

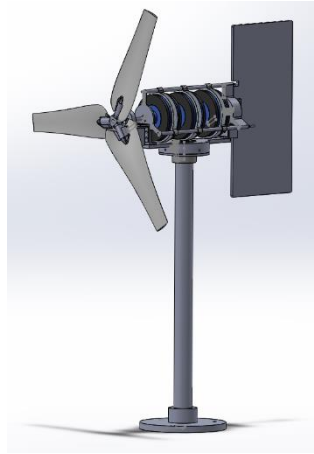
The Pennsylvania State University

2017 Department of Energy Collegiate Wind Competition

Technical Challenge Report

Elise DeGeorge / AFC-5-52004-04

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Team Members/Contributors:

Aerospace Engineering Majors

Jason Cornelius (Team Lead/Aerodynamics Lead)
Milton Rahman (Aerodynamics)

Electrical and Mathematics Major

Patrick Nicodemus (Electrical Design Lead)

Mechanical Engineering Majors

Mitchell Proulx (Team Lead/Generator Lead)
Adam Proulx (Generator)
Emily Kaercher (Generator)
Jared Franz (Generator)
William Gladden (Engineering Design/Machinist)
Jason Ochs (Generator)
Colin Krohto (Generator)

Computer Science Engineering Major

Joseph Miscioscia (Electrical Design)

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Senior Research Associate & Associate Professor, Aerospace Engineering
Senior Research Assistant, Laboratory Director, Aerospace Engineering
Outside Consultant, Retired Penn State ARL & Mechanical Engineering

Executive Summary

The Penn State Collegiate Wind Competition team has been committed to improving the design and efficiency of their wind turbine from the 2016 competition. The team diagnosed the past design performance deficiencies by component including the rotor aerodynamics, the generator, the pitching mechanism, the controls, the yaw mechanism, and the load. The team improved past component designs by performing research and development in unique ways. Even though some of these design features will not be implemented in this year's turbine, the design improvements are a strong start for the future. The following document explains the unique research and development Penn State has pursued this year.

The Penn State team organized and broke the work down by components. The sub-teams are aerospace, generator and electrical. Each of the teams worked individually during the week and met on a weekly basis to coordinate progress with other sub teams. The aerospace sub-team was led by Jason Cornelius, who was responsible for the blades and rotor system on the turbine. The team successfully designed new blades to better accommodate the torque of the generator. The aerospace sub-team also designed a passive pitching rotor system to reduce the energy used by the active pitching system in last year's competition. The generator team was led by Mitchell Proulx who was responsible for designing the generator along with a new design for the structure of the generator. The electrical sub-team was led by Patrick Nicodemus who was responsible for improving the efficiency of the electrical system downstream of the generator.

This is the first complete year of the Penn State Wind Energy Club which formed because of the Collegiate Wind Competition. This allows the club to recruit new students and allows them the opportunity to consider working in the wind industry. In the past, at the beginning of every competition, Penn State has had to recruit an entire new team because students had graduated. The Penn State Wind Energy club can now build on a strong foundation of students who are interested in competing in the Collegiate Wind Competition. As most of the individuals are seniors on the team and will be graduating, the goal was not only to do well in the competition but also to teach a group of underclassmen to be leaders and to leave the club in good hands with promising technologies to implement.

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1. Design Overview Methodology

The system design methodology was to increase the overall efficiency of the wind turbine. The team identified components of the turbine and aspects of their design where efficiency could be improved. The system methodology was determined by knowing and calculating the individual speed-torque and power-rpm curves of the turbine and generator. It was determined there was a mismatch between the tip speed ratio for the highest efficiency for the rotor and the match of the rotor and the generator torques at the previous tip speed ratio. The system design solution was to design a lower tip speed ratio turbine and a higher torque generator by using three parallel rotor stages. A future rotor control system was designed to replace an active pitching system with a passive pitching system to reduce the energy loss. The load was redesigned to have a variable resistance so that a maximum amount of power was drawn from the energy available in the wind at a given speed.

1.a. Blades and Rotor System

The main focus of the rotors sub-team this year was to increase the overall efficiency of the rotor system. This started with designing blades to match the torque requirements set by the generator design. The high torque requirement of the generator in past competitions prevented the blades from reaching their optimum RPM. This year a higher tip speed ratio design was pursued providing a higher torque at lower RPM. The blades were produced through additive manufacturing, however, in order to save weight much work has been done to study the possibility of creating blades using a carbon fiber layup. Details about the composite blade manufacturing are in Appendix A. A key feature in the previous competition's rotor design was the active control pitching method and this was maintained in this year design. As this approach uses some of the energy produced to control the collective pitch of the blades, research was conducted on a passive pitch method. The technology used in the competition this year is detailed in section 2, and the research endeavors are described in appendix B.

1.b. Generator Design

The generator sub-team focused on improving the efficiency of the axial flux generator designed in the 2016 competition and decreasing the torque. To increase the efficiency of the generator, the team decided to increase the number of stages within the axial flux generator which is explained in Section 2.b. One of the key issues that the generator team faced was the amount of torque that was required to spin the generator. The high torque at high RPMs occurred because the generator's rotors weighed significantly more than needed. To reduce the weight, 3D printed rotors were used in place of metal rotors, removing a significant portion of the weight.

1.c Rectifier, Load, and Control

The rectifier on the 2017 turbine is, as in previous years, a standard line-commutated three-phase bridge rectifier. They are simple, inexpensive, reliable, and available off-the-shelf.

The design efforts in the electrical and control sub-team were focused on the load design. In past years we used a simple resistor as the load. However, this creates design conflicts. At low wind speeds, the power contained in the wind is lower than the power demanded by the load at the ideal tip-speed ratio. The turbine is unable to spin at the ideal TSR and struggles to supply this power, so the true tip-speed ratio is below the ideal. At higher wind speeds, the power delivered by the wind is higher than the power the load is able to accept at the given TSR and so the load does not take advantage of all the power available. The tip-speed ratio of the blades is then above the ideal. The competition rules award points heavily for power supplied at low wind speeds. This creates an awkward situation where, in order to

perform well at low wind speed, the blade designers must try and create blades that supply a great deal of torque at low TSR - that is, the power-coefficient vs. tip-speed-ratio curve is biased to the left. This has the design cost of sacrificing performance when wind speeds are high.

We resolved this conflict by changing the power drawn by the load dynamically depending on the wind speed. At low wind speeds, the load is designed to draw very little power, to allow the rotor to spin up to the ideal tip speed ratio without being heavily taxed. At high wind speeds, the load should draw a great deal of power, taking advantage of the high power at these wind speeds. This is achieved with a buck converter which alters the current drawn by the load according to the speed seen by the turbine.

The control system is responsible for fulfilling the various design challenges of the competition, including the "Control of Rated Power and Rotor Speed Task" and the "Safety Task." We used a microprocessor to monitor the voltage output from the rectifier and inferred the turbine's velocity from bench-top calibration measurements of the generator's speed-voltage characteristics. The processor controls a servo motor which pitches the blades according to wind speed and context (for example, whether the turbine is connected to the load and whether the emergency stop button has been pressed). When the turbine is operating normally, the servo pitches the blades to maximize power. When the rotational speed goes above the 11 m/s cut-off, the blades are pitched to a less efficient angle to lower the rotational speed and power coefficient (C_p) for the rated power/wind task. When the processor detects the STOP button being pressed, or notes that there is no current passing through the Point of Common Coupling (PCC) due to a disconnect, it pitches the blades in reverse, so that the wind slows the rotor to a halt for the safety task. During the safety task, when the PCC is disconnected, the blades stop spinning and generating power. Because no power can be supplied from the load end, the processor shuts down. It is necessary for the processor to turn on again in order to pitch the blades back to the normal position, so we designed a circuit that supplies power from the load to the turbine's control system after the PCC is reconnected.

1.d - Structural Design of Generator

The structural design of the generator was changed from the design in 2016 because of the time it took to assemble the turbine. Since the generator only had one stage in 2016, it was not too complicated to assemble. As more stages were added to the generator, the time to assemble the turbine significantly increased. To reduce assembly time which is especially valuable and limited during the competition, the team redesigned the structure of the generator in case of a mishap. Further explanation of the structure of the generator can be found in Section 2.c. If a need arose during the competition where there was little time to assemble the generator, it would not be possible with the old structural design.

2. Technical Design

The 2017 team has done much work in improving the design beyond last year's competition. The following sections detail the underlying technology of this year's design and also highlights the advancements that have been made. The turbine's subsystems are described in four key areas: aerodynamic, generator, structural, and electronic design. The theoretical design presented coupled with test experience guided the iterative process to a final configuration. Performance data of the final configuration is included, as well as comparisons to last year's turbine.

2.a - Aerodynamic Design

The aerodynamic design is centered around a system incorporating a new blade design and an active pitch rotor. The blade subsection will detail the initial design constraints, the iterative process used to obtain

the final geometry, and the manufacturing process. Following that is the rotor design subsection which will discuss the mechanical aspect of the active pitch control. Next is the static performance analysis and annual energy production metrics. Section four goes through the mechanical loads and safety factors of the rotor and blades. The last topic to be addressed is the yaw system for turbine control with regard to varying wind direction and gyroscopic precession of the rotor. Additional research endeavors that have not yet been implemented on the competition turbine are included in Appendices A and B.

2.a.i - Blades

A completely new blade was designed using a blade element momentum theory Excel code developed in-house. The code takes a set of input parameters and outputs blade geometry and performance predictions such as the C_p , total rotor torque produced, and hub bending moment. The code's accuracy has been improved since last year's competition to include tip and hub losses.

The first parameter was the wind speed to design the blades for. A game theory analysis showed that designing the blades for optimum performance at 8 m/s would provide the maximum possible points. The next parameter selected was the tip speed ratio (TSR). A low TSR was selected as an initial guess in order to cater to the high torque requirement of the generator. A low TSR is synonymous with operating at a low rotational speed, this in turn led to selecting a three-bladed rotor with high solidity in order to achieve acceptable Reynolds number along the blade. The optimum TSR value was then determined by iterating on the initial value to obtain the desired balance between C_p and torque produced. The torque requirement was set by the generator team and was determined through dynamometer testing. The shape and size of the blade was also a design constraint. The blade's chord distribution needed to be smooth in order to avoid harmful spanwise flow effects. This was taken into consideration when manually tapering the root to fit around the rotor. The blade's final twist distribution was produced by the BEMT code on the basis of maintaining a preselected angle of attack along the span of the blade.

The final design's performance was validated with a Penn State wind turbine BEMT code, PSU-XTurb (Schmitz, 2017). The code's input file includes blade geometry, airfoil lift and drag data, and operating parameters, and then outputs rotor performance. A MATLAB script was created to calculate the Reynolds number at several radial locations along the blade for a given RPM, and MIT's XFOIL (Drela, 2017) was used to generate viscous polar data based on these Reynolds numbers for the XTurb input file. A performance analysis of the new rotor is included in Section 2.a.iii.

2.a.ii- Rotor Design

The turbine's rotor utilizes an active pitch control system to keep the blades operating at optimum efficiency throughout the wind speed range. The rotor consists of three blade grips with pitch horns for collective pitch control. A servo set behind the rotor actuates the collective through a pitch link connected to the stationary swashplate. The rotating swashplate then transfers the collective input to the blades; this system closely resembles that of a helicopter. Wind tunnel testing has been conducted to experimentally determine the optimum pitch angles of the rotor at each



Figure 1: Active Pitch Rotor System

operational condition. These values were implemented into the Arduino control code which is detailed in the electrical systems section.

2.a.iii - Static Performance Analysis and Annual Energy Production

PSU-XTurb was used to produce performance predictions of the new blades. Plots are shown below of rotor power, rotor C_p , and rotor torque versus collective pitch at 8 m/s and 775 RPM. This test point was selected based on prior wind tunnel testing. The generator torque requirement at this test point is also included on the torque versus collective pitch plot. As the turbine's torque at this condition well exceeds the generator requirement, the rotor speed will increase until the opposing rotor and generator torques reach a stable equilibrium. This means that a higher power output will be observed in wind tunnel testing. The rotor torque plot also validated that the new design was capable of spinning the generator at the design speed before physically manufacturing and testing the blades.

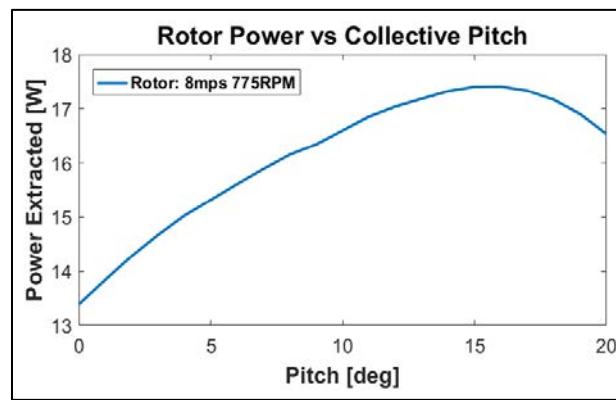


Figure 2: Turbine Power vs Rotor Pitch

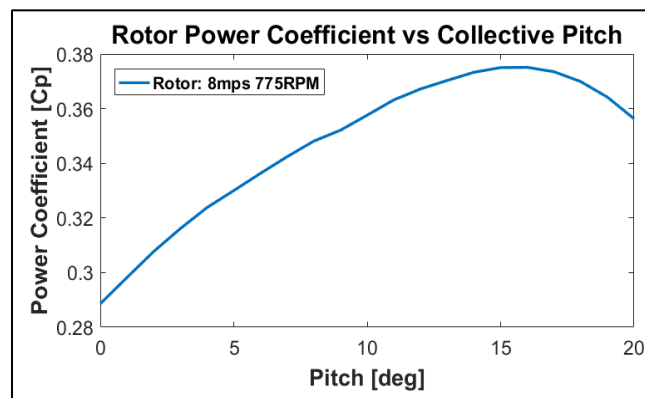


Figure 3: Turbine Power Coefficient vs Rotor Pitch

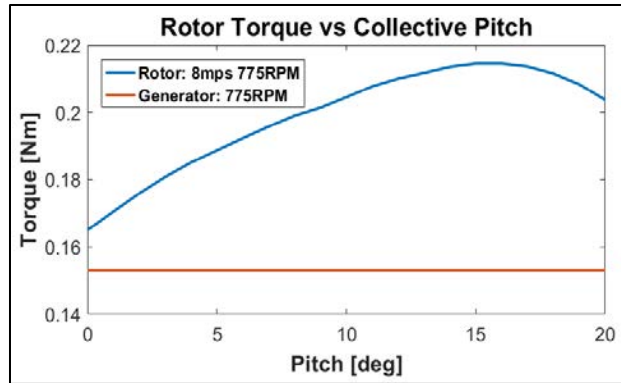


Figure 4: Turbine Torque vs Rotor Pitch

Three-dimensional surface plots of C_p versus TSR and collective pitch were also produced with PSU-XTurb. A side-by-side comparison of this year's design to last year's is shown below. The plots show a significant improvement of power produced over a wider range of tip speed ratios. This is key to operating efficiently throughout the entire competition wind speed range.

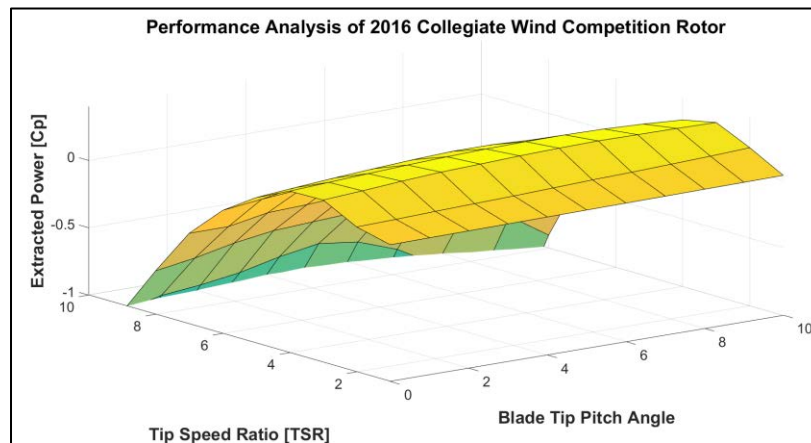


Figure 5: C_p -Lambda-Rotor Pitch Surface Plot of 2016 Turbine

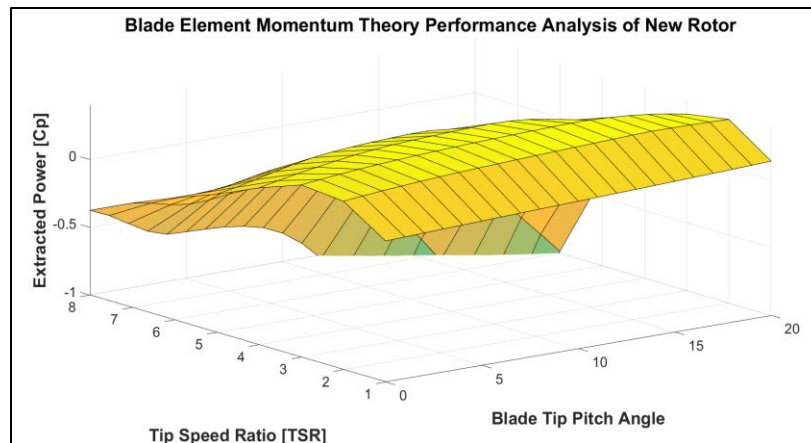


Figure 6: C_p -Lambda-Rotor Pitch Surface Plot of 2017 Turbine

The power curve shown in Figure 7 is based on the maximum C_p value from the above surface plot multiplied by the power in the wind for the 45 cm diameter turbine. Annual energy production was found

by using a Weibull distribution to determine the amount of time the wind blows at each speed from 0 to 25 m/s. The Weibull function is defined using two parameters, a scale factor and a shape factor, which is related to annual average wind speed. For this analysis, a shape factor of 2 was assumed and a variety of annual average wind speeds were considered. The Weibull probability distribution was then multiplied by the power produced at each speed and the number of hours in a year to give the amount of energy produced at each wind speed over a year. The energy produced at each wind speed was then summed to determine the total energy produced in a year. This information is plotted in Figure 8 for a range of annual average wind speeds from 4 to 8 m/s.

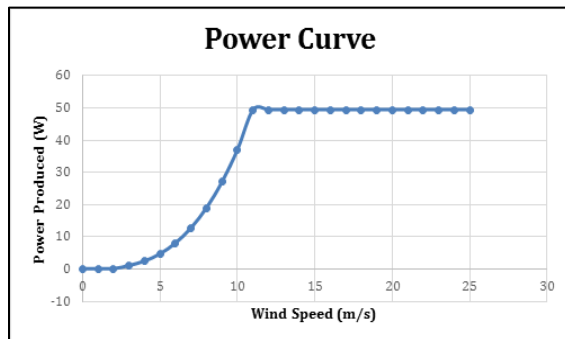


Figure 7: Turbine Power Curve

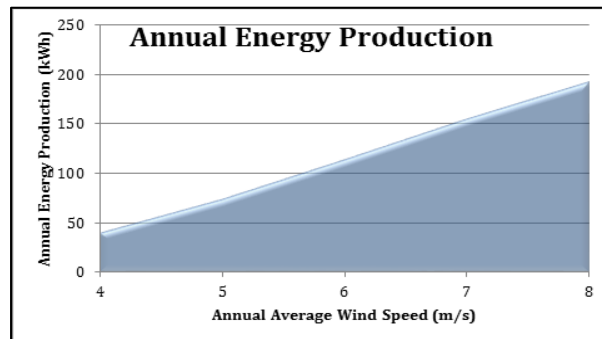


Figure 8: Turbine Annual Energy Production

2.a.iv - Mechanical Loads and Safety Factors

The maximum mechanical loads on the turbine were calculated using the highest wind speed in the competition at a blade pitch angle which will hold the power output at the maximum rated power. The rated power was taken as the maximum attainable power output at 11 m/s. This resulted in an RPM of 1400 which was used to determine the necessary pitch at 13 m/s. These parameters were run through PSU-XTurb to determine the torque, thrust, and bending loads on the turbine. The turbine was then load tested with weights supported by the blades in various configurations to ensure appropriate safety factors. The safety factor was defined as the load tested divided by the maximum load the turbine will encounter in operation. Yield and ultimate stress limits were not calculated as to not permanently damage the turbine components. A table of the tested loads and safety factors is included below.

Max Load Conditions	
Wind Speed [mps]	13
RPM	1400
Total Rotor Torque [Nm]	0.32
Total Rotor Bending Moment [Nm]	1.06
Rotor Component and Loading	SF
Single Blade and Blade Grip Torque	9.5
Total Rotor Torque	3.1
Single Blade and Blade Grip Bending	2.8
Total Rotor Bending	2.8
Total Rotor Thrust	1.4

Figure 9: Max Loading Condition and Associated Safety Factors

2.a.v Yaw Control

A phenomenon was identified in last year's design which involved the gyroscopic precession of the rotor disk at high wind speeds. This was due to the torque about the yaw-axis becoming comparable to the weathercock-stability provided by the tail fin. Analyses were conducted to determine what impact a slight yaw angle of the rotor disk had on the turbine's performance. As the yaw angle observed in the tunnel was small, wind tunnel testing confirmed the hypothesis that a small angle approximation would hold. This meant that a high majority of the flow still passed through the rotor disk resulting in no measurable decrease in turbine performance. As a result of this study, the tail fin design has not been modified from last year's design in order to maintain as little interference as possible with the downstream wake of the rotor.

With the addition of the yaw testing component this year, experimentation was conducted to ensure that the turbine would remain pointing upwind during a simulated change in wind direction through rotation of the turbine base. The testing focused on the yaw bearing which connects the tower and generator assembly base. It was determined that the friction in this bearing is negligible when compared to the weathercock-stability from the tail fin such that the torque produced during a rotation of the tower can be disregarded. In other words, the tail fin will keep the turbine aligned with the freestream flow during this portion of testing. It was also experimentally proven that the tail fin will correctly place the turbine into the wind from any yaw angle.

2.b Generator Design

An axial flux generator was selected by last year's competition because the low cogging torque of the generator meets the competition objective of producing power at low cut-in wind speed. Even with the low cogging torque the generator can still produce sufficient power at high rpm to meet the competition requirement of the power curve performance. This year's team has continued to use the axial flux generator because of its low cogging torque and ability to produce power across all wind speed conditions. Appendix C further explains the component of axial flux generator and the research completed for the 2016 competition.

One of the goals of the generator team was to reduce the torque required to spin the generator at high rpm. As mentioned earlier, the axial flux generator design has very low cogging torque upon start up. The torque is essentially zero upon start up but the torque increases relatively linearly with the rpm of the generator. This was proven when the team tested the torque vs rpm on a varying number of generators. Figure 10 shows the RPM vs Torque of a few varying generators. Figure 11 is the corresponding RPM vs Electrical Power for each generator tested. Table 1 shows the difference between each generator. The team has currently only tested three of the five generators. Continuing research will be done leading up the 2017 Collegiate Wind Competition.

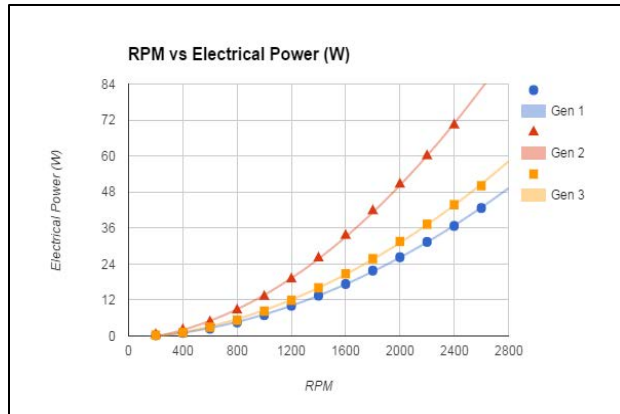


Figure 11: RPM vs Electrical Power (W)

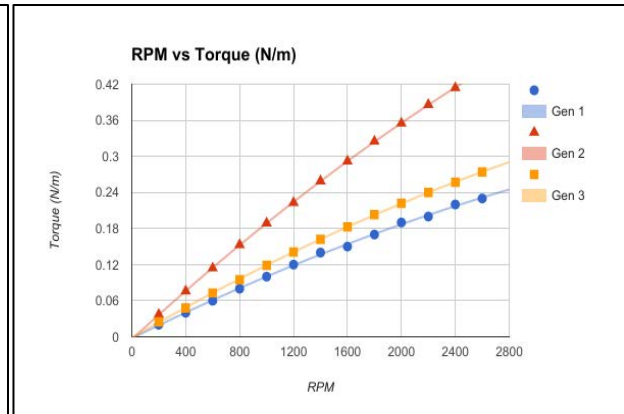


Figure 10: RPM vs Torque for the first three generation of generators

Table 1: Variations of generators

	Generator 1	Generator 2	Generator 3	Generator 4	Generator 5
Number of Stages	1	2	1	2	3
Number of Coils	9	9	9	9	9
Number of Magnets	12	12	12	12	12
Material	Iron	Iron	Iron/Plastic	Iron/Plastic	Iron/Plastic

The team tried to reduce the torque of the generator by reducing the weight of the rotors. The rotors consisted of the magnets and an iron backing which increases the magnetic flux density. Most the weight in the rotors is the iron backing. Through research, the team identified that the only iron that was necessary was the iron directly right behind the magnets as seen in Figure 13 and Figure 12. A cross section of the rotors can be seen in Figure 14 which can be compared to Figure 27 in Appendix C. The rest of the iron was replaced with plastic. The plastic sections were 3D printed to reduce the lead time. The team reduced the weight of the rotors by 3D printing which also reduced the lead time.

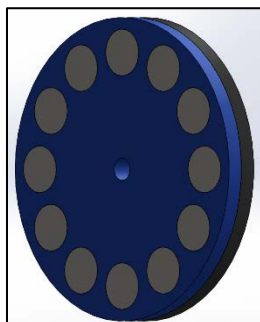


Figure 13: Front of rotor with plastic in blue, iron in black and magnets in gray

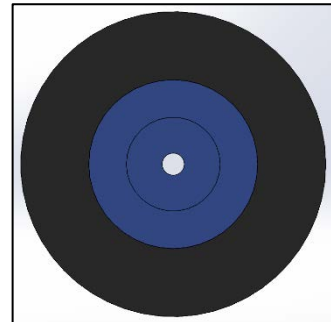


Figure 12: Back of rotor

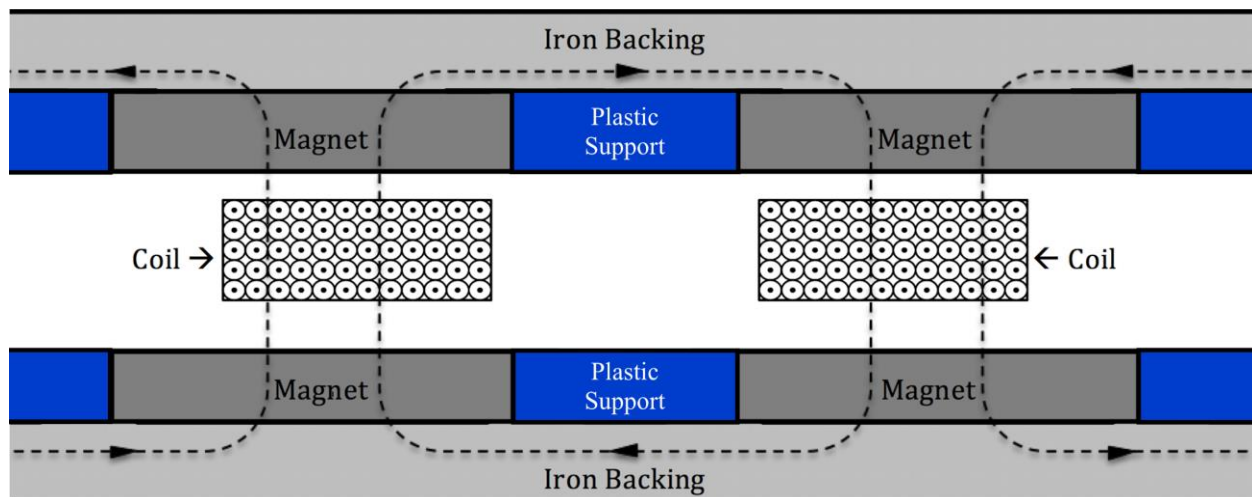


Figure 14: Sliced view of rotors and stator

The axial flux generator used in the 2016 competition only had 1 stage. The team decided research the effect of the number of stages in the axial flux generator. The theoretical power output was calculated for two and three stages which showed a significant increase the power output of the generator. Through testing the two stage axial flux generator, the data has shown that as the number of stages increase, the efficiency of the generator also increases. The configuration of multiple stages can be seen in Figure 15. The team has only been able to test two stages but plans to test a three stage axial flux generator.

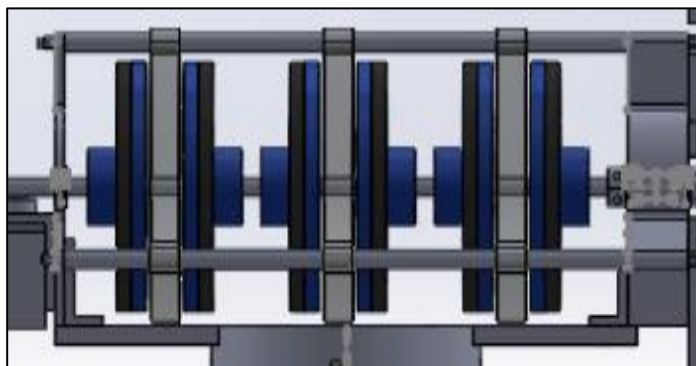


Figure 15: Stages of the generator

2.c Structural Design: Shell and Support

The structural components of last year's generator functioned as planned but took too long to assemble the generator. The team took on the challenge of redesigning the support system which consisted of an acrylic cylinder as seen in Figure 16. The acrylic cylinder held the coils in place while surrounding the shaft. The problem is that the stators and rotors needed to be assembled on the shaft before the shaft could be inserted inside the cylinder. Once the shaft was in place, the stators could be fastened down with screws that went through the cylinder into the stators. The process of assembling everything on the shaft was measured by hand and needed to be within thousandths of an inch. This is extremely important when it comes to the distance between the magnet the coils which is explained in Appendix C. If everything did not fit perfectly, the generator needed to be taken apart and adjusted. This process was repeated until the generator was assembled perfectly. Since time is valuable, especially during the competition weekend, the teamed design the structure that can be seen in Figure 17.

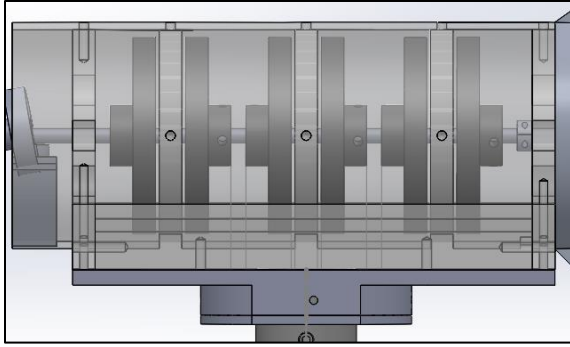


Figure 16: Structure of old generator with acrylic cylinder

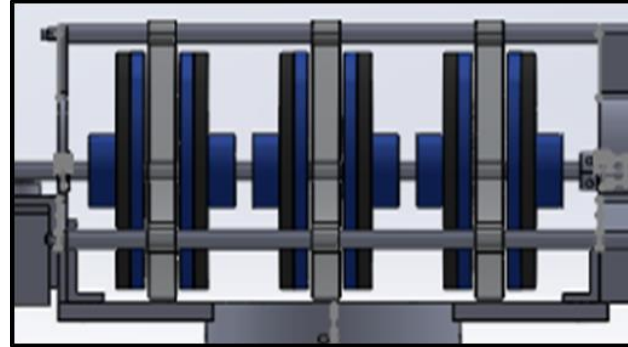


Figure 17: Structure of new generator with three support rods

The new structural design was to allow the individual assembling the generator to adjust the generator while it is on the shaft. This would eliminate the need to take the generator apart to adjust everything until it is as desired. As seen in Figure 17 there is a minimalistic design which uses three rods to support the stators of the generator. As mentioned earlier, the distance between rotors and stators had to be measured by hand using a micrometer. To eliminate some of these hand measurements but not all the measurement, the team used spacers which were pre-machined to separate the stators as desired. The spacers can be seen in Figure 17 which eliminate human error reducing the time to assemble the turbine.

Another inconvenience with the old structural design was that the acrylic cylinder could only support that particular generator of nine coils and twelve magnets. If the team wanted to test a generator with less or more coils and magnets, another acrylic cylinder would have to be bought and machined. From the team's past experience, machining an acrylic cylinder is a challenging process and was one of the major aspects of the old design that the team tried to avoid. Through this new design, the lead time and assembly time of any new generator will be significantly shorter.

2.d. Rectifier and Load

The rectifier is a line-commutated three-phase bridge rectifier as shown below, paired with a capacitor to attenuate voltage harmonics at the output. We used an off-the-shelf model rectifier. These are simple, inexpensive, reliable, and in widespread use. We made the choice to use Schottky diodes in the rectifier because they have a lower voltage drop and a faster switching time than a normal silicon diode, and are thus slightly more efficient.

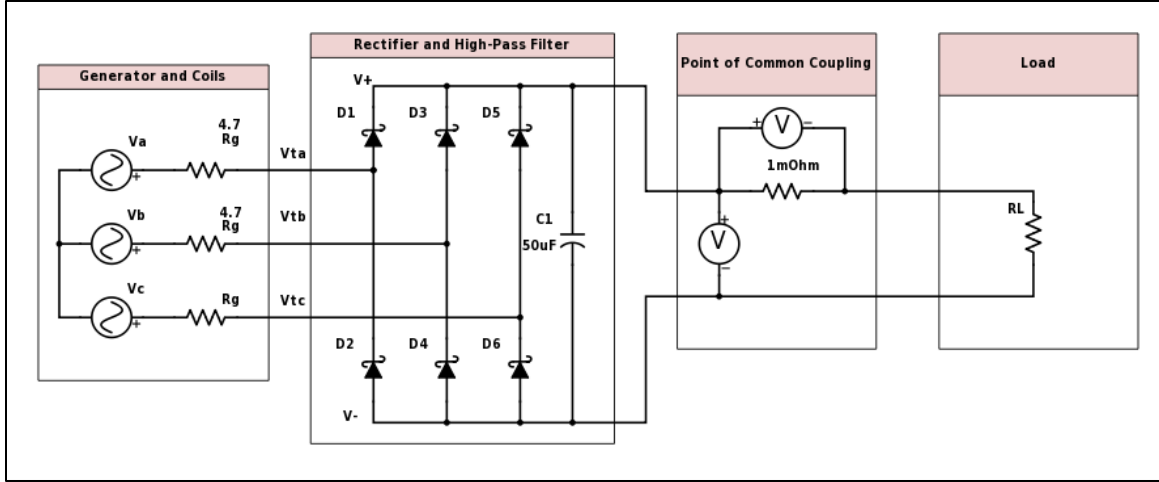


Figure 18: Model of electrical system from a power flow perspective

The above diagram also includes the model of the generator we used for our calculations - three AC sinusoidal voltage sources, each 120 degrees out of phase, whose amplitude varies linearly with the rotational velocity of the shaft. The resistors labeled R_g represent the resistance of the internal coils of the generator.

If R_g is small compared to load resistance R_L , then we can make the simplifying assumption that only two of the three phases labeled are conducting current at any instant. The highest-voltage phase is supplying current to the load, and the lowest-voltage one is absorbing this same current. If the voltages involved are large compared to the turn-on voltages of the diodes, then we can also simplify our calculations by assuming that the forward voltage drop across them is zero. At any instant, then, we can replace this model of the generator with a simpler one:

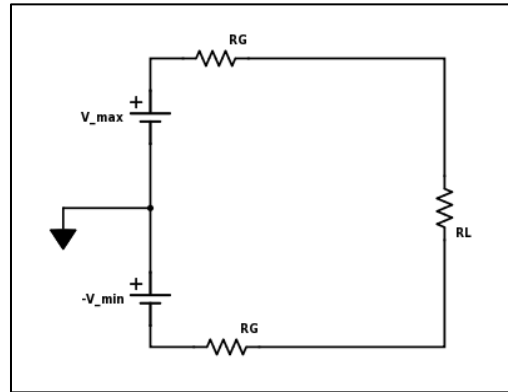


Figure 19: Simplified circuit diagram representing instantaneous flow of power

where V_{max} and V_{min} represent, respectively, the highest-voltage phase and the lowest-voltage phase respectively. From this diagram, the instantaneous power being drawn from the generator is

$$P(t) = \frac{(V_{max} - V_{min})^2}{2R_G + R_L}$$

The average value of P is dependent upon the RMS value of $(V_{max} - V_{min})$. If the amplitude of the three phase sources is called A , then the RMS value of $(V_{max} - V_{min})$ is about $1.655A$ (roughly $\frac{\sqrt{27}}{\pi} A$).

$$P_{avg} = \frac{(1.65A)^2}{2R_G + R_L}$$

Our analysis of the generator, and extensive testing, predicts that the generator voltage amplitude should rise linearly with the rotational velocity.

$$A = V_0 \omega$$

where V_0 is a constant coefficient determined by the generator design (number of turns, strength of magnets, etc.). For our generator, our choice of V_0 was shaped by the rules of the competition (PCC voltage below 48 volts) and the ability of the turbine blades to supply torque. Its numerical value is approximately 0.102 Volt*seconds/radian in our turbine. We can then write the power equation as

$$P_{gen}(\omega) = \frac{(1.65V_0\omega)^2}{2R_G + R_L} = \frac{27V_0^2\omega^2}{\pi^2(2R_G + R)}$$

which is a quadratic equation in ω , all other components being held constant.

In the steady state, the power that is delivered to the generator is equal to the power delivered to the turbine:

$$P_{turb} = P_{gen}$$

where

$$P_{turb} = \frac{1}{2} \rho A V_W^3 C_P(\lambda, \beta)$$

where ρ is the mass density of the air, A is the surface area swept by the turbine blades, V_W is the wind speed, and the C_P is a highly nonlinear function of tip-speed-ratio (commonly denoted λ) and blade pitch (β). At a constant wind speed V_W , the tip-speed ratio λ is a linear function of ω .

$$\lambda = \frac{\omega R}{V_W}$$

At a given wind speed, then, we can re-label the axes of this graph in terms of ω , scaling by a factor of R/V_W . Here is a sample mechanical power vs rotational velocity curve (solid black line) at a wind speed of 5m/s. On top of it is superimposed a plot of the power delivered to the generator at each rotational velocity - the solid red line.

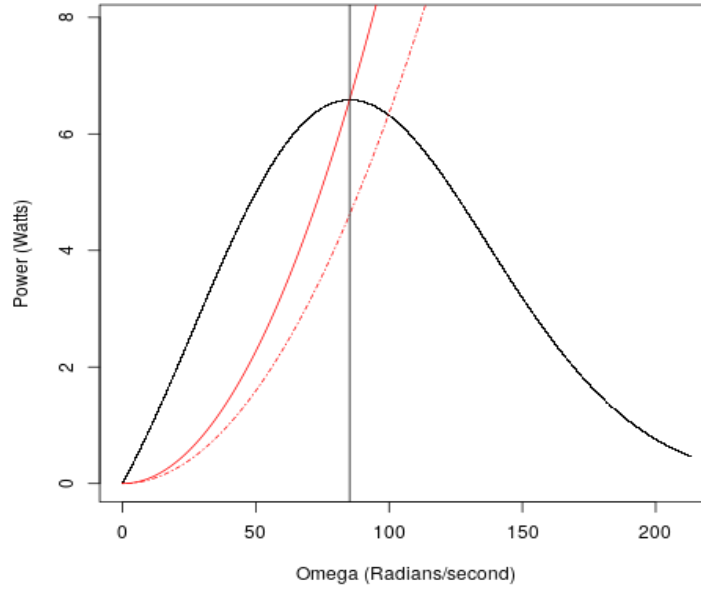


Figure 20: Wind power, electrical power, and load power at $V_w = 5\text{ m/s}$

In the region where the black line is above the solid red line, the wind is delivering power to the shaft at a greater rate than it is being drained by the generator. The imbalance of energy causes kinetic energy to accumulate in the shaft system, increasing its speed. In the region where the solid red line is above the black line, the opposite is true and the turbine tends to slow down. The stable equilibrium occurs where the solid black line intersects the solid red line.

The shape of the solid black curve is a rescaling of the C_p -lambda curve, and so is determined primarily by the blade design. The shape of the solid red line is determined by the generator design, and by the choice of R_L (load resistance). By making R_L large, the coefficient of ω^2 can be made small. This causes a vertical compression of the red curve, moving the point of intersection along the black curve to the right.

By making R_L small, the red line curves up more steeply, moving the point of intersection to the right. Choosing R_L so that the red line intersects the black line at its maximum value has the effect of maximizing the power which the turbine supplies to the generator.

The efficiency of the generator is also a function of R_L . Our model suggests that the generator efficiency is

$$Eff(R_L) = \frac{R_L}{2R_G + R_L}$$

which is a strictly increasing function. In the diagram above, R_L is chosen at 22 ohms to maximize power supplied to the generator, giving a generator efficiency of 70%. By increasing R_L beyond this point we can increase the efficiency of the generator, but at the cost of decreasing the C_p of the turbine blades. The ideal value of R_L is the one that maximizes the product of these two stage-wise efficiencies. The dashed red line in the diagram above represents the power which is actually delivered to the load at a given omega - power delivered to the generator multiplied by the efficiency. The point where the dashed red line intersects the vertical solid black line represents the real power which is actually delivered to the load under the given conditions.

To illustrate this point, this diagram displays the power delivered to the load at different values of R_L , again at the same wind speed. The solid green line above represents the power which is actually delivered to the load for different choices of R_L . (The fact that it is zero for small ω means that at the given wind speed, the turbine will never spin this slowly for any nonzero load. The green line peaks somewhat after the black line peaks, implying that maximal power delivery to the generator is not the same as maximal power delivery to the load.

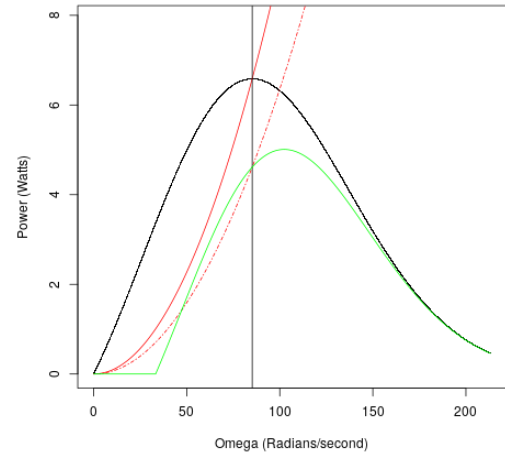


Figure 21: Power delivered to load at each R_L

As wind speed V_W increases, the black line $P_{turb}(\omega)$ is increased vertically in proportion to V_W^3 . The solid red line also increases vertically, in proportion to V_W^2 . The result is that the height of the solid red line shrinks relative to the black line and the equilibrium point of intersection travels right along the curve. To illustrate, consider the following two graphs. In both of these diagrams, the generator parameters and R_L are constant and identical to the previous diagrams, but in the first one, wind speed is 2.5 m/s and in the latter, it is 11 m/s.

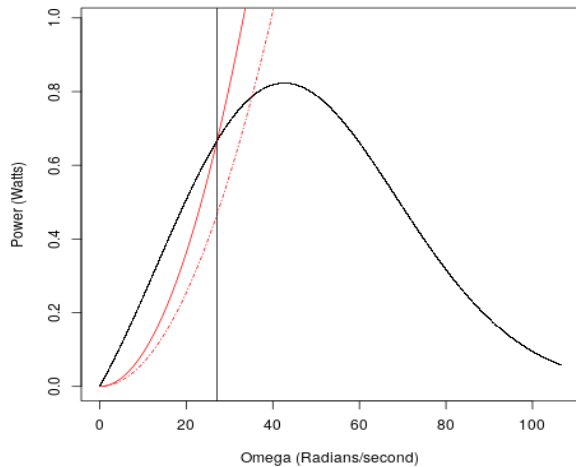


Figure 22: Wind speed = 2.5 m/s

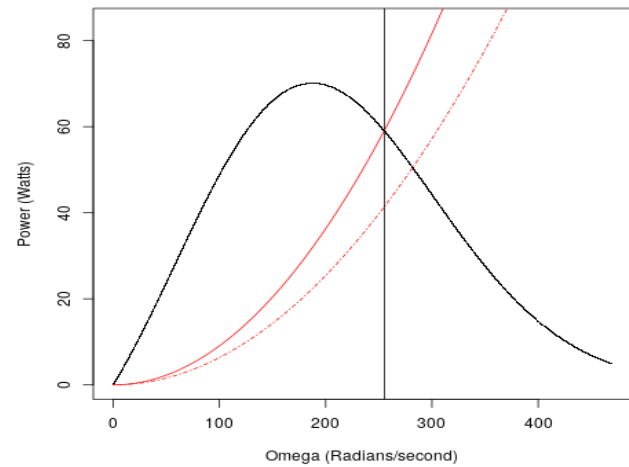


Figure 23: Wind Speed = 11 m/s

Notice that in the first diagram, the point of intersection is too far to the left and should be shifted to the right by increasing R_L . In the second diagram, the point of intersection is too far to the right and should be shifted to the left by decreasing R_L .

This means that the ideal value of R_L is not a constant, but varies with changing wind speed. At small wind speed, we should have a very high resistance R_L , reflecting the fact that very little power is available in the air at these low speeds. Under these conditions, the turbine will speed up easily because its output is almost an open circuit - it is effectively freewheeling. At high wind speed, R_L should be made small, increasing the power demanded of the turbine to take advantage of the high-energy density of the air at higher speeds.

We implement the variable resistor R_L in the form of a buck converter whose duty cycle is a function of the voltage across it.

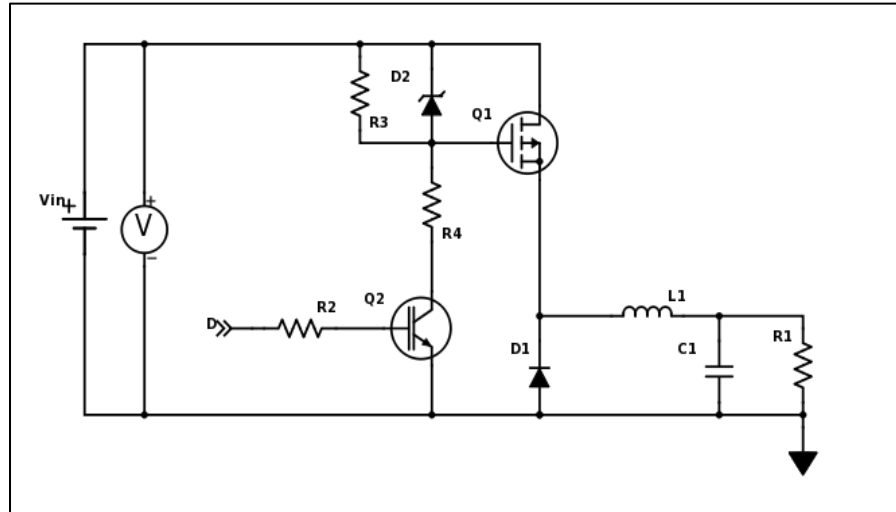


Figure 24: Diagram of a buck converter. The PWM input is at D. The voltage V_{in} may vary.

A microcontroller monitors the input voltage across the buck converter. The microcontroller contains a table of the desired equivalent resistance R_L at each voltage. It looks up the desired R_L at the table and sends a PWM signal to the transistor Q2. The duty cycle of the PWM signal determines the current I which passes through the transistor; by setting the current $I = V_{in} / R_L$ we can make the converter behave as though it has an equivalent resistance R_L .

Our control schema, and our strategies for handling the rated power / rated speed task and safety task, is much the same as in the 2016 turbine design with minor changes.

Through wind tunnel testing, we empirically determine the ideal blade pitch that corresponds to each rotational speed. A microcontroller located on the turbine side constantly monitors the voltage at the generator output by reading a voltage divider circuit, (R_{d1} and R_{d2} pictured below), and calculates the corresponding rotational speed of the turbine. It then looks up the ideal blade pitch angle in a table and drives the servo motor which controls the blades to the required pitch.

The button labeled "STOP" is the emergency off switch. When the switch is open, the voltage across the switch is 5 V. When the switch is closed, the voltage across the switch is 0 V. The microcontroller constantly monitors the voltage across this switch. If it ever drops to zero, the microcontroller brakes the turbine as described above.

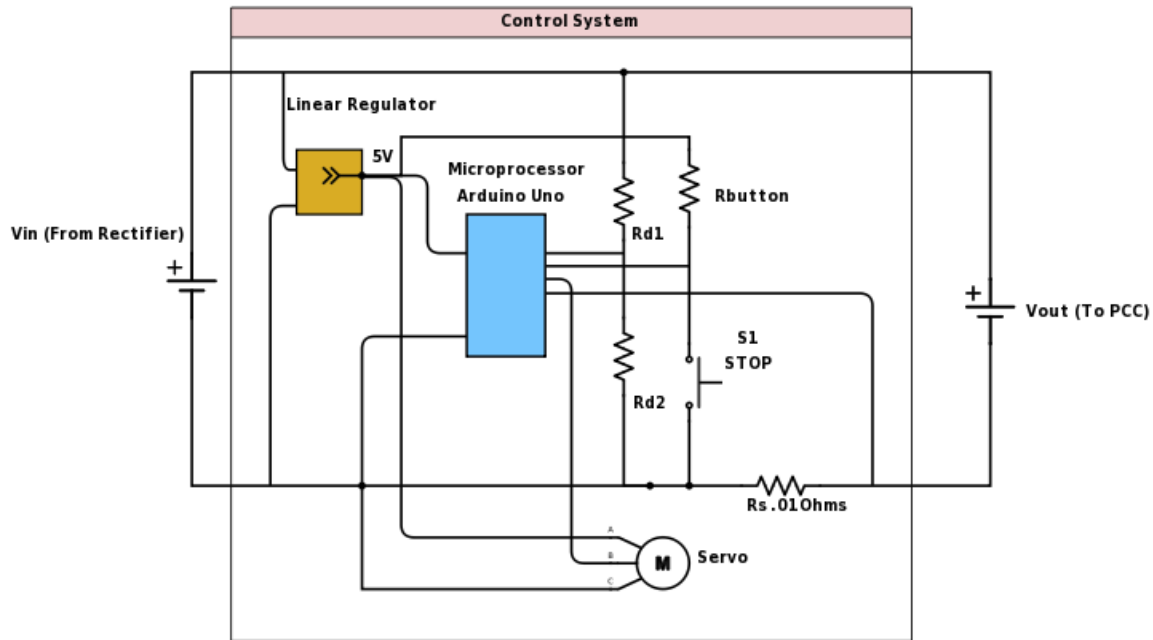


Figure 25: Diagram of the control circuit on the turbine side.

The load side of the turbine also has a microcontroller. The load must read the voltage across the DC output of the turbine and adjust the duty cycle of the buck converter accordingly. The load's controller also must be designed to respond to the unique challenge presented by the safety task. To ensure a low cut-in wind speed, it is desirable that no power be flowing from the load to the turbine at start-up of the system. However, after both safety tasks, the turbine has halted and stopped generating power, so it cannot run the control system which restarts the blades. Therefore, the load must supply power to the turbine when it shuts off.

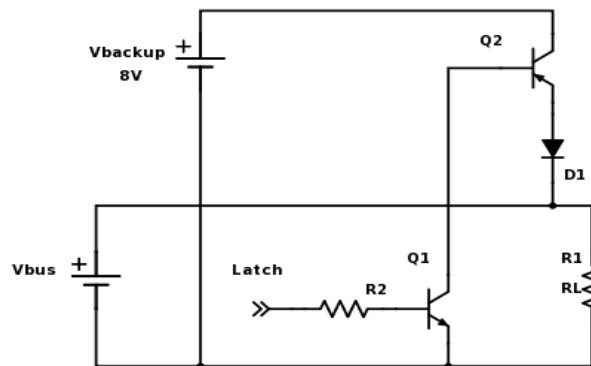


Figure 26: Latch to provide power from load to turbine when the turbine is braked

The value of the input "Latch" in the above diagram is initially zero. When the voltage V_{bus} exceeds a threshold of 8 V, the signal Latch is turned on, which indirectly opens the switch Q2. When the turbine voltage is greater than 8 V, the diode does not conduct, and all power dissipated in the load comes from the turbine. When the turbine voltage drops below 8 V, (as when the turbine shuts down for the safety task) the diode then begins to conduct, supplying power from the power supply V_{backup} to the turbine.

3. Conclusion

The goals set at the beginning of the fall 2016 semester by the Penn State Collegiate Wind Competition team have been outlined and discussed throughout this document. The overarching theme was improving over the previous year's technical design. Advancements were attempted from the 2016 competition in a multitude of areas related to aerodynamic, mechanical, generator, and electrical design. The aerodynamics team has successfully created a new blade design, and begun experimentation with a new passive pitch design and blade fabrication methodology. Opening up the turbine housing has been a great accomplishment on the mechanical side, allowing for easier access to the generator. Quite possibly the greatest advancement from last year to this year's competition was the team's knowledge of the electrical subsystems and how they can be used to optimize the turbine's performance. Successful improvements have been implemented into the competition turbine, and research endeavors still underway have been documented and will continue on into the future.

Through this year's DOE Collegiate Wind Competition, many Penn State students have been able to get hands on experience with wind energy. Most of these students plan to continue on as participants of the 2018 competition team. The competition has also provided Penn State a foundation to build a wind energy club on, as previously mentioned, whose impact extends out into the local communities. The Penn State team would like to thank the DOE and NREL staff for their work in making this competition possible.

4. Acknowledgements

The students of the Penn State Collegiate Wind Competition team would like to award special thanks to Dr. Susan Stewart, Mr. Richard Auhl, and Dr. Frank Archibald. Their guidance and encouragement throughout the entire competition year has been invaluable.

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Appendix A - Composite Blade Manufacturing Research

This year a manufacturing process has been developed to create composite layup blades. This is an advancement endeavor to move away from the current manufacturing method of SLS plastic. The benefits that a composite blade provide are highly increased strength, a smoother surface finish, and a drastically lighter design. Creating a rotor that weighs less will reduce the rotational inertia about the hub and therefore increase the torque generation capability.

This method has three main steps: creating the mold in solidworks, machining them, and carrying out the carbon fiber layup. Creation of the mold started with the slicing of the new blade in SolidWorks into two halves along the chord line. This left two surfaces that could be used in CAM (computer aided manufacturing) software. The second step involved matching the two mold halves. This was done by

creating CNC toolpaths in mastercam and running that code in the CNC to create the mold. The metal used for the mold was aerospace grade 6061 aluminum. This material was chosen due to its ability to be easily machined, and because it provides the necessary strength for the compression mold. The last step consists of using the mold for the carbon fiber layup. The plug for the mold is a slightly scaled down hollow version of the blade. This fits within the mold and leaves some space for the carbon. Then the plug is wrapped with the prepreg carbon and the molds are sprayed with release agent. Finally, the blade is placed in the mold, bolted together, and inserted in an oven to cure. The process is still being adjusted to obtain a finished product, and the endeavor will be pursued for use in the 2018 competition.



Figure 27: Aluminum Mold for Composite Layup Blades

Appendix B - Passive Pitch Control Rotor System Research

The turbine blade pitch is currently actively controlled via a microprocessor controlled servo. This configuration is detailed in the aerodynamics and electrical control system sections. The following section details ongoing research efforts to reduce the power consumption of the pitch control system.

The team has considered creating a passive pitch mechanism in order to maximize turbine power output across the PCC. The design uses a system of springs that connect the blade grips to the rotor assembly. The rotor has twisted splines built into it that the blade grip follows while moving radially in or out. Through balancing the centrifugal force of the blades with the spring force, the pitch of the blades is passively controlled. This method does not use a servo and thus theoretically will pass more power through the PCC.

The first proof of concept design of this system is based on the 2016 competition's blade design. Optimum pitch angles for the blades were determined experimentally from wind tunnel testing using these blades and last year's generator. The turbine's peak power output was measured at each wind speed to find the ideal pitch angles. This was done by setting the wind speed and sweeping an angle of attack range of the blades. Once the maximum power output was found, the RPM, pitch angle, power output, and wind speed were recorded. A table was created with the ideal pitch and RPM at each wind speed from 5 m/s to 11 m/s. The RPM was then used to compute the centrifugal force at each wind speed. To control exactly how far the blades will travel radially, a sum of forces was used between the centrifugal force and spring force in order to determine the spring constant needed for a desired maximum displacement. After determining the spring constant, the same force balance was used to determine how far the blades will be along the rotor at each wind speed. Putting these parameters in cylindrical coordinates makes the theta component what was determined from wind tunnel testing, the z component from the force balance, and the radial

component is constant in order to sit on a circle about the rotor grip. A rotor was then designed in SolidWorks which has grooves to follow the calculated coordinate spline. The parts for the assembly are currently being put together, and wind tunnel testing will be taking place this semester. The design will be iterated on for use in the 2018 competition. Pictures of the SolidWorks model and partially assembled rotor are below.

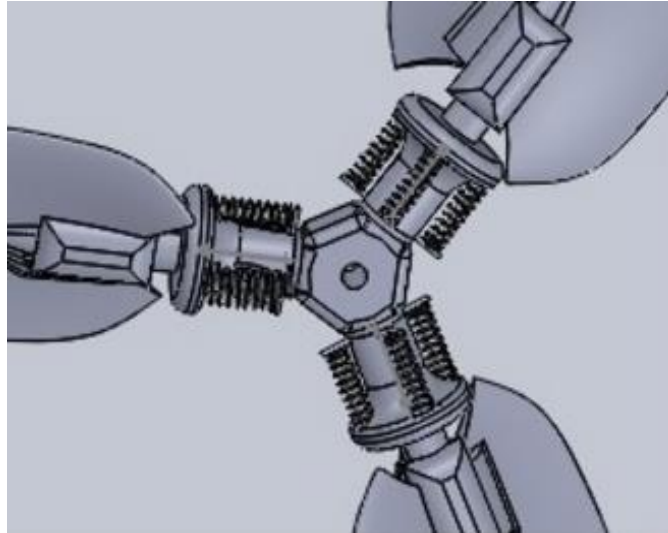


Figure 28: SolidWorks Model of Passive Pitch Rotor System



Figure 29: Additive Manufactured Passive Pitch Rotor System

Appendix C - Pulse-Width-Modulation Converter Research

In the body of this paper it is described how the tip-speed-ratio can be maintained at the ideal value by varying the power drawn from the turbine. In the 2017 design this is accomplished by a PWM buck converter in the load. This, in itself, opens up new possibilities for the design of other components of the turbine.

Because the torque of the turbine can be controlled at any desired value, it is not necessary to design the blades to supply a great deal of torque at low wind speed. Rather, the blades can be designed to yield the

highest possible C_p , without regard to the torque or tip speed at which this occurs. We believe that by designing blades at a tip-speed ratio of around 6.5-7, we can reach higher values of C_p than we can currently. This has the double benefit that the generator itself is more efficient at a higher TSR - a higher TSR means a higher voltage at the same wind speed, so we need to draw less current through the generator to draw the same power, which in turn means less energy lost as heat in the generator coils. Therefore, we are working on blade designs for the future which have a higher TSR.

We are also planning to move the torque and power control from the load to the rectifier, in the form of a PWM rectifier. The existing rectifier is simple and inexpensive, but has some problems, including significant current harmonics through the generator coils and a relatively high total harmonic distortion (THD). Using a capacitor to smooth out the output voltage (or an inductor to stabilize the current) actually worsens the problem. These current harmonics are wasteful, as they result in reactive power which is dissipated in the internal resistance of the generator. We can improve the power factor with a PWM rectifier, which draws current from the three phases of the turbine in a more egalitarian way so that the power drawn from the turbine is constant. The PWM rectifier is also capable of regulating the torque and power of the turbine to keep it at the ideal TSR. This semester we designed our initial model of the rectifier in MATLAB Simulink, and intend to continue developing it next year.

Appendix D - Past Axial Flux Generator Designs

This section is about the research and testing completed for the 2016 Collegiate Wind Competition. The information contained within this section describes how an axial flux generator works and the progress made before this year's competition.

An axial flux generator was selected for the designs because the low cogging torque of the generator meets the design objective of a low cut-in wind speed. Between the cogging torque and the desire to produce power at low cut-in wind speeds, the team has researched generators to meet the torque and power demands. Research shows that most off the shelf products have high cogging torque and do not meet the teams design objective. Therefore, the team decided to design and build its own generator. Due to the simplicity and relatively zero cogging torque, the team chose an Axial Flux Permanent Magnet Generator (AFPMG). The next step was to study the parameters that affect the performance of the AFPMG [Latoufis, Messinis, Kotsampopoulos, Hatzargyiou, 2012]. The parameters listed in below each influence the power output of the generator.

Magnets: The magnets chosen for the test turbine are D82-N52 magnets by K&J Magnetics, Inc. because of the magnets size, strength, and cost. When comparing magnets, D82-N52 had the best strength to cost ratio. In theory, the thicker the magnets are, the greater the magnetic density. Early in the design process, the team used magnets with a thickness of $\frac{1}{8}$ inches but later moved to magnets with a thickness of $\frac{3}{16}$ inches to improve performance. The power output of the generator is directly proportional to the thickness and the strength of the magnets.

Gap Between Magnets: The design of the generator allows for the distance between the magnets to be adjusted, as seen in **Figure 28** As the gap between the magnets is adjusted, the magnetic flux density passing through the coils is directly affected. By decreasing the gap between the magnets, the magnetic flux density is increased therefore creating a greater power output. The gap between magnets is directly proportional to the power output of the generator.

Magnet Core Material: The material used for the rotor, which holds the magnets, is iron. The iron, which backs the magnets, increases the magnetic flux density passing through the coils. In an early design, the team used plastic for the rotor and saw a significant increase in power output when a future design using iron was tested. The material used for the rotor backing is directly proportional to the power output.

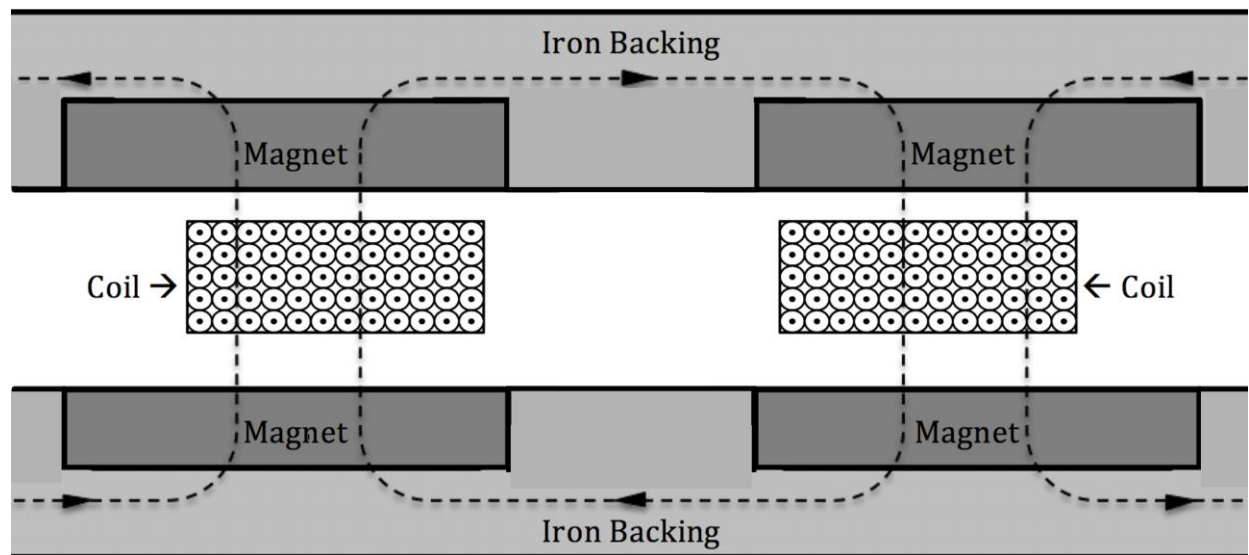


Figure 30: Displays gap between magnets and backing of magnets with iron for 2016 competition

Wire Selection: The diameter of the wire for the test turbine was chosen carefully to provide enough turns to produce the desired power output because “EMF” induced in the coil is proportional to the number of turns. On the other hand, if the diameter of the wire is too small, the resistance of the wire gets too high, which decreases output. Another downside of a small wire size is that it can be burnt with high currents that occur at high RPM. Also, the wire must be insulated because the skin effect induced by stranded wires makes the core of the wires carry less current, which also diminishes the generator’s output. Considering these interrelated variables, the wire size for the test turbine design selected was 26 gauge, which is slightly bigger than the 30 gauge of the wire used in the first and second generation designs.

Wire Configuration: The wiring arrangement of the coils influences the internal resistance of the generator and also the power output of the generator. The two arrangements of the generator that were tested were the star and delta wirings. The team is currently using the star wiring because of the slight increase in power output.

Number of Turns per Coil: The more turns in each coil will increase the power output of the generator. The issue the team faced was that by increasing the number of turns, it also increased the thickness of the coil and distance between the magnets. The team chose a thickness of the coils of .375 inches.

Ideal Shape of Coils and Magnets: The ideal shape of the coils and magnets is a trapezoid. Due to the ease of manufacturing, circular coils and magnets were used.

Magnet to Coil Ratio: The optimum ratio of magnet-to-coil per phase is 4:3. Any other magnet-to-coil ratio will not produce power because the current produced by the magnet’s magnetic flux through the coils will cancel each other out. The current will cancel because the magnetic poles of two magnets are facing in opposite directions as they pass a coil. Therefore, the current travels in an opposite direction and

cancels out. To keep the 4:3 ratio, twelve magnets on each magnet plate and 9 coils on each coil plate were built in the generator.

From the information collected above, a spreadsheet was created which contains a theoretical analysis and a prediction of performance. The spreadsheet allows for theoretical changes in the design before physical changes. The theoretical analysis was completed to show the effect each of the parameters, stated above, has on one another. The Excel code calculates the voltage output, current output and the power output of a particular set of parameters. This allowed the team to perform a sensitivity study by changing a parameter to help understand the effects each parameter has on the output of the generator. For example, to determine the number of turns in the coil, see the equation below.

Table 2: Definition of Symbols

Symbol	Definition
Φ_{max}	Maximum Flux per Pole (Wb)
B_{mg}	Magnetic Flux Density
n	(RPM) from Blade Design,
E_f	Voltage from a Single Generator
k	Winding Coefficient
q	Number of Coils per Phase
p	Number of Pole Pairs

$$N_c = \frac{\sqrt{2}E_f}{q2\pi k_w \phi_{max} np / 120}$$

Different Generator Design: The performance data shown in Table 3 illustrates nine different test results from three different generations of the generator. All the electric outputs in the table were recorded at 1600 RPM. The first-generation design built in the summer of 2015 was tested first with two different changes to improve its performance. In the first-generation tests, the wiring configuration was changed from Star to Delta, and various small electric loads were tested. However, it did not improve performance. After that, a second-generation generator was designed with one more stage. As a result of the second-generation test, the performance was improved from 2.67 W to 7.12 W. However, that power was only 35% of what the team was shooting for at the competition. There were several big changes made in the third-generation generator design. The wire diameter was decreased to 26 gauge, the numbers of the magnets and coils per stage were increased to 12 and 9, respectively, and disks of the magnets were changed to Iron. The rectifier was replaced with a more efficient Schottky diode. At the end of the 3rd generation design tests, the power output was increased from 7.12 W to 16.16 W.

Table 3: Output of each generation of the generator

	Tests	Electric load	Stage Number	Wire thickness	# of turns	# of magnets	Voltage(V)	Current(A)	Watts(W)
1	1st generation	20	1	30	300	8	7.3	0.364	2.67
2	1st (High RPM)	various	1	30	300	8	N/A	N/A	N/A
3	1st (Delta Wiring)	10	1	30	300	8	3.76	0.375	1.41
4	2nd (Phase 45)	40	1	30	300	10	N/A	N/A	N/A
5	2nd (1 Rectifier)	40	2	30	300	8	15.72	0.393	6.18
6	2nd (2rec in series)	40	2	30	300	8	16.9	0.422	7.12
7	3rd generation	9	1	26	250	12	10.4	1.16	12.13
8	3rd (Iron Disk)	9	1	26	250	12	11.6	1.29	14.95
9	3rd (Iron, Schottky)	9	1	26	250	12	12.06	1.34	16.16