Washington State University-Everett and
Everett Community College
Collegiate Wind Competition
Final Report
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Executive Summary

This report summarizes collective knowledge and documents to date practical results in the field of wind power generation, achieved by WSU-EvCC cross institutional team. Additionally, a portion of this work concerning electrical engineering, signify a senior capstone project achievement for the WSU electrical engineering team. Current academic year's success recognizes and builds on the previous year's wind energy team's extensive research and is grateful for their intellectual legacy. This year, the team has taken a top-down approach in research and development of the prototype. It was decided to avoid extensive fundamental research and study of competitors achievements. Design priority was given to the commercially available components based on a trial-and-error approach. This permitted relative freedom from the burdens of predisposition to operate in the wake of someone else's success, allowing more experimental courage and satisfaction with the accomplishments. This year, the team has returned to the traditional horizontal-axis wind turbine design with autonomous pitch, yaw, and load control. Although autonomous yaw control was beyond the CWC requirements, the design experience was determined to be beneficial to the achievements within the scope of the senior capstone project, and perhaps future teams' research. The electrical team has expanded on the previous year's turbine and load control component ideas and developed its own robust approach to power management, voltage regulation and generator selection. The mechanical team had less luck with previous year's work since very few design solutions of last year's vertical-axis turbine design were applicable in the horizontal-axis design. After initial experiments and conceptual deliberation, the control team has settled with selecting the rotational speed of the machine as the primary pitch control input and wind speed as primary load control input, implementing separate controllers for each device connected via communication bus. Additionally, beyond the CWC requirements scope, some team member's time was dedicated to the development of the HMI, data acquisition and live power output monitoring systems, this was done with consideration for broader wind farm project development. For this purpose, MakerPlot software was chosen, and a suitable application was developed, however because of limited competence in this field of work and limited human resources it was not integrated into the final design. The immediate state of the prototype and the project progression is determined satisfactory. The team was able to achieve its selected objectives in control of the turbine and power generation. Work is continuing to finalize turbine-load communication, final blade, and foundation design along with revisions to the pitch actuator mechanism.

I. Introduction

Our team has picked the horizontal axis turbine because we wanted a more conservative approach in wing energy generation, compared to the previous year. The team's main goal this year was to come up with a functional generation system, that could create a base line for future experiments and designs. The advantage of the horizontal axis was in the fact that its design concept has been well research and a wealth of information is available on the topic. This way more time could be spent, trying out different working designs in the attempt to develop our own. Nevertheless, a fair share of challenges had to be overcome by the team. One of the critical concerns this year is involving the weight and balancing of the prototype since this year's competition has an offshore theme and the turbine structure will need to reside on the simulated ocean floor. Because of this reason, vibration, weight, balancing, and aerodynamics became very important design criteria. To maintain minimal weight and have adequate aerodynamical properties, there was no other option but to use the 3D printing technology. This insured light weight of the structural elements, fast prototype turnaround and allowed to model and produce complex aerodynamic shapes of the turbine housing structure. Another set of technical challenges was due to the active pitch control design, initial attempts to control the actual degree of the pitch did not come to fruition, because the team did not find a solution to accurately control the position of the blades. This led to a more elegant idea of the “speed control”, where turbine control system is monitoring rate of speed change, and makes decisions to pitch up, pitch down or to do nothing if it is at the target speed. Active yaw control was mostly for the team’s own research to develop understanding on how larger wind turbines that do not have passive yaw control are positioned into the wind. The original load control idea was to have a continuous load control, the team has settled for discrete control because resistive load range was not yet understood in the beginning of the design process and since the CWC rules wind speeds are also discreet a simpler wind sensor dependent load control solution was adopted. Generator selection just happened to naturally work out in terms of wight distribution, because its stack could be evenly split over the center of the pole, this has proven to be one of the benefits of axial flux permanent magnet (AFPM) machines, compared to permanent magnet brushless machines that need counter balancing. An additional feature of the AFPM was the fact that its fundamental geometrical design properties provide for relatively large hollow center in its stator. This gives significant flexibility to the pitch actuator design approach, which our mechanical team has successfully implemented using linear actuator mechanism powered by DC/Stepper motor.

II. Design Objectives and Components

The objective of our turbine design team was to create a turbine that performed well in the CWC test environment. The turbine had to fit within the bounding box shown in Figure 1. The bounding box is a $45\,\mathrm{cm}$ cube mounted on a $15\,\mathrm{cm}$ diameter cylinder which extends downwards to the underwater foundation attachment resting on the $24 \times 25 \times 15$ cube of water immersed in sand. The turbine blades needed to be completely enclosed in the cube. The turbine was supposed to start at the lowest wind speed possible, then produce power of varying levels until wind speeds of $11\,\mathrm{m/s}$ and respond to load disconnect scenario in a controlled manner. All turbine components were to be designed to withstand wind speeds of $22\,\mathrm{m/s}$. The electrical system needed to work with an out of box motor to be used as a generator. The motor produced AC power which needed to be converted to usable DC power. A system to adjust resistance on the circuit to maintain optimal power output during the variable conditions needed to be designed. Finally, a control system needed to be designed to adjust pitch based on rotational speed of the turbine and maintain maximum torque generated from the wind.

III. Electrical Design and Controls

A. Introduction

In the small-scale turbine design, it is critical to identify the type of the generator that would be used through the design process because mechanical designs and modeling are time consuming and constrained by the academic year’s available man hours. It is important to limit complete change of design course to one or two instances and even that is only affordable at the initial stage of the design. The team did not have a ready generator solution from previous project and had no practical experience in assessing the scale or the needed parameters in selecting the generator for such a miniature design. The only notion that was passed down from previous team was the understanding of the electrical motor KV rating and importance of minimizing cogging torque at cut in speed. Thus, these became the starting point parameters in the generator selection. The team has encountered several challenges over the power electronics selection process. Ideas have been tried and discarded, some because component selection process was not taking into the account the component’s self-power demand, others because the nature of the component’s operation was not fundamentally understood. In some instances, where a

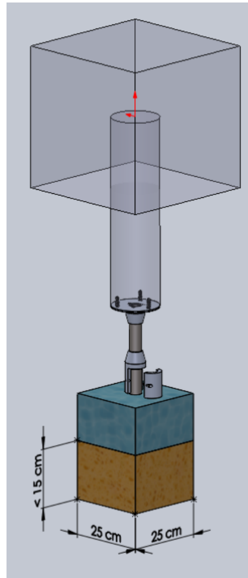

Fig. 1: Design constraints

solution was not found by direct approach, like in voltage regulation attempts, the team has paused on that front and shifted attention to better understood sections of the design, allowing for continuous progress. This approach proved to be very effective, and more elegant and natural solutions were found as a result.

B. Generator and Load

Faraday's Law indicates that *"Any change in the magnetic environment of a coil of wire will cause a voltage (emf) to be induced in the coil"*. Formulation (1) demonstrates the physical relationship described by Faraday using mathematical interpretation,

$$\text{emf} = -N\frac{\Delta\phi}{\Delta t}\,, \tag{1}$$

where N represents the number of turns in the coil, $\Delta\phi$ represents a change in magnetic flux over time, and Δt is the change in time.

Magnetic flux is given by formulation (2),

$$\phi = BA\sin\theta\,, \tag{2}$$

where B representing magnetic field produced by opposing permanent magnets of the rotors, A represents area of the coiled wire in the stator and θ represents the angle between the coil area plane and the magnetic field and since the coil area and the magnetic field are orthogonal to each other in the AFPMG.

Formulation (2) can be restated as

$$\phi = BA\,. \tag{3}$$

According to Lenz's law, the negative sign of (1) indicates that the current produced by the change in magnetic flux creates its own magnetic field that opposes the change in flux that produced it. When applying this notion to a generator this indicates that current induced in the generator coils will provide an opposing force to the one that is responsible for the rotation of the generator shaft. Since the force is rotational it could be restated in terms of opposing torque τ_G and compared against aerodynamic torque τ_W extracted from the wind,

$$\tau_W = \frac{P_W}{\omega_{rotor}} = \frac{\rho\pi R^3 C_p(\lambda, \theta) V_W^2}{2\lambda}, \tag{4}$$

where P_W, in watts, is the power available in the wind and is given by (5), ω_{rotor} is the rotational speed in (rad/s), ρ is the air density in (kg / m3), C_p is the power coefficient expressed as a function of the tip speed ratio and pitch angle and is given by Eqs. (7) and (8):

$$P_w = \frac{\rho\pi R^2 C_p(\lambda, \theta) V_W^2}{2}, \tag{5}$$

$$\tau_R = \frac{P_W \times C_p}{\omega_{rotor}} C_p(\lambda, \theta) \tag{6}$$

$$= 0.22\left(\frac{116}{\lambda_i} - 0.040 - 5\right) e^{\frac{-12.5}{\lambda_i}}, \tag{7}$$

$$\lambda_i = \left(\frac{1}{\lambda + 0.8} - \frac{0.035}{\theta^3 + 1}\right)^{-1}. \tag{8}$$

In Equation (5), R is the wind turbine rotor radius in meters, V_W is the wind velocity in m/s, and λ is the tip speed ratio (TSR) given by Equation (9),

$$\lambda = \frac{R\omega_{rotor}}{V_W}. \tag{9}$$

It could be further inferred that wind turbine operation could be imagined as a system of two opposing torques τ_W and τ_G whenever torques are equal the system is in equilibrium and is generating constant power. Any time τ_W changes in response to change in V_W, (for the experimental environment ρ is assumed constant) there exists a new equilibrium state of τ_W and τ_G torques. Simply put, anytime V_W increases it creates conditions for a new and greater power equilibrium state, this means the resistance of the load could be decreased, which will increase the current flow, and thus more power could be extracted from the wind.

The KV rating of the generator is responsible for predicting the magnitude of the generated voltage as a function of the rotor speed. In the wind turbine controls it is sometimes important to maintain relatively low rotational speed and at the same time maintain voltage magnitude that is high enough to keep the microcontroller active. Equations (10) and (11) show this relationship,

$$\text{KV}_{rating} = \frac{\text{rotor speed}}{\text{voltage}}, \tag{10}$$

$$V = \frac{\text{RPM}}{\text{KV}_{rating}}. \tag{11}$$

Cogging torque is a magnetic interaction between the iron teeth of the stator and magnets of the rotor in a brushless DC motor for instance. The team did not know how to assess the magnitude of such torque and its effect on the cut in speed of the future turbine so naturally attempts were made to find a motor with little to no cogging torque. This led to the discovery of the axial flux permanent magnet motor (AFPMM) which could be used as a three phase DC generator if coupled with a three-phase full rectifier circuit.

Figure 2 shows the single rotor and the stator of the 12 pole 9 coil AFPMG used in the prototype. A set of two motors were purchased for initial evaluation of the KV rating. Using dynamometer, it was experimentally determined that the KV rating of the single motor was 96. This was very low comparing to all other available options that also had the appropriate dimensional scale. Evaluating the mechanical construction of the motor's design, it was observed that it appeared to be relatively simple to create a stack of these motors coupled by a single axle. Once the team recognized the flexibility in the connection schemes, ability to reduce the

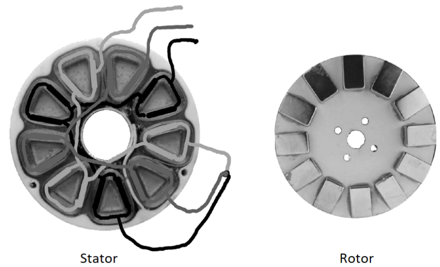

Fig. 2: Stator and rotor

KV rating to 24 by stacking motors on the single axle, and the virtual absence of cogging torque in this design, two more motors were immediately ordered.

Figure 3 demonstrates the midterm version of the generator design. The housing assembly consists of five main parts: (b and c) front and back bearing supports, (d) housing block, (e) stabilizer bar, and (f) yaw pivot assembly.

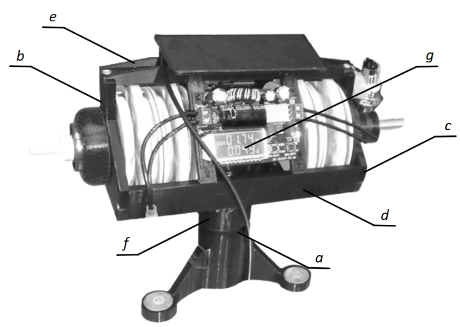

Fig. 3: Housing assembly

The drivetrain assembly is shown in Figure 4. It is composed of the central axle (a) that connects four pairs of inline rotors (b and c) and two pairs of stators (d and e). The stators are supported by the housing assembly and are independent of the rotation of the rotor assembly. Connected to each pair of stators are housing assemblies that contain two pairs of internally connected full bridge rectifiers potted in epoxy. Once the generator selection was settled on, mechanical design and power electronics work began.

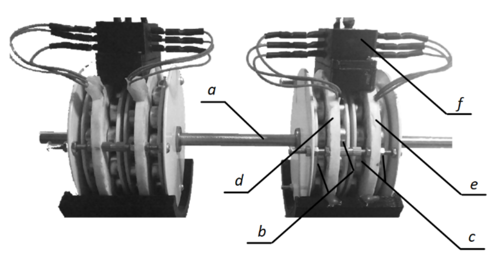

Fig. 4: Drivetrain assembly

Figure 5 shows the systems power distribution of the most recent design review.

The load chosen is constructed of a $200\,\mathrm{W}$ variable resistor with coils and contacts throughout to select the desired resistance for the appropriate wind speed and scenario. Supplemental resistance was needed for the lower wind speed and lower load conditions, so additional resistors are combined in series to acquire these values. The resistance values used in the load box vary from $45\,\Omega$ up to $420\,\Omega$. A relay bank controlled by a separate Arduino from the turbine is used to select the load by closing the contacts on the desired resistor value. The Arduino is receiving commands from the turbine through an optically isolated TX and RX line. This Arduino will send commands to the turbine if a manual shutdown is required.

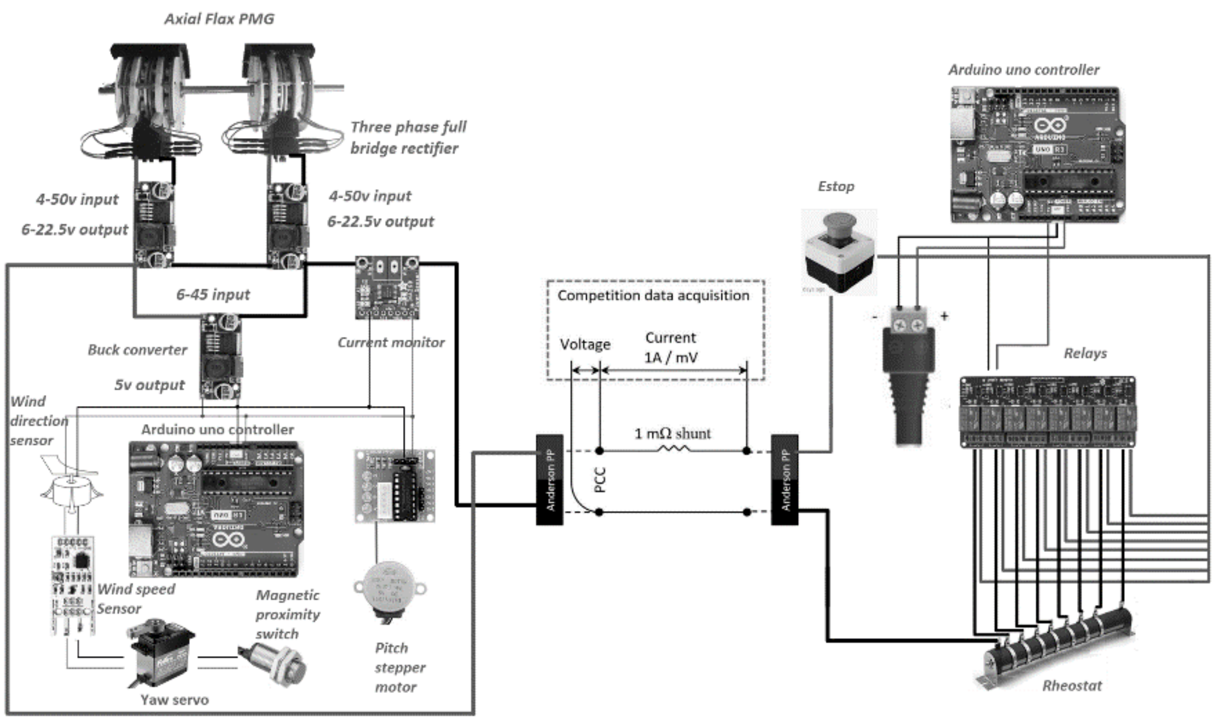

Fig. 5: Pictorial schematic of the turbine's control and load power distribution

C. Control Theory

The pitch control scheme is made up of a methodology called Fuzzy Logic, as shown in Figure 6. The tachometer measures the RPM of the turbine and then the controller determines how far away that the current RPM is from the desired RPM of the turbine. The previous RPM record is also taken into consideration when determining whether to make a pitch adjustment or not. If the turbine is rotating too slowly, but is speeding up, the algorithm will wait another cycle to see if the pitch has continued to increase the RPM, and if not, it will then make an appropriate adjustment based on how far away from the desired RPM it is. If the turbine RPM is within acceptable bounds to the desired RPM, then no adjustments will be made.

The tachometer utilizes a Hall effect sensor that counts the number of pulses it receives, which happens once per revolution, and calculated the period it takes for 20 revolutions to occur and determines the RPM from this math. There is a timeout scenario where if 20 revolutions have not been completed in 5 seconds the loop will break and the RPM will still be calculated, just with less accuracy because the time period over fewer revolutions will be averaged.

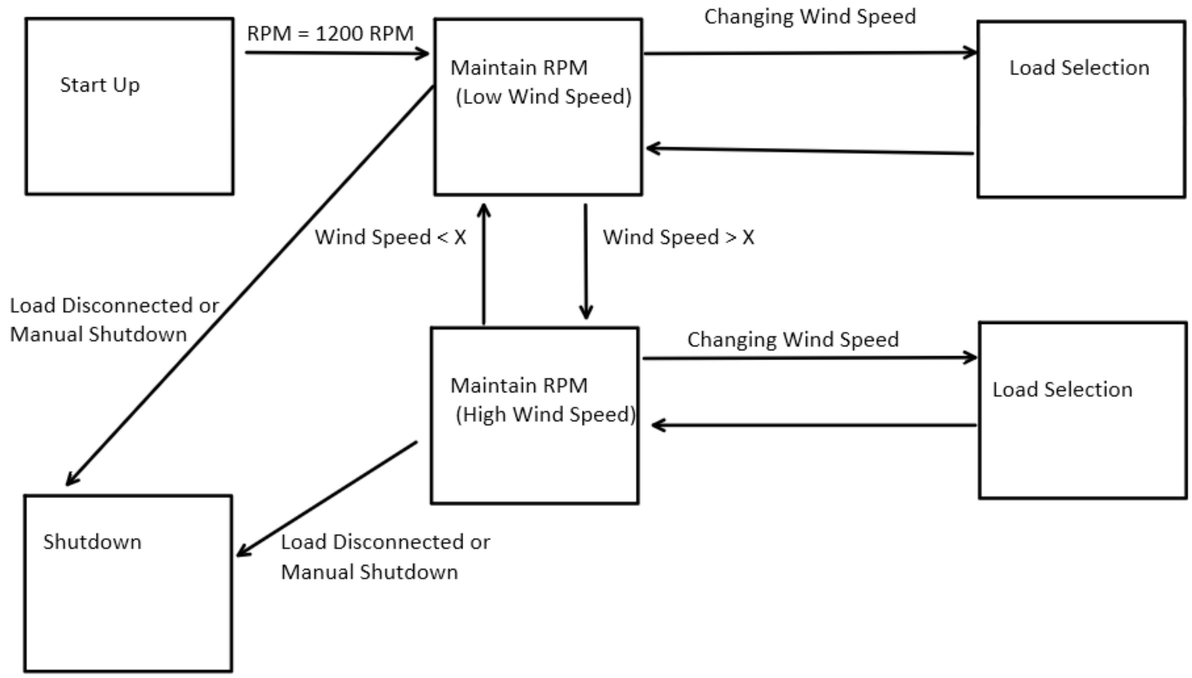

Fig. 6: Canonical control model

A current sensor must be used to determine if the load has been disconnected from the turbine. An ADA260 module communicates with the Arduino via an I2C connection. When the load goes above $50\,\text{mA}$ the load is detected, and any drop below that will trigger the pitch to adjust to slow the blades down to a stop. The minimum load expected at a wind speed of $5\,\text{m/s}$ is around $80\,\text{mA}$ so this is not something that could be accidentally tripped.

The wind speed sensor determines the wind speed utilizing the "hot wire" method. This method heats up a wire and as the wind passes by, it cools the wire off changing its resistance and the voltage across it. The voltage is read by the Arduino and then the Arduino can determine the wind speed the sensor is experiencing.

Delays are important for the pitch control system because it takes some time for the system to stabilize and the RPM to cease any fluctuations. The problem with using the built-in delay functions is that the Arduino cannot do anything else while this is happening. A modified delay function was made so that crucial measurements can be made in this idle time to allow action to be taken if something doesn't look right. The current is monitored so if the load is disconnected, the turbine can immediately begin slowing down to prevent over speeding the turbine and damaging both the physical and electrical components.

Currently, the pitch control mechanism is adjusted by a stepper motor, but through testing it has been noticed that the stepper motor has a few flaws, being it is slow, and it draws a lot of current. The stepper motor takes more than 20 seconds to move from one extreme pitch setting to the other. This affects the RPM when the load is disconnected because the elimination of torque due to the load results in the turbine increasing by several hundred RPM during disconnects. With faster pitching speeds, this RPM overshoot can be minimized. Because the stepper motor draws around $300\,\text{mA}$ the added load during pitch adjustments slows the blades down and results in more time needed for the RPM to stabilize after pitch adjustments are made. It is being considered to change to a DC motor with a gearbox and H-bridge configuration which alleviates both concerns in preliminary testing, with the current selection having more speed while also drawing less current.

D. Voltage Regulation Description

The voltage regulation system consists of four axial flux motors tied in series after their respective voltages have been rectified. This allows for a high KV rating which is important for low RPM operation of the Arduino. Two adjustable buck converters are each attached to two rectifier outputs in series, limited to $22.5\,\text{V}$. When these two buck converters are connected in series the system total voltage is limited to $45\,\text{V}$. Two buck converters connected in series are needed because each is rated for $52\,\text{V}$, allowing for a maximum turbine voltage of $104\,\text{V}$ which is achieved at around $2400\,\text{RPM}$ or twice the $1200\,\text{RPM}$ normal operational speed of the turbine. The initial intent was to achieve a high voltage quickly to run the Arduino at low RPMs and sustain it for the manual and emergency stop scenarios so that the turbine could automatically restart.

Unfortunately, through testing it was discovered that each of the buck convertors requires a minimum of $4.5\,\text{V}$ to operate, which now brings the minimum operating voltage to $9\,\text{V}$ instead of the $5\,\text{V}$ that the Arduino needs to say alive. Applying the KV rating formula from (10) gives $216\,\text{RPM}$ as the minimum rotational speed for turbine's control system to operate. This would require the normal operational speed of the turbine to go up by 960 to $2160\,\text{RPM}$, this is according to CWC 10% of maximum speed requirement during load-disconnect shutdown procedure.

Because during the emergency shutdown it takes time for the system to respond to the load being disconnected, there exists a time were RPM continuous to rise. Having only $240\,\text{RPM}$ buffer before buck converters' operational limit is surpassed by overvoltage, brings a self-restart operation of the turbine to the unpredictable operation conditions, where buck converter failure is very likely.

From observation, the system can surpass the 240 RPM buffer zone faster than the control system can respond to slow itself down. At this time, the team was not able to find a solution for this problem and turbine is designed to be manually restarted after emergency stop. A faster pitch control system is being designed, using DC motor, gear box and limit switches to prevent over travel. More tests are needed to determine if new pitch control scenario will deliver the self-restart capability.

E. Software Development

A lot of adjustments and improvements have been made to the pitch control algorithm. At first there were five choices the program could make to adjust the pitch: no adjustment and small/big adjustment to make the blades go faster/slower. Later it was observed that if the blades were accelerating towards the desired RPM, there may not need to be any adjustment made. The pitch adjustment motor used also requires power to use, and so with every pitch adjustment, not only is there a delay required due to the change in aerodynamics, but the additional load that the motor requires will slow the turbine down as well, which may need additional time to allow for RPM stabilization. As the wind speed increases, because there is more power in the wind, the turbine reacts more quickly to pitch changes, and so the delay times must be shortened as wind speed increases. The turbine is also more sensitive to pitch changes at high wind speeds and RPM, and so the adjustments made are smaller as the wind speed increase. If the turbine is trying to supply more power than it can extract from the wind, which would cause the RPM to drop due to blade stall. The blades will pitch back to a previous setting to try and reduce or save the stall condition if too many “large pitch adjustment faster” conditions occur consecutively. While the delay functions built into the Arduino software work well, the current cannot be measured during this delay time, and so if the load is disconnected it could be up to three seconds before it is noticed by the software, which could cause the blades to overspeed. A modified delay function had to be created so that sufficient delays could still be implemented, and the current could be checked in case of a disconnect, immediately pitching the blades back and breaking the turbine.

Wind speed measurement has been more difficult than it was anticipated. The Rev C wind speed sensor is very sensitive at low wind speeds, but at high wind speeds the voltage it sends out only varies by a couple hundredths of a volt per meter per second of wind. This made it challenging to know exactly what the wind speed was so a lot of measurements are taken and averaged and then compared with previous wind speed measurements to try and verify if the wind speed is constant or it is changing to a higher or lower speed.