC power has only two polarities (positive and negative, or positive and ground), positive power is pushed into the top common wire and negative power pushed into the common bottom line, or ground. With two diodes on each phase, the positive power of each AC phase is sent to a common line (top line). With each phase being 120° (or one-third) out of phase with the other lines, this creates an average single-phase power.

For a power application, Schottky diodes are used because of their small forward voltage drop, or voltage loss, as they conduct current. This feature allows for less power loss and higher efficiency across the rectifier. Additionally, a capacitor is added for signal noise reduction on the output.

DC-DC Boost Converter



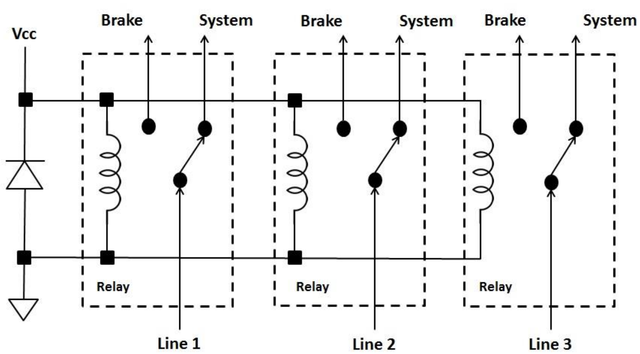
The boost converter is a DC-DC converter that takes an input voltage and increases it to a higher output voltage. This is accomplished through the use of an inductor, diode, and switch, with the switch being operational control of the circuit with two states: on and off. When the switch is on, current passes through the inductor and switch to ground, energizing the inductor. When the switch is off, the inductor discharges its energy through the diode and into the capacitor and load, charging the capacitor. When the switch is once again closed, the current charges the inductor and ignores the diode due to the switch being a less resistive path to ground. During this time, the capacitor discharges into the load, once again applying power to the output. This operational functionality of a boost converter is called “continuous-current mode”.

By changing the frequency and duty cycle (percentage of time closed over its period) while in continuous-current mode, the output voltage can be regulated at a particular level. This allows for a changing voltage input to be held at a constant output at a desired level by controlling the switch with a pulsed signal from the microcontroller.

Microcontroller

The microcontroller used for this system is the STM32F4 Discovery; a powerful ARM processor capable of sensing and controlling multiple facets of the electrical system and generator operation. Primarily, the microcontroller serves the system by applying a pulse signal to the switch to toggle it on or off. By adjusting the percentage of time that the switch stays on, or open, the output of the boost can be regulated to maintain a constant 5V to the output. Additionally, the switch's duty cycle adjusts the resistive load "seen" by the generator, adjusting the turbine's rotational velocity to increase or decrease the current through the system. To adjust this duty cycle, the microcontroller analyzes the rotor frequency and current across the load to calculate the system power and torque on the generator. The duty cycle is altered and then maintained at a level that matches the desired torque for a power output based upon the system's power curve.

Relay System and Dynamic Braking



The braking system is a set of three relays, each of which is connected to one phase of the generator and act as a switch to toggle the path of incoming power. Each relay has a main input line that is connected to one of two output pins. When an internal coil is energized, the switch that connects the input with one output toggles to the other, holding that state until the coil is de-energized. The coil itself is energized by a digital output of the microcontroller. When braking is activated the switch closes, allowing for current to pass into each relay and energize them synchronously. This diverts all three phases into a bank of very low-Ohmic resistors at once, essentially shorting the system and causing a large amount of current to feed back into the generator and stop it. In order to limit the amount of surge current generated from the short, the toggle between primary system and braking bank is toggled by pulsing the switch on and off, eventually keeping the brake constant after a short period of time.

Additionally, a second digital switch exists in parallel with the first that is kept closed by signal from the controller and logic inverter. If the controller dies or fails, the inverter signal goes from low (off) to high (on) and opens the gate to allow current to bypass the primary switch. This is called a “dead-man’s switch” and serves to protect and halt the system during controller failure.

Modeling and Testing

The blade design utilized blade element momentum theory, which calculated the lift forces generated by the airfoil. For the initial design, we chose a tip speed ratio of 4.5. At a cut in wind speed of 5 m/s, this corresponds to a rotation of ~1000 rpm. The twist and chord distributions were calculated using Betz theory. The profiles are shown below.

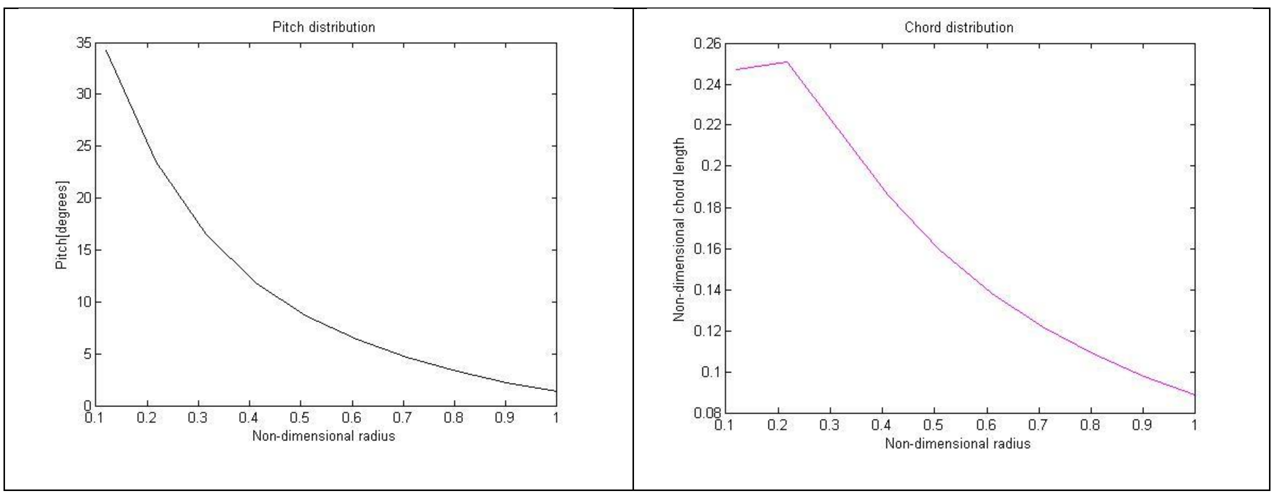


Figure 1. Pitch and Chord Distribution

These profiles allowed for force distributions to be calculated. Figure 2 shows the forces along the non-dimensionalized radius between 5-14 m/s.

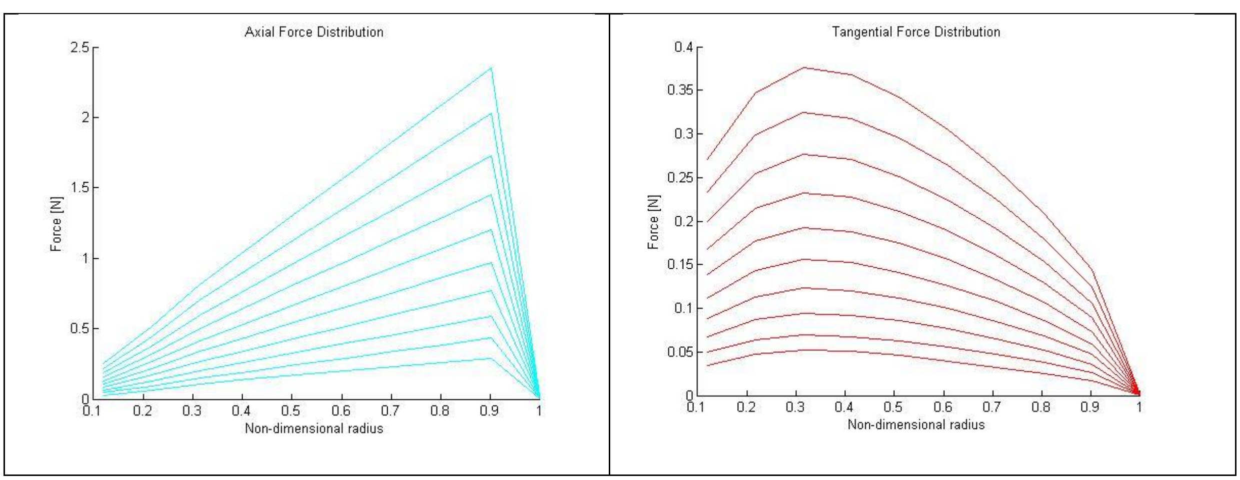


Figure 2. Blade Forces

The tangential forces cause torque, which allows the power to be calculated. The theoretical power curve for the system is shown in Figure 3.

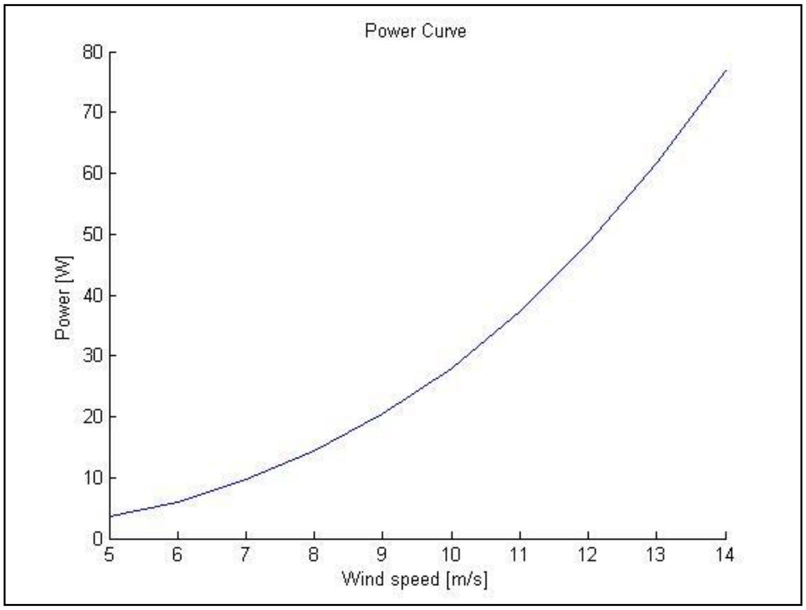


Figure 3. Power Curve

The theoretical cut in power of the wind turbine, at 5 m/s wind speed, was 3.55 W. The maximum theoretical power occurred at a cut out speed of 14 m/s and a power of 77 W. The power coefficient is ~.3. This is higher than expected, but with no drag forces, it is a reasonable initial estimate.

The testing procedure for our prototype was split into three phases: component level tests, tests of the mechanical system, and tests of the complete integrated system including optimization. The tests were centered on the testing procedure for the NCWC.

Phase I, the component testing and modeling, consisted of tests of the three subsystems: blade/hub, drivetrain, generator, and nacelle/tower.

For the blade and hub modeling, FEA was used to determine the durability of the parts. The blade forces were calculated in the tangential, axial, and radial directions, and applied to the blade/hub assembly in the appropriate locations (See Figure 4). The blade forces in the tangential and axial directions are the summation of component forces from the airfoils, calculated using blade element momentum theory. The radial forces are caused by centripetal acceleration due to a high rate of rotation and deceleration of the blades during braking. The maximum estimated forces were all applied to the blade at the tips to give a conservative estimate of the stresses. Figure 5 shows the FEA analysis on the original blade.

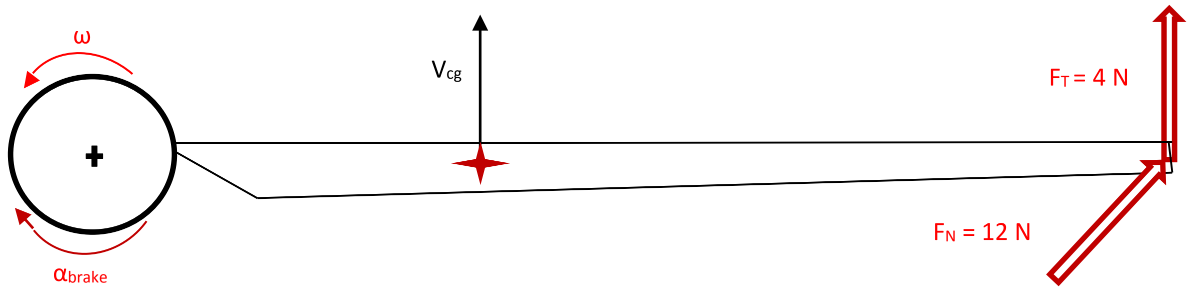


Figure 4. FBD of single airfoil. This diagram shows the placement of the loads for FEA modeling.

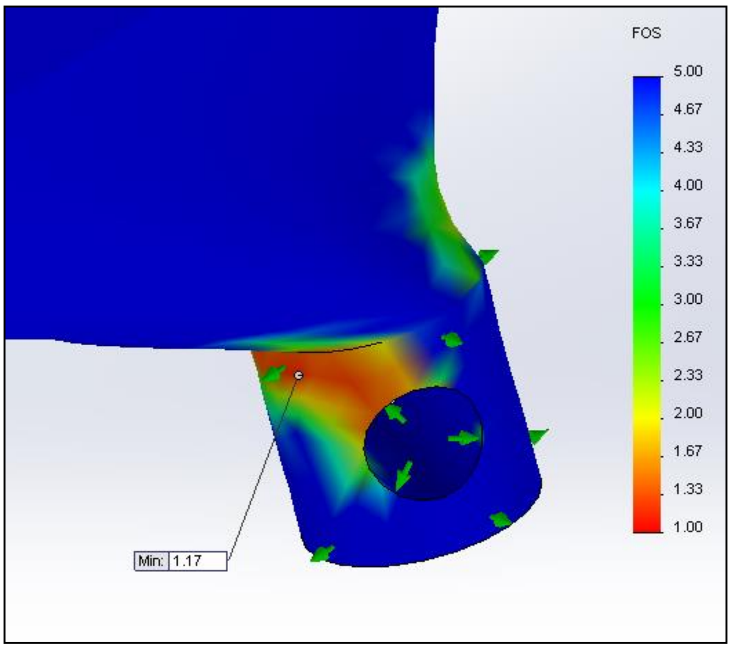


Figure 5. Initial FEA performed on original blade design at 4000 RPM and 0.1 s braking time

The original nacelle and tower tests were similar to the blade/hub assembly—performing FEA—but the force analysis of the blades showed a very low overall force of less than 50N on the nacelle and tower. Since the nacelle and tower were designed with relatively thick aluminum, the forces were determined to be negligible.

The drivetrain test was relatively simple, but was crucial to the operation of the entire system. The goal of the test was to ensure that the gear train properly translated and increased the rotation of the input shaft to the generator. After determining that our drivetrain was working properly by connecting the gearbox to the generator, we moved to Phase II of our testing.

Phase II consisted of constructing the entire mechanical system and verifying proper operation. First we verified that the rotor could spin properly, that the driveshaft was connected to the generator through the gear box, and that the generator was producing a voltage.

Once the turbine was working properly, we tested the turbine in a wind tunnel. Without the electrical load, we attached the turbine to the wind tunnel base and increased the wind speed until a voltage was recognized between the blades. Because the dynamic braking system wasn't included at this point, we only tested at low wind speeds.

Phase III of the testing was where the NCWC objectives were attempted to be met. The first test measured the cut-in wind speed of the turbine. The cut in wind speed is defined as the lowest wind tunnel wind speed at which the turbine generates 5V with a positive current. To test the cut-in wind speed, we connected the turbine to the load and steadily increased the wind speed until a 5V voltage was measured.

The second test was designed to measure two properties at once: the rotational speed of the turbine and the power curve at every wind speed between 5-14 m/s. We started by increasing the speed in the wind tunnel to the cut-in speed, then attempted to record the power and rotation at every wind speed between 5-14 m/s. However, during the first round of testing, the blades failed under a sudden surge of current due to the unrefined dynamic braking system. Instead of slowly dissipating power through a resistor, the leads to generator were shorted, causing a large surge in torque and a rapid deceleration of the rotor. When the dynamic braking system was applied, failure occurred at the interface between the hub and airfoil which was determined to be a critical point during initial modeling. The FEA performed on the blades did not account for a sudden stopping force, as we had assumed the braking would occur over 10 seconds. An example of the stresses the blades experienced is shown below in Figure 6.

To prevent future failures and ensure safety of operation, the connection point between hub and airfoil was modified. To improve the strength, the diameter of airfoil connection pin was increased by 0.25 cm and the width of the hub was widened. These changes significantly increased the strength of the connection between the hub and airfoil. Testing of the new rotor design proved it is capable of withstanding 17 m/s winds while operating at 3500 RPM.

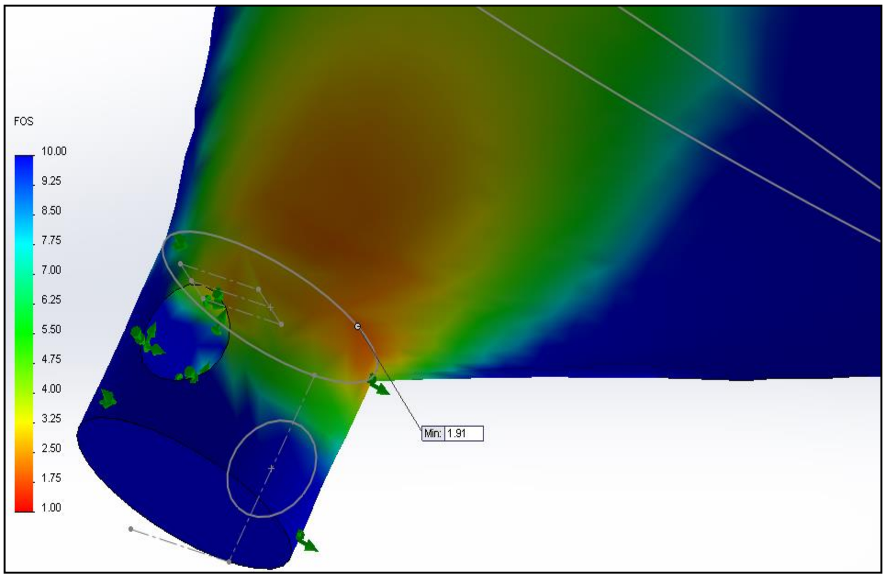


Figure 6. FEA results after redesign. RPM = 4058 and stopping time = .1 seconds.

For the second iteration of the blade design, the pitch angle at the root was increased 5 degrees, and the root of the blade doubled in size. The purpose of these changes was to decrease the cut-in wind speed, and to decrease the likelihood of failure at the blade root. FEA was performed on the blades with higher forces due to more extreme braking conditions, and the blades still passed the FEA.

For the second round of testing (with the new blades), cut-in wind speed was again tested, along with the power curve and RPMs. The new results are shown below.

Table 1. Testing Results

Wind Speed (m/s)	5	6	7	8	9	10	11	12	13	14
Power (W)	0.083	1.2	2.1	3.5	4.1	6.1	8.0	9.6	11.6	13.8
Rotor RPM	484	1161	1548	1839	2110	2458	2845	3194	3465	3832

Once these tests were performed, the emergency stopping time was tested. The NCWC required that the braking system bring the turbine speed to 10% of the rotation at 17 m/s constant wind speed in less than 10 seconds. To ensure safe braking conditions, we used dynamic braking to steadily increase the torque on the driveshaft until the rotation was 10% of the rotation at 17 m/s. We performed this test 5 times to verify that the braking system was working.

ELECTRICAL

Testing the electrical system involved three phases: testing of individual modules and components, electrical system testing with a controllable motor system, and system testing involving the actual turbines. With this order, module functionality could be confirmed before introducing more complex systems.

Figure 7. Controllable Motor Test Setup

In order to properly test each module, a controllable-motor system was developed to properly drive the generator in a similar manner to an actual turbine. This was essential to continue testing in a laboratory environment where no wind tunnel or turbine was available for testing and debugging the electrical system. This system operates with two identical motors, one driving the other as a generator. The second motor is only used for in-lab testing, and is not used in the turbine.

With a means to simulate the generator being driven by an actual turbine, we were able to begin Phase I testing with the power electronics. Testing the three-phase rectifier involved attached the phase leads to the diode-bridge rectifier system, using a variety of load resistances to characterize generator behavior, and then measuring the voltage and current through the rectifier. The three-phase input from the generator was successfully converted into a rectified DC output, though it was noted that generator shaft RPM did not change with resistances higher than 100Ω, with very little change between

10Ω and 100Ω. Values beyond this level allowed the generator to free-run with very little torque and minimal change in power.

Boost converter testing was more complicated and involved a bench-top power supply input to the circuit with the switch operated by a signal generator. Load values were tested between 0.2Ω and 10Ω to get a range of boosting ability. Results showed a difficulty boosting properly with 0.2Ω loads, but good boosting ability with loads upwards of 10Ω. An output power of 10W was achieved using the 0.2Ω load, demonstrating the functionality of the boost when simulating a connection to the grid. Switching frequencies were changed in order to find the best frequency for boosting and limiting voltage ripple.

Microcontroller functions were analyzed by printing the sensed values and calculations to a terminal window via UART protocols. Primary tests included the rotor frequency sensing, current sensing, and PWM signal for toggling the boost switch. Rotor frequency sensing involved checking the sinusoidal-to-square-wave translation and correct counting by the controller's external clock timer. Current sensing involved correctly analyzing the ADC input from the sensor and converting to an equivalent current based on sensor resolution. The PWM signal needed to successfully toggle the switch with various duty cycles. Testing showed successful functionality with analyzing the current sensor's ADC feedback and translating the value into sensed current, as well as having a defined PWM signal sent to the switch with a varying duty cycle. Initial frequency readings used a software-implemented Schmitt trigger application for digitally reading a sinusoidal wave, but inaccurate readings prompted a switch to comparator circuitry for more accurate sinusoidal-to-square-wave translation.

Phase II combined the rectifier, boost converter, and microcontroller functionality into one system. Our testing procedure was as follows:

- Measure input and output values at cut-in speed for controllable motor
- Microcontroller correctly prints frequency and load current to terminal screen
- Boost converter boost to predictable levels based on constant duty cycle
- Step through duty cycle percentages
- Measure boost levels at duty cycle levels
- Check adjustable duty cycle based on set torque values
- Check for varying generator speeds from changing duty cycles

Results showed successful operation, though boost converter output differed than when tested individually. This was due to the bench top's ability to act as an ideal power supply, whereas the generator is not. However, the boost was able to achieve 5V output and the microcontroller was able to assess the frequency and current while changing the duty cycle appropriately to maintain a constant torque. A level shifter (hex inverter) was added in order to increase the 3V microcontroller signal to 5V to correctly toggle the MOSFET switch, which required a minimum of 3V to switch appropriately.

The dynamic braking and rectifier was added during this phase. In order to check for proper functionality of the braking system, the coil needed to be energized and de-energize to show toggling between outputs. This was initially performed using LEDs with a bench-top power supply. Afterwards, the microcontroller signal was implemented to open a MOSFET gate and energize all relay coils at once, followed by testing the dynamic braking with the controllable motor system. Lastly, the relay testing involved braking activation due to microcontroller failure or loss of power. During system operation, the dynamic braking system with the relays worked very well, bringing turbine speed well below 10% of its operating RPM. For the dead-man's switch, a secondary MOSFET was used in parallel to the primary MOSFET, and held low by a high signal fed through an inverter. Power loss of the board correctly inverted the absence of a signal high, opening the switch and bypassing the primary MOSFET to activate the brakes. Initial designs had the relay coil remain energized until the brakes were activated or power was lost, but this resulted in a constant current consumption that drained the system batteries far too fast. The system was changed to have relays only draw current when activated, thus preserving battery life.

Phase III electrical system testing went hand-in-hand with the testing of the turbine by the mechanical teams. Due to the electrical system being tested with the controllable motor, much of the functionality was anticipated to work going into Phase III. The overall testing procedure for the electrical system during Phase III included all tests from Phase II but with the turbine rather than the controllable motor system. The turbine performed well during rectifier-only testing, providing input voltages and power much greater than first anticipated. Since input voltages must be lower than 5V, steps were taken to reduce the generator RPM and increase the torque instead, providing more current. Adjusting the duty cycle also lowered the input voltage to the boost while increasing the current to the output. The boost converter was able to take these lower voltage inputs and successfully boost them up to 5V, producing over 10W on the output after reassessing components to take into account minimal parasitic resistances. High resistances drastically affect the output of the boost, and many components were replaced by those of the same value but with much lower intrinsic resistance. The duty cycle was able to regulate the system's power based upon frequency and current calculations that achieve the desired torque at a certain place on the power curve. Turbines showed a better cut-in speed during low duty cycles due to the generator seeing a higher resistance on the output. Because of this, the software was modified to hold the switch open during startup in order to have a better turbine cut-in speed. Instantaneous dynamic braking proved to be highly dangerous due to the momentum of the turbine as it came to an immediate stop. Pulsed dynamic braking made the turbine much safer, as it applied the effect of the dynamic braking over time rather than instantaneously.

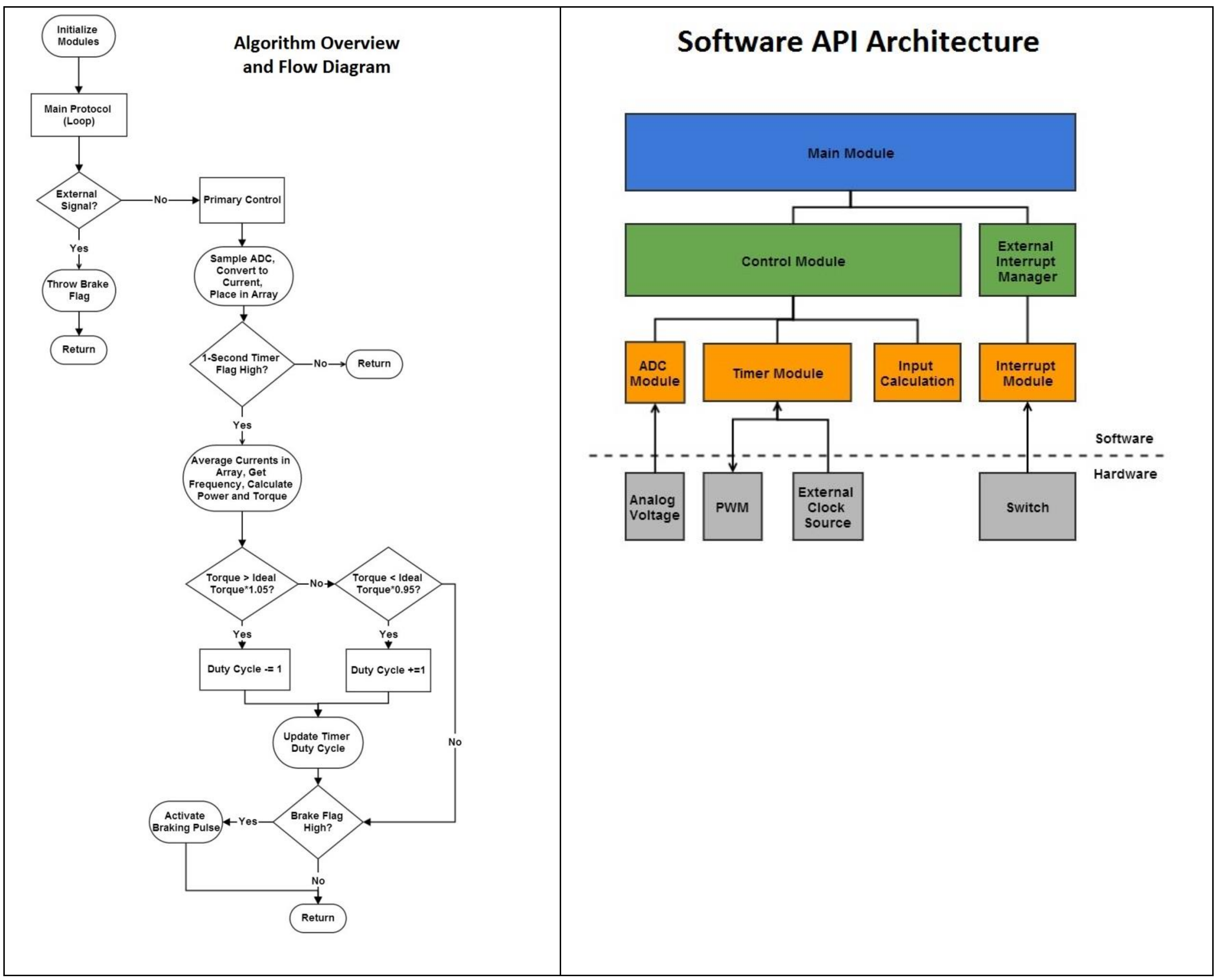


Figure 8. Algorithm and Architecture

Engineering Specifications

The prototype turbine was designed using specifications that directly corresponded to the requirements of the competition. After thorough testing, these specifications were measured to satisfy the design requirements. Table 2 below shows the requirements, design specifications, and actual specifications of the prototype model.

Table 2. Specifications

Competition Requirements	Design Specifications	Actual Specifications
1. Produce consistent power	1. Power--10 Watts	1. Power—14 W
2. Wind used as power source	2. Max RPM-- >3050 RPM	2. Max RPM—4500 RPM
3. Rotate motor shaft	3. Operating Wind Velocity— 5-14 m/s	3. Operating Wind Velocity— 5-14 m/s
4. Small Size	4. Prototype Cost-- <$500	4. Prototype Cost-- $390
5. Withstand high speed winds	5. Max Wind Velocity w/o Failure-- >17 m/s	5. Max Wind Velocity w/o Failure-- >17 m/s
6. Durable	6. Continuous Operating Time-- >5min	6. Continuous Operating Time-- >5min
7. Portable	7. Cut-in Wind Velocity-- <5 m/s	7. Cut-in Wind Velocity—7 m/s
8. Low cut in speed	8. Cut in Amperage-- >.1mA	8. Cut in Amperage-- 2mA
9. Use supplied generator	9. Length x Height X Width-- <45x45x45cm	9. Length x Height X Width <45x45x45cm
10. All components are easily accessible	10. Shutdown Time (<10 s)	10. Shutdown Time-- 8s
11. Mounted on supplied bracket	11. Operation from Microcontroller Software and Signals	11. Software Control with Hardware-Aided Signals
12. Under budget	12. Regulated 5V Output with 0.5V – 3V Input	12. 2-3V Input for 5V Output
13. Battery Operated Circuit	13. Two 3V, 250mAh cell batteries	13. Two 3V, 255mAh cell batteries

In the modeling and testing section above, the power and rpm rating of the turbine was measured at every wind speed required for operation. This data was used to generate the chart below:

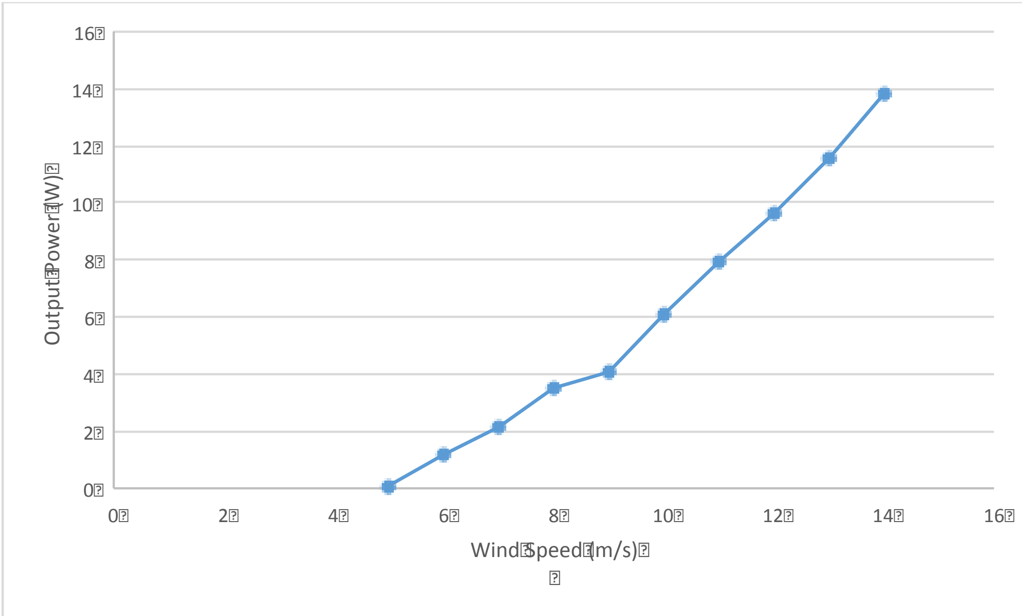


Figure 9. Power Curve