NAU Collegiate Wind Competition 2016 Tunnel Team B (Electrical Design)

Final Report

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2015-2016

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DISCLAIMER

EXECUTIVE SUMMARY

The Collegiate Wind Competition is an undergraduate student competition that takes place biannually. It is put on and managed by both the US Department of Energy and the National Renewable Energy Laboratory. Any number of schools may enter the competition, and each school sends two teams to the competition: a Tunnel team and Deployment team. The role of the Deployment team was to develop a market plan which identifies a viable market that can use renewable wind energy turbines, which are disconnected from the nearest electrical grid due to distance. Then the deployment team had to design a turbine which can excel in this market.

The Tunnel team, which was split into two teams divided by discipline, needed to design a turbine for a smaller-scale testing event held at the competition. This turbine must produce at least 10 Watts of power in a given range of wind speeds, and pass a number of other tests to score points. Also, two presentations will take place, one for the public and one for industry professionals in a private setting, both of which are scored as well. Whichever team has the most points at the end of the event wins, and receives an award.

The Electrical portion of the Tunnel team was focused on four distinct portions of the design:

- Controls, system which regulates the electronics through switches and brakes.
- Load, the device which stores or dissipates power in a safe and efficient manner.
- Power Electronics, the devices which regulate the power coming out of the turbine and make it usable for whatever sort of Load is connected.
- Software, the code written so that the Controls system can perform the correct tasks.

These four areas of discipline became the sub-teams of the Electrical Tunnel team. After market research, literature reviews, and design proposals, the sub-teams prototyped their components and began small-scale tests. Afterwards, they moved to manufacturing and final testing, combining their components with the Mechanical Tunnel team. Once the testing results came in, redesigns were implemented and then retested, to ensure the best score possible for our design at the competition.

ACKNOWLEDGEMENTS

The Collegiate Wind Competition, Tunnel Team B (Electrical) would like to extend their heartfelt thanks to the following people:

David Willy, Faculty Advisor
Karin Wadsack, Faculty Advisor
Our fellow CWC Teammates on the Mechanical and Deployment Teams
Dr. Venkata Yaramasu
John Sharber
The US Department of Energy
The National Renewable Energy Laboratory
Novakinetics Aerosystems

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1 – Background

The US Department of Energy's (DoE's) Collegiate Wind Competition (CWC) involves 12 colleges around the United States, and is designed to give students a better understanding of wind energy. The competition also gives students real-world experience in the design, construction, and testing of a wind turbine generator and related turbine components (e.g. turbine controls). These aspects are coupled with drafting a deployment and business plan of a larger scale turbine that mathematically corresponds to a proof-of-concept scale model. Employers attending the competition will be interested in the experience attained by students and competition attendees.

1.1 – Introduction

This section contains the information regarding the purpose and goals of the Collegiate Wind Competition Tunnel Team B. Tunnel Team B is responsible for the following turbine components: power electronics, software, controls, and load. The project overview contains a general introduction to the competition, a description of competition requirements, and details surrounding previous year's competition models.

1.2 – Project Description

The objective of Tunnel Teams A and B was to design a highly competitive wind turbine, which fulfills the requirements illustrated in Section 2. The turbine will be taken to competition in New Orleans and tested against turbines designed by other colleges. The tunnel teams have followed the guidelines that were given by the DoE in order to be eligible to participate in the competition. The turbine is being built to specific size, design, and safety requirements and care was taken to create a turbine that has a competitive advantage when compared to the turbines from previous years at Northern Arizona University (NAU).

1.3 – Previous Competition Turbines

Tunnel Team B has the ability to look back at the turbines designed from the 2014 and 2015 competitions. By reviewing methods used previously, the current team learned from old mistakes and improved on some of the previous design ideas. Along with having the previous turbines to acquire information from, the team has kept in contact with participants and clients from previous years.

2 – Requirements

This section gives an in depth analysis of the requirements for the CWC, based on the rules and regulations issued by the DoE. The input from the faculty mentors assisted Tunnel Team B in deriving the preliminary interpretation of the engineering and customer requirements.

2.1 – Customer Requirements

The DoE *CWC 16 Rules and Requirements* document [1] generated a complete outline of customer requirements for the competition. Many of the customer requirements were also emphasized by David Willy and Karin Wadsack. The weighting for each section reflects the DoE's expectations of the team in terms of project grading. In order of highest weight to lowest weight, the customer requirements are as follows:

Power Curve Performance: The power curve of a wind turbine is represented by a plot of power generated, versus wind speed (m/s) or revolutions per minute (RPM) of the turbine blades. There are four states to a power curve: state 1 represents the turbine prior to spinning, state 2 consists of turbine power production approaching rated (maximum) power, state 3 encompasses power production control, such as staying close to the system's rated power as possible, and state 4 outlines an automatic braking system to reduce turbine RPM in high wind speeds. More points will be awarded at competition if Tunnel Team B's turbine fully adheres to power curve performance.

Control of Rated Power: State 3 of the power curve is where the controls make changes to the system in order to control rated power. A DC/DC converter allows voltage to be increased or decreased through rapid switching between various circuits. Modifying voltage allows for finer control of rated power, especially when rated power is a maximum amount of power produced by the turbine.

Control of Rotor Speed: Tunnel Team B will be using brake systems to control the RPM of the turbine blades. Turbine RPM control improves power curve performance by improving control of rated power. Turbine RPM control also greatly improves design safety, as unregulated turbine RPM is a major safety concern in events like storms and other weather conditions that include high wind speeds.

Cut-in Wind Speed: The cut-in speed is the speed of the wind when the turbine blades first start rotating. The lower this number is, the more points the team gains during testing.

Safety and Braking: The safety section relates to the braking of the turbine under two conditions: disconnecting the load from the turbine, as well as on command (push button). The team must reach 10% rated RPM within a short window of time in order to pass these tests and earn any points at all for this section.

Supply a Load System: A load is the device that the turbine powers. It serves as a way to store and/or apply the electricity generated by the turbine, and is necessary to succeed at the competition. Requirements for suitable load designs are shown in "Design an Innovative Load" in Section 2.2.

Provide Appropriate Wiring and Connections: Tunnel Team B must use wiring with consistent gauge and insulation thickness, with an American wire gauge (AWG) specification of 22 - 28. In addition, the team plans to follow standard procedures for wiring coloration. Electrical connections should follow a consistent design, so that the turbine may be easily taken down and put together.

Redundant Braking System: Faculty Advisor David Willy gave the team a requirement to have a redundant brake, in the event that one of the turbine brakes fails.

Durability: The turbine must function under the highest wind speed testing conditions present, and during a variable wind speed test, in which wind speed fluctuates over time.

Small Scale: All of the components used by the team must prevent the entire turbine from exceeding the size limitations of a 45 x 45 x 45 cm cube.

2.2 – Engineering Requirements

All of the Engineering Requirements are derived from the team's constraints in the competition, or the team's own personal goals for this project.

Produces Sufficient Continuous Power: The wind turbine must be able to produce an output power of at least 10 W within a wind speed of 5 to 11 m/s. Alongside this, testing and simulations will also have to be done to make sure that the load designed for the team will supply enough power to operate accordingly.

Withstand High Wind Speeds: The max wind speed of the wind tunnel the turbine will be subjected to is 18 m/s. It is required that the wind turbine be durable enough to sustain any physical harm to the individual pieces as well as the circuitry. Both aspects – physical and electrical – carry equal weight within the design of the wind turbine.

Design an Innovative Load: With respect to the load there are many aspects that need to be met; the load must have a visually appealing aspect that is both creative and can also provide an informative display of power production. Alongside this, the load must allow observers to be able to see what state the turbine is in as well as effectively demonstrate the power being applied to the load of interest.

Fit the Design within the Testing Space: The wind turbine has been given specific instructions for overall size; the wind turbine rotor dimension cannot exceed 45 cm in length, width, and height. The turbine parts must fit within a cylinder located at the mounting point of the wind tunnel with a height of 45 cm and a radius of 45 cm.

Quick Assembly and Disassembly: The total time duration for the wind tunnel test will be 30 minutes. Breaking this time up, 25 minutes will be given to install the turbine and for all testing to be done, and 5 minutes will be given to remove the turbine. There are multiple tests that the wind turbine needs to go through so to ensure the most amount of points awarded during testing, a quick assembly time is needed.

Shut Down on Push Button Activation or Loss of Power: This is in reference to stage 4 of the wind turbine power curve. Essentially, there needs to be a way to sense when there is a button being pressed, signifying an all stop, and when the turbine has lost power. In both cases, the team needs to bring the RPM of the turbines blades down to 10% of what they would be when subjected to a wind speed of 11 m/s.

2.4 – Testing Procedures (TPs)

The following testing procedures (TPs) outline how Tunnel Team B plans on verifying the functionality of its turbine design, and how the turbine conforms to customer and engineering requirements.

2.4.1 - Continuous Power

In order to test continuous power, Tunnel Team B ran simulations in OrCAD or another electrical simulator for the entire electrical system. The team entered different variables into the system to simulate voltages at different wind speeds. Through a variety of simulations, the team determined that the design provides continuous power past the given cut-in speed of the wind turbine, all the way up to the maximum speed of the wind tunnel test.

2.4.2 - Withstand Wind Speeds

One of the competition tests checks if the turbine fails structurally or doesn't produce power for wind speeds up to 18 m/s [1]. To assure that the turbine will pass this test, the team plans on testing to see if the vibrations caused by wind speeds up to 18 m/s loosen any connections or disrupt turbine performance. The team will test their hardware in the local wind tunnel in Flagstaff to determine if there are any faults in the electrical components at any possible wind speed in the test.

2.4.3 - Fit within the Testing Space

The team's design must fit within a 45 cm cubic volume, excluding any components located outside the wind tunnel. Since turbine electronics are smaller than turbine blades and structure, Tunnel Team B did not have to significantly account for size in its designs. Tunnel Team A has assisted in the allocation of space for all components, in order to ensure that the design still fits within the required space.

2.4.4 - Assembly and Disassembly

In order to test turbine assembly and disassembly times, Tunnel Team A and B must time their own process for assembly and disassembly. Once all hardware is finished, the teams may practice their put-up and take-down times. Since the entire Tunnel Team only has 25 minutes for assembly and testing and 5 additional minutes to disassemble [1], both teams agreed to only take 5 minutes for the assembly, and 5 minutes for disassembly.

2.4.5 - Shutting Down

Tunnel Team B is still testing the turbine's brake system through the usage of relays and triggering them with the microcontroller to activate the braking circuits. Once the hardware is assembled, the team may test the reduction in RPM that the brakes provide. While the wind speed is at 10 m/s, the brakes must slow the turbine down to 10% of the rated turbine RPM or 10% of the maximum RPM, whichever is larger [1].

2.5 – Design Links (DLs)

Tunnel Team B's design links (DLs) illustrate how the turbine controls, load, power electronics, and software satisfy the competition (customer) requirements.

2.5.1 - Controls

Tunnel Team B's brake system fulfils Engineering Requirements 2, 5, and 6. The controls are integral in the regulation of the RPM, which will stop the turbine from damaging itself in high wind speeds. Without this, the team would fail the high wind speed tests. Assembly time is linked as well, as the braking system must be easy to set up and attach to the turbine to allow for 5 minute assembly. Finally, the push button and loss of power braking system utilize the braking system designed by controls.

2.5.2 - Load

The diversion load that the team has designed relates to Engineering Requirements 1, 3, and 5. The turbine's power output drives a load, and all measurements by the DoE will be taken at the area between the turbine and the load. If there is an issue with the load, it will reflect poorly on the readings the DoE sees in the power output. The innovative load concept is a bonus challenge [1], but one that only the load sub-team will participate in. Assembly and disassembly time is highly affected by the setup of the load. Setting up displays and connections, as well as connecting DoE sensors between the turbine and load are all time consuming, but are necessary for the competition.

2.5.3 - Power Electronics

Both the rectifier and the DC/DC converter are linked to Engineering Requirements 1, 2, and 4. Each system is absolutely necessary for the transfer of power from the generator to the load, and the team will earn no points for Engineering Requirement 1 if the turbine power electronics fail. Also, the power electronics must be rugged enough to survive a high wind situation as well, and the size of the components will greatly affect the overall size of the structure.

2.5.4 - Software

The state diagram and algorithms that the microcontroller utilize to combine the controls and the power electronics directly correlate with Engineering Requirements 1, 2, and 6. Without proper software, the power electronics would not function at all, and the turbine would not generate power. In addition, faulty software could activate the brake system at inappropriate times

2.6 – House of Quality (QFD)

In Appendix A, the team's House of Quality (HoQ) is displayed. Due to the split between Tunnel Team A and Tunnel Team B, there are new changes to the correlation between the customer and engineering requirements. The team went row by row, column by column, to determine which correlations needed to be changed.

There are number of correlations that are noticeably stronger than the rest, mainly in the Produce Sufficient Wind Power and Withstand High Wind Speeds columns. Both of these columns relate highly to the bulk of the points in the tests that the DoE will subject the turbine to, so the team judged the strong correlations to reflect their goals. Design an Innovative Load is highly correlated with a number of customer requirements due to the important to those sections of the tests, as is Shut Down on Push Button Activation and Loss of Power. Areas where correlation was low usually involved the portions concerned with the Load or with setup and take down times. These two sections are highly specific and do not correlate much with other requirements outside of some very specific cases.

In the Targets section, the team pulled various details and requirements from the CWC rules. The team agreed that the targets should be the middle point of the tests, if there was one, or a simple pass for the pass/fail tests. Tolerances were determined by using the range of points available to the team, then comparing them to the difficulty with obtaining those points.

3 – Existing Designs

The Tunnel Team has broken the wind turbine design down to seven subsystems: controls, software, power electronics, and load. Each subsystem will be designed separately while also ensuring that each component is compatible with the rest of the system.

3.1 - Full Turbine Designs

The market for off-grid small-scale contains a plethora of different designs and manufacturers. The team chose the following three designs to use as references.

3.1.1 - Aleko WGV75 Vertical Wind Turbine Generator

The Aleko turbine is a vertical axis wind turbine whose main rotor shaft is typically perpendicular to the ground. This turbine's voltage and power values (12V and 50 W, respectively) are much closer to the Tunnel team's value determined by the constraints of the competition [2]. Compared to other small scale turbines this design is incredibly small, but it is still larger than the model that the team will build for the competition. Vertical axis wind turbines are less efficient and have a physical profile that exceeds the size constraints for the team's Customer and Engineering Requirements. A horizontal axis wind turbine has blades that face into the wind, driving the motor shaft that is parallel to the direction of the wind, and is more commonly used for the benefits inherent in this system.

3.1.2 - SunForce 400 Watt Wind Generator

SunForce's 400 W wind turbine is comparable to the HAWTs behind the College of Engineering, Forestry, and Natural Sciences at NAU. A single one of these turbines can produce a relatively large amount of power throughout the day and is much more comparable to the final turbine design that the deployment team is using [3]. The primary difference is the scale and power rating, but the scaling is linearly related.

3.1.3 - Xzeres Skystream 3.1

The Xzeres Skystream 3.1 is a much larger wind turbine, with a rated power of 2.1 kW [4]. The Skystream is another horizontal axis system, which reflects the scale of the deployment team's design and one of their chosen uses: Telecommunications. Examining this design will help the tunnel team scale up to the deployment team's final design.

3.2 – Controls

Controls for the turbine will consist of various pieces of hardware and software that will work together to control important parameters, such as turbine RPM, and related power output. Many components exist for use in different subsystems of the control system, including different electrical/electronic (transistors, microcontrollers, relays) and mechanical (disk brakes) devices. Microcontrollers, one of the electronic types of components, need software to carry-out their control function. Tunnel Team B has separated controls (braking systems) and software as two different disciplines/sub-teams.

3.2.1 – Market Research

Research for controls consists of a review of appropriate literature, as well as shared information acquired from knowledgeable faculty, team members, and students. The team always needs to carry out further research on more specific control methods; new research also needs to substantiate knowledge supplied by individuals.

3.2.1.1 – Ideal Power Curve of a Wind Turbine

To prevent unsafe operation, wind turbines are designed in consideration of something called a power curve. This type of analysis compares wind speed to power output of the turbine. Tunnel Team B prevented unsafe levels of power output and turbine RPM by designing the turbine with respect to the power curve illustrated in Figure 1 [5]. At V_{min}, the minimum, or "cut-in" wind speed needed for the turbine to start producing power, the turbine design allows for power output to increase exponentially with wind speed, allowing for maximum efficiency. This is displayed as state I on the x-axis of Figure 1. At state II, the turbine's output power starts to approach P_N, the rated power of the turbine. Rated power is the upper limit of power that can be produced safely. As a result, the turbine regulates RPM and/or power output in states II and III. At wind speeds higher than those encompassed by state III, or V_{max}, the turbine shuts down to prevent unsafe operation. Thus, V_{max}, is the maximum safe wind speed for turbine operation.

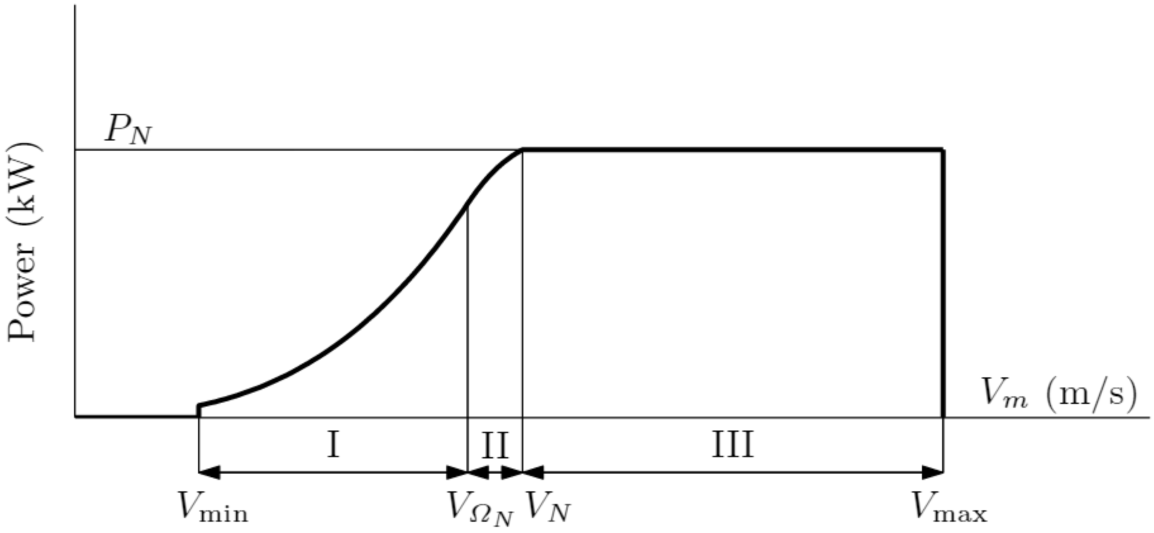


Figure 1: Ideal Power Curve of a Wind Turbine [5]

3.2.1.2 – Adjustable Speed Drives

Devices called adjustable speed drives (ASDs) can be used to control induction motors. Although induction motors are not equivalent to generators, they are relevant in their inverse nature: motors use principles such as induction to produce mechanical work, while generators convert mechanical work into electricity via principles like induction. Microcomputers, microcontrollers, and digital signal processors (DSPs) can be used to control ASDs. ASDs can implement methods that include direct field orientation (DFO), indirect field orientation (IFO), indirect rotor flux orientation, and stator flux orientation, as mechanisms of operation [6].

3.2.1.3 – Other Important Resources

Relevant topics include generator-side control, power control, and logic and safety function. The generator-side control system implements changes on the AC/DC converter, and receives signals from the generator itself. Power control, logic, and safety function implement changes on the generator-side control system, and receive input from a gearbox attached to the generator and turbine. So far, Tunnel Team B is not using a gearbox in the turbine, and is applying power to the generator straight from the turbine shaft.

Brake systems must be used to stop the turbine blades from spinning and producing power in the event of a system disconnect or on command (see Sections 2.2 and 2.3). Possible brake systems include the following: an AC brake placed between turbine and AC/DC converter, a DC brake placed between AC/DC converter and DC/DC converter, and a mechanical brake placed in or around the turbine. AC and DC brake systems involve shorting the output wires of the generator for the AC brake, and shorting the output wires of the rectifier for the DC brake (see Section 4.1).

A phenomenon known as proportional integral derivative (PID) can be used to monitor and decrease turbine RPM. One key danger that lies within decreasing turbine RPM is the generation of RPM fluctuations that result from imperfect control systems. PID creates a steady RPM by constricting RPM into two counteracting integral and derivative curves. The integral curve is concave-up, while the derivative curve is concave-down.

3.2.2 – Benchmark Testing

Previous CWC teams, like NAU and Kansas State University's (KSU) 2014 team have used transistors including bipolar junction transistors (BJTs) and metal-oxide-semiconductor field-effect transistors (MOSFETs) in their brake systems [7]. This team's brake system involved the same mechanism of shorting +, -, and GND leads described in Section 3.4.2.3, and was designed to automatically switch on in the event of power loss. The 2014 NAU/KSU team also employed an Arduino microcontroller to implement controls. In order to effectively test the generator controls, each piece of hardware (transistors, microcontrollers), and software (code programmed onto the microcontroller) must work as expected from the CWC rules and regulations.

3.3 – Software

The purpose of the software team is to consolidate with both the controls and power electronics teams in order to design a control system that meshes well with the power electronics components chosen. Furthermore, the master code for the system will be compiled by the software team using the individual algorithms composed by the controls team.

3.3.1 – Market Research

Two main choices the team is currently debating on for a microcontroller is either the Arduino or the MSP430. Both components have their pros and cons and will need to be weighted accordingly for what best fits the overall needs.

Arduino handles complex algorithms well because of the large amount of ram that is present on the board. However, one major drawback to the Arduino is that it has a large power draw. When dealing with a low power system like the teams CWC wind turbine, unnecessary power draw could cause the system to underperform expectations.

Looking at the MSP430, it has a smaller onboard ram than the Arduino; however, it works well in many other areas, such as the following:

- Remote control
- Digital motor control
- Measurement of voltage, current, apparent power, and reactive power
- Robotics
- Solar applications

From this, the MSP430 is capable of handling complex algorithms, more so than what will be used within this project. Alongside that, the MSP430 as a much lower current active draw at 300 µA versus the Arduino idle current draw of 50 mA [8]. The control boards for both the MSP 430 and the Arduino can be seen in Figures 2 and 3.

Figure 2: MSP430 Launchpad [9]

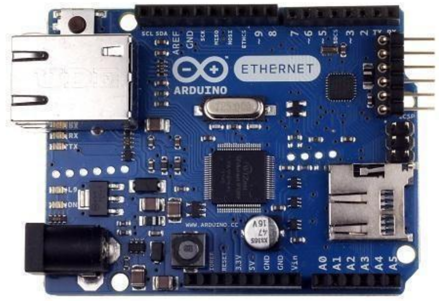


Figure 3: Arduino Control Board [10]

3.3.2 – Benchmark Testing

Testing for the software portion of the turbine involves teaming up with both the controls and power electronics teams in an attempt to make sure that all pieces designed by the controls team are compatible with the power electronics team's goals. There are four main controls aspects that the team needs to take into consideration (start point, cut in, rated power, and brake point); each control point will have to be individually tested to ensure proper function alongside the selected power electronics components. Finally, the team will need to write master code composed of all the individual control aspects of the turbine. Final testing involves the master code and hardware of the power electronics team.

3.4 – Power Electronics

Power electronics are the circuits between the generator and load, to put it simply. The main topology of these parts follows as such: Generator feeds into a rectifier, rectifier feeds into a power converter, and power converter feeds into the load [8]. Rectifiers are circuits that convert AC power to DC power, and power converters are DC-to-DC converters that adjust voltage, and thus power, as current flows through them. There may also be a DC-to-AC converter between the power converter and the load, if the load design is not DC-based. Figure 4 shows a visual breakdown of the power electronics structure.

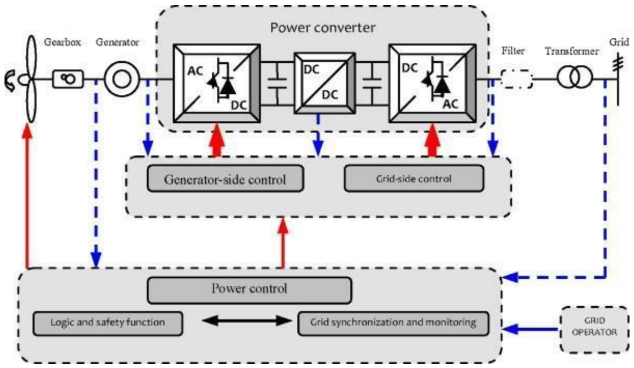


Figure 4: Power Electronics Flowchart [11]

3.4.1 – Market Research

For market research, the power electronics sub-team decided what qualities of design are important to the team's goals. After performing a literature survey, the team found three important qualities: power curve performance, safety, and use of safe wiring conventions.

The power curve is the graph of power versus wind speed, and is made up of four regions. Region 1 takes place before any power is generated, region 2 involves power being generated below the rated power of the system, region 3 is the level at which the power must be adjusted to match rated power, and region 4 is where the system is forced to brake [12]. In this power curve is where most of Tunnel Teams B's points will be made at the competition, so here is where the focus of the power electronics sub-team will work. Figure 5 shows the visual representation of the power curve breakdown.

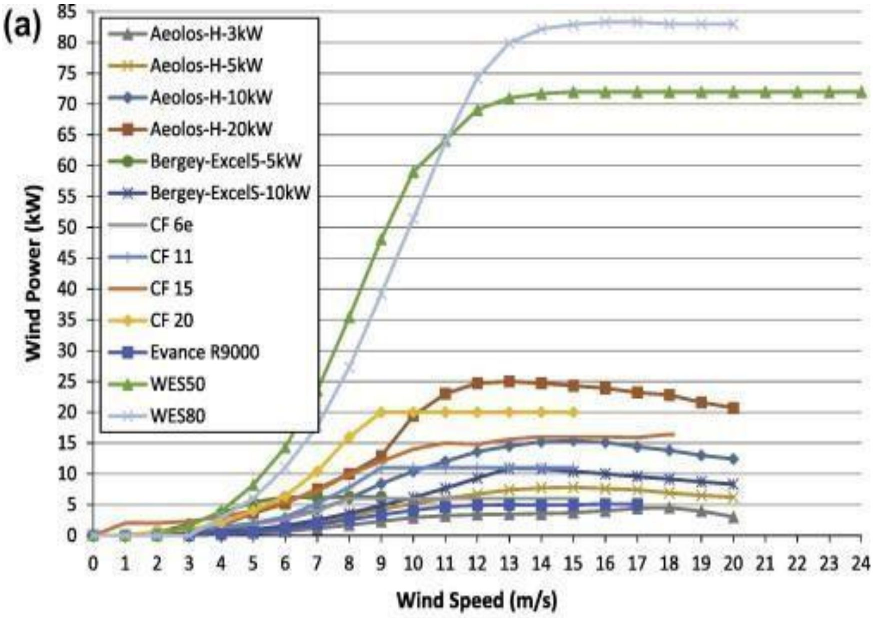


Figure 5: Power Curve for Various Wind Generators by Speed [13]

There are two main safety concerns for Tunnel Team B: the insulation of the electrical components, and the braking capabilities of the system. Two separate brake-engaging events are necessary for Tunnel Team B's design: a button-activated brake event, and the sensing of load disconnect from the turbine. Some possibilities for braking systems are as follows: a mechanical brake, an AC brake, or a DC brake [10].

The AC brake can use three switches to divert current into a resistive load or the generator itself, which provides torque to the generator and reduces turbine RPM. The DC brake uses only one switch to do so, but does this at the output side of the rectifier, which lessens the effect. By using quality parts to cut down on power loss ($P_{loss} = I^2 R$), the power curve performance of the turbine can be improved. Spending time using simulation software and practicing with physical circuits, will help perfect the design parameters required for the competition.

3.4.2 – Benchmark Testing

The power electronics sub-team performed analysis on previous years' projects, both those in which NAU had a hand and those by other colleges. By analyzing their designs, numerous ideas and benchmarks became apparent to the sub-team. The differences between the various power converter designs proved useful in narrowing down the possibilities for further simulation, and the braking systems in previous years will prove useful when designing and testing the sub-team's own design.

In addition, the power electronics sub-team determined the necessity of working together with the software and controls sub-teams from previous designs. Algorithms were the primary focus of this benchmarking, as designing a proper algorithm to read data from the power electronics and then perform actions on the rest of the turbine is a major portion of the technical design reports submitted by previous teams.

3.5 – Load

Tunnel Team B's load (the device the turbine will be powering) will need to be large enough to store all power generated by the wind turbine. The design of the load depends on the amount of power the wind turbine can generate.

3.5.1 – Market Research

All wind turbines are designed to run while connected to an electric load, which can consist of components like a battery bank or an electrical grid. If a wind turbine spins without an attached load, it runs the risk of damaging itself. This is because a disconnected turbine performs no work and spins at an unpredictably high velocity.

Wind turbines also utilize something called a diversion load. When the turbine fully charges the battery bank, the turbine needs to stop charging in order to avoid overcharging the battery. However, the wind turbine still needs to be hooked up to a load. This is where the diversion load comes in. A diversion load charge controller is a sensor switch that monitors the voltage of the battery bank. When the battery bank reaches its maximum voltage the sensor switch disconnects the wind turbine from the battery bank and connects it instead to the diversion load. Once the diversion load charge controller senses a drop in voltage in the battery bank it reconnects the turbine to it.

This presents two options for the load design that hinge on the amount of power the load can hold. If the load cannot store enough power to serve the competition purposes then it will require a diversion load and a diversion load charge sensor. However, if the load is large enough, then there will be no need for either a diversion load or sensor switch.

3.5.2 – Benchmark Testing

Tunnel Team B is going to use a dynamometer to measure the amount of generator power dissipated in the load. A dynamometer can measure force, power, or speed -- to measure needed and maximum power levels. Dynamometers come in all shapes and sizes. How the dynamometer works is by soaking up or absorbing the power that the engine/motor produces.

4 – Designs Considered

In order to generate preliminary designs for the competition turbine, Tunnel Team B generated design concepts in each of its four disciplines/sub-teams: power electronics, software, controls, and load. These designs are described in the following sub-sections.

4.1 – Power Electronics Designs

In a wind turbine, most generators output in alternating current (AC). AC is useful for immediate use, but the design in question requires a direct current (DC) point of common coupling (PCC). At the PCC, the judges will be measuring the characteristics of the turbine, so it is necessary to convert the AC power to DC power. A device known as a rectifier will convert the AC power into DC for the team's design but there are many types which need to be considered.

In addition, usually the DC power coming from a rectifier is not the ideal power the team wants to be measured. In order to fix this, the team will be using a DC-to-DC converter to change the voltage characteristics, and thus the power ($P = IV$). Again, there are a number of different designs for DC*DC converters which need to be considered.

4.1.1 – Passive Rectification with Schottky Diodes

There are generally two forms of rectification: active and passive. The two are mutually exclusive, so there cannot be both an active and passive rectifier. Passive rectification is a simple method of rectification that requires diodes in order to restrict the flow of current in one direction. There are two diodes per phase of AC power, and the generator design for this project needs to be 3-phase AC, meaning a minimum of 6 diodes is necessary for the passive rectifier. Basic diodes are not the ideal diodes for such a small-scale application in the tunnel tests, as each diode can lose an entire volt or more across that component. As such, Schottky diodes are a much more appealing alternative for the team's application, as they have anywhere from 0.33 Volts to 0.65 Volts lost across a single diode instead [14]. However, with six diodes total, the voltage lost can range from 2 Volts to 3.9 Volts, which hinders the team's design greatly.

4.1.2 – Active Rectification with MOSFETs

Active rectification, however, uses transistors to restrict current to only flowing in a single direction, mimicking diodes. Each transistor carries a much smaller voltage drop across it, and as a result it is much more attractive for the small scale design the team is attempting. However, the transistors require a controlling voltage to be applied to them in order to open or close their gates. This adds some complexity to the design, and as such they should be equally considered alongside the passive rectification method.

4.1.3 - Active Rectification with MOS-controlled Thyristors

Another way to actively rectify AC power into DC is to use Thyristors. These are devices that function as diodes that switch on or off, similar to transistors. Here, the extremely-low voltage required to turn on the MOS-controlled Thyristor (MCT) is a major benefit, but it is in the middle range for the voltage loss across the device when on. As such, it is a good choice, but not perfect either [15].

4.1.4 – Buck-Boost Converter

The buck-boost topology uses a power MOSFET as a switch to control the flow of power from the source, an inductor to supply and store energy in the form of a magnetic field, a diode to regulate the direction of power flow, and a filter capacitor to supply and store energy for the load. While the switch is closed, the voltage source charges the inductor and reverse biases the diode, blocking the flow of power to the load. In this stage, the filter capacitor supplies its stored energy to the output load. Pchannel MOSFETs are most commonly used due to the relative ease of driving the gate compared to Nchannel MOSFETs [16]. While the switch is open, energy stored in the inductor is discharged into the filter capacitor and the load. The switching of the power MOSFET is controlled using pulse-width modulation (PWM). Pulse-width modulation uses a periodic signal from a controller with period T, duty cycle D, and $t_{on} = DT$.

A disadvantage of the buck-boost converter is the relatively high current seen by the power MOSFET when the switch is closed and a high blocking voltage when the switch is open. This requires a higher breakdown voltage V_b of the power MOSFET in order to prevent the drain to source dielectric from breaking down and becoming conductive. Breakdown voltage for MOSFETS is directly related to the on resistance $\square_{\square\square(\square\square)}$, and thus increases the power dissipated by the power switch by $\square_{\square} = \square^{2}_{(\square,\square\square\square)}\square_{\square\square(\square\square)}$ [17]. Another disadvantage of the buck-boost converter is the lack of a ground connection to the drain side of the p-channel power MOSFET, which complicates the drive circuit [18].

4.1.5 - Flyback Converter

The flyback converter is essentially a buck-boost converter with the inductor replaced by a transformer. Typically used in low-power applications, flyback converters are rated for power levels between 20 and 200W [19]. The transformer not only performs the task of primary energy storage, but it also provides isolation between the source and the load. While isolation is essential in many applications of DC/DC converters such as grid-tied power generation, in this case isolation provides no pertinent benefits. By using a transformer instead of an inductor, the power MOSFET may be repositioned so that the gate may be driven with respect to ground, making driving the gate of the power MOSFET easier [20]. This also allows for a power MOSFET with a lower breakdown voltage V_b and subsequently lower power losses while the switch is conducting [18].

The diode at the secondary side also now only has to block a high voltage while the current is low, making it possible to select a diode with smaller capacitances and thus, higher switching speeds, which is an important property to consider when selecting a diode for the design. By careful control of the turns ratio of the transformer, much higher or lower voltages can be obtained than with the flyback's transformerless counterparts. By using a transformer, however, the circuit design becomes more complex to design, more expensive, and bulkier due to the coupled inductors of the transformer. While flyback converters are well suited for high-output voltages, the topology does not perform well at output currents above 10A [21].

4.1.6 - SEPIC Converter

The single-ended primary-inductor converter (SEPIC) is another DC/DC converter capable of stepping up or stepping down an input voltage to a desired output voltage controlled by the duty cycle of the transistor's controller. The primary feature of the SEPIC is its use of two inductors, either wound on a common core to form a coupled dual-winding inductor or separate windings of two uncoupled inductors. The use of coupled inductors provides the advantage of providing a smaller footprint on the board and also requires only half the inductance to get the same inductor ripple current of a SEPIC with two separate inductors [22]. The SEPIC also utilizes a capacitor-input filter and a coupling capacitor in addition to the smoothing capacitor found across the load that is common to almost all DC/DC converters.

A major disadvantage of this topology is its complexity, and subsequently its difficulty in comprehending its benefits and downfalls. However, it is certain that due to the additional components it will be more costly than the previously mentioned topologies. The increase in its footprint due to the size of the additional inductor windings will also make it more difficult to fit within the nacelle of the wind turbine.

4.2 – Software Designs

The Software team is to confer with both the controls team as well as power electronics team in order to design a controls system that meshes well with the power electronics components chosen. Alongside this, the software team has been tasked with finding the best possible method in which to control the overall system of the wind turbine. Furthermore, the master code for the system will be compiled by the Software team using the individual algorithms composed by the controls team.

4.2.1 - Tie Push-Button and Loss of Power Together

For this design, a single algorithm takes effect in the event of a button being pressed and loss of power. In the case of a push button, one input would be associated with reducing turbine RPM. With loss of power, the team would need the braking system to be normally closed. This means that while the turbine generates power, a control algorithm keeps the brakes from interfering with the power production. On event of power loss, the brakes would go into their "normal state" and begin to slow down the turbine. For this design concept, the team considered finding a way to use the same algorithm used to sense the push button, and incorporate that algorithm into the loss of power situation. For this design concept to work, the team would need to incorporate loss of power circuits as a way to sense when power loss has actually occurred. This method would greatly reduce the amount of code needed to control the turbine for these specific tests, but it would also increase the amount of circuitry needed.

4.2.2 - Sensing Circuits to Activate Switches

For this design, the group would incorporate sensing circuits to allowing for a method to see the voltage and current levels at any given time. In turn, the values obtained from the circuits are used as inputs for the microcontroller and thus used in the algorithms designed to control the turbine. For example, if the turbine does not produce an adequate voltage to supply the current load, by use of the sensing circuits, the team can adjust the load as needed to keep the system stable.

4.2.3 - Using PID controller and PWM to control TSR

PID stands for Proportional Integral Derivative control, which takes an output variable and feeds it back to the input. At the input the difference between the desired input and the actual output is calculated and this is known as the error. The error is then sent to the PID which then makes adjustments to the system by use of an algorithm, in order to achieve the desired effect. In the case of the wind turbine, it gives the team a strong way to control the output generated at maximum wind speed of the tunnel. When designing a PID controller for a given system, the steps shown below need to be followed to obtain the desired response [23]:

1. Obtain an open-loop response and determine what needs to be improved.
2. Add a proportional control to improve the rise time.
3. Add a derivative control to improve the overshoot.
4. Add an integral control to eliminate the steady-state error.
5. Adjust the constants until a desired response is obtained.

PWM stands for pulse width modulation, which is used in the DC/DC converter. PWM adjusts the efficiency of the converter, allowing for control of the output based on a specific input. By controlling the efficiency of the converter, the team can control the current flow of the system. With the ability to control the current Tunnel Team B can essentially add a cogging torque to the generator, functioning as a type of brake. By using PWM the team can limit the amount of power generated by the turbine, such that the turbine will have a constant RPM no matter how high the wind speed. This is because only a set amount of current is allowed to be produced [24].

The PID controller could be the algorithm used to control the output that is desired at any given point whereas the PWM would be added along with this as a way to control the RPM of the rotor and thus the tip speed ratio of the rotor.

4.2.4 - Arduino Sleep Library

For this design concept, the focus is more on the power consumption and its effect on the system. In reference to the Arduino microcontroller (see Section 3.2.1), the boards have a maximum current draw of 50 mA while active. However, some of the Arduino boards have a sleep/idle function that allows them to lower their current draw to about 20 mA until an external input is given. When dealing with lower power generation it is best to have as small of a power consumption overall allowing most of the energy generated to be delivered to load [25].

4.3 – Controls Designs

For the purposes of concept generation and selection, Tunnel Team B decided to focus on turbine brake systems as the most important aspect of controls designs. For consistency, the team's electrical brake systems (sections 4.3.1 and 4.3.2) operate using relays (mechanically controlled switches), instead of transistors (electrically controlled switches). Many types of relays and transistors exist for these types of brakes, so variation in design is possible.

The team decided to use latching relays for the electrical brake system designs, such as the TE RT314A06 [1]. Latching relays only use power in the moment that the switch in question opens or closes, as opposed to using power constantly to hold that switch open or closed. This reduced power consumption would be important for producing reliable turbine brakes.

In addition, Tunnel Team B investigated two methods of operation for disc brakes (sections 4.3.3 and 4.3.4): hydraulic control and pneumatic control. Although many other mechanisms of operation exist, hydraulic and pneumatic serve as a sufficient starting point.

4.3.1 - AC Wye-connected Brake

Since both sections of the Tunnel Team have currently agreed to use an AC motor as a generator, electrical braking can occur before the AC current of the generator/turbine is converted into DC current. This AC electrical braking involves connecting, or "shorting" the turbine's three power output wires (positive, negative, and ground), which represent a three-phase AC signal. This action increases cogging torque of the turbine, reducing turbine RPM.

Tunnel Team B can use the TE RT314A06 latching relay [1] to make the appropriate connections mentioned above. Tunnel Team B proposes that this connection be made in a Wye fashion. The three wires need to be connected upon load disconnect, or on command (push button) to ensure that the turbine shuts down (10% of rated RPM) at these times.

Figure 6 illustrates this Wye connection made between the positive (+), negative (-), and ground (GND) wires coming out of the turbine, toggled using latching relays (switches) that are controlled by a control signal. The control signal comes from a microcontroller (discussed in Section 3.2.1), which senses turbine RPM. When the three wires are connected, the turbine slows down by a mechanism known as cogging torque. Cogging torque increases during this event, increasing turbine rotational resistance, and decreasing turbine RPM as a result.

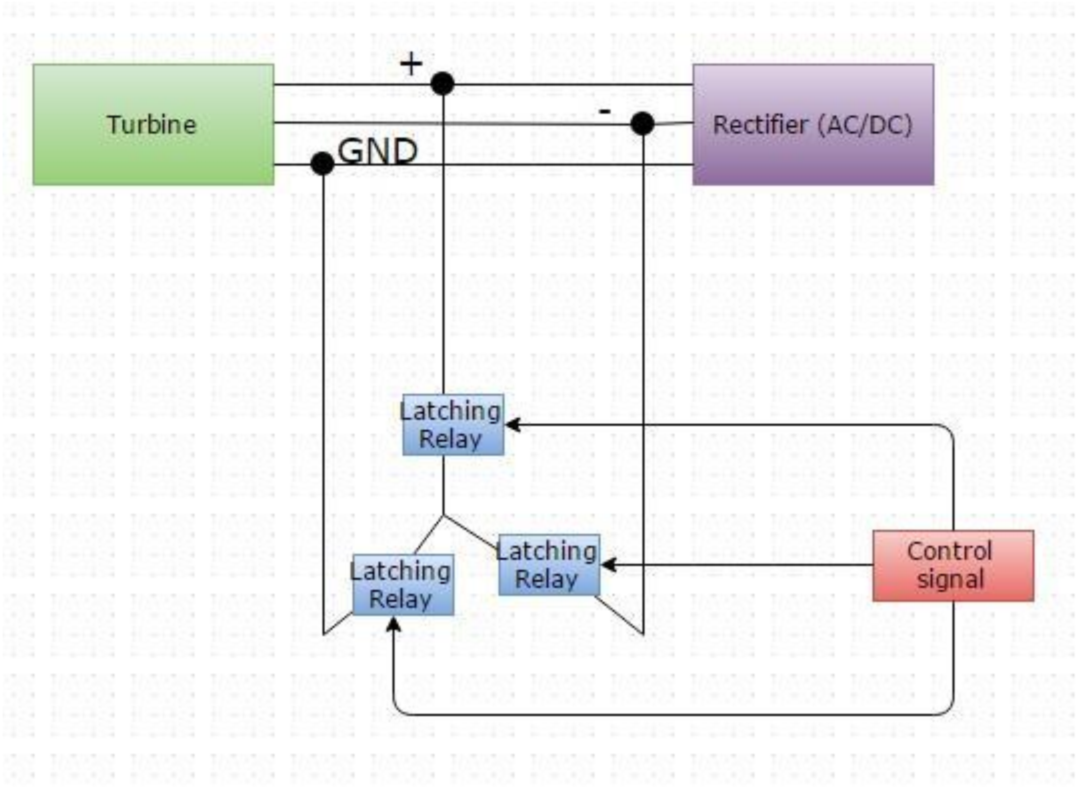


Figure 6: AC Wye-Connected Brake Configuration

4.3.2 - DC Dynamic Brake

Similar to an AC Brake system, Tunnel Team B could use a mechanism known as a DC Dynamic Brake to connect the two wires coming out of the turbine's AC/DC converter. The AC/DC converter converts the AC output of the turbine to DC current suitable for the load. By connecting the two output wires of the AC/DC converter, the turbine RPM will decrease by way of increased cogging torque. The TE RT314A06 latching relay [1] can also be used to connect/disconnect these wires.

4.3.3 - Mechanical Disc Brake -- Hydraulically Controlled

Turbine disc brakes consist of a disk surrounding the turbine shaft, and a caliper mounted to the turbine that clamps down on the disk, generating friction, and reducing turbine RPM. One way to control this caliper involves using a hydraulic system to engage and disengage the caliper by precise amounts, so as not to abruptly and completely stop the turbine. Hydraulic systems use water or another liquid to generate pressure, which can accomplish tasks like engaging a caliper.

Kobelt, a company that manufactures disk brakes, steering systems, and other devices, provides a hydraulic high pressure caliper model that can be connected to an existing hydraulic system, known as the 5027-H [25].

4.3.4 - Mechanical Disc Brake -- Pneumatically Controlled

In addition to using a hydraulic system to engage/disengage a disc brake caliper, Tunnel Team B can also use a pneumatic system. Pneumatic systems work by using pumped air to generate the pressure necessary to operate a disc brake.

Kobelt's 5027-A and 5027-S models of disc brake caliper both allow for connection to existing pneumatic systems [17]. Kobelt's 5027 disc brake, which includes the H, A, and S models that could be used with pneumatic or hydraulic systems, is pictured below.

Figure 7: Kobelt 5027 Disc Brake [17]

This very durable disc brake caliper would have to be controlled in such a manner (via pneumatics or hydraulics) that would prevent the turbine blades from abruptly stopping completely. Abrupt changes in turbine RPM would present a safety concern, due to larger amounts of momentum present in largescale turbines. Also, competition rules only require a 10% reduction in rated (during maximum power generation) or maximum RPM [26], allowing Tunnel Team B to focus more on power consumption than braking power.

4.3.5 - Hysteresis Brake

Hysteresis brakes are rotor and stator based, and consist of a field coil and magnets [25]. When power is applied to either the field coil or magnets, the rotor is magnetically restrained. Tunnel Team B could attach a hysteresis brake to the shaft of the turbine to decrease turbine RPM. Hysteresis brakes operate under a similar mechanism that allows electric motors to produce motion, only hysteresis brakes hinder motion instead. An example diagram of a hysteresis brake is shown in Figure 8.

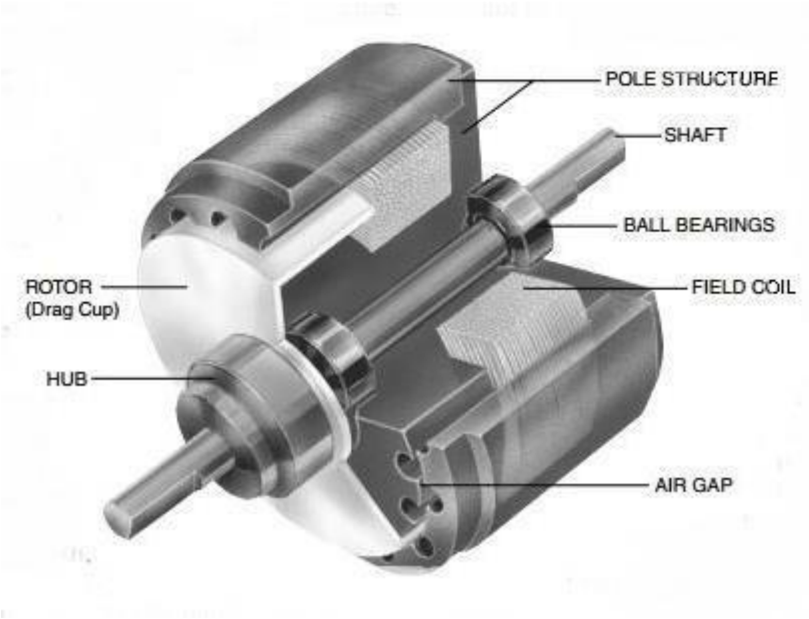


Figure 8: Hysteresis Brake [18]

Magtrol Inc., a company that makes hysteresis brakes and other machinery components, models a typical hysteresis brake in the above diagram. The shaft and rotor assembly spin inside of the pole structure, which contains magnets. The mechanism discussed above reduces turbine motion despite the presence of an air gap between the rotor and the pole structure (stator). This air gap allows for increased durability, without friction being a factor in the degeneration of the brake system.

4.3.6 - Webbed Frog Feet Air Brake

Certain leaping frogs are equipped with webbed feet that allow them not only to swim, but to land more gently by way of gliding [27]. Tunnel Team B could use a similar mechanism to decrease turbine RPM. This mechanism would consist of attaching “webbed” air brakes to the turbine blades. Under normal conditions, the brakes would act in a “closed” position, not sticking out of the turbine blades. When braking is needed, the brakes would “open” as flaps on the blades, generating drag, and generating a reduction in turbine RPM.

4.4 – Load Designs

The turbine’s load will store the generated power and display relevant information through some form of portable computer, such as a tablet or even a cellular phone. The load should not be the most complicated part of the entire design. The load should also facilitate future alterations for the load bonus challenge.

4.4.1 - Diversion Load

All wind turbines are connected to a battery or power grid as a load. In the case of a battery there’s always the issue of overcharging it. In order to get around this issue one could add a diversion load. A diversion load is a second load that the generator can connect to when the battery bank is fully charged with a diversion load charge controller switching between the two. A diversion load charge controller is a sensor switch that monitors the voltage of the battery and disconnects from the battery bank and then connects to the diversion load until the battery voltage drops. Once the voltage drops the generator switches back to the battery bank [28].

4.4.2 - Smart Material Load

Smart materials are compounds (usually metal) that reshape in reaction to changes in electric fields. Two examples of smart materials are dielectric elastomers (DEs) and Ionic polymer metal composite (IMPC). DEs have been used to develop actuation systems for the transformation of electrical power into controlled mechanical work. They have a relatively low cost and are highly efficient [29]. Today DEs are being implemented in wave energy converters (WEC). IPMC is an electro-active polymer (EAP) that is used as an electro-mechanical sensor and is currently being studied as an energy harvester [30].

4.4.3 - Heat Sink Fan as a Load

Inspired by the test load, the Heat Sink Fan involves a resistor that heats up with electrical current. The team would use a heat sink fan to make sure the resistor does not overheat. The heat sink also allows the resistor to work at is optimum level [30]. Just like a fan that cools a laptop on one’s lap as it heats up, the heat sink reduces the heat coming from the resistor.

4.4.4 - Loads Inspired by Nature

Two ideas considered for the load are inspired by nature. The first is a smart material load shaped like butterfly wings that will flap when a current is going through them. Aside from that it does not have any other application, it is just a simple load. The other idea is inspired by the electric eel. Essentially it is a load designed to safely discharge all of its stored power when the turbine brakes.

4.4.5 - Use a full-sized monitor to display Load Characteristics

Using a full-sized monitor is an idea of how to satisfy the CWC bonus challenge of making a creative and useful load. It requires a battery bank as the load to power the display. The display would show useful information such as wind speed, blade speed, power generated, etc. It could also show different states (if any) that the subsystems are in.

5 – Designs Selected

For the design selection process, each sub-team used a Pugh chart to eliminate the ideas with least merit. Afterwards, the sub-teams used decision matrices to further narrow ideas down to one idea for each sub-team/discipline. The criteria chosen for each sub-team varies, as the issues each sub-team faces and what is important to them are not the same for the rest.

5.1 – Power Electronics

Tunnel Team B split Power Electronics into two smaller groups: Rectification and DC/DC conversion. Because of the differences between the two topics, the team used two decision matrices instead of one Pugh chart and one decision matrix.

5.1.1 - Rectification

The three rectifier designs were rated according to their voltage drop (the amount of voltage lost between the input and output of the device), power draw (the amount of power required to keep the device working), complexity (the difficulty of building a device from scratch without error), and cost (the cost of individual parts and assembly). Each criterion is rated on a scale from 0 to 10, with ten being the best, and 0 being the worst.

Table 1: Rectifier Decision Matrix

Criteria	Weight	Passive	**Active MOSFET**	Active MCT
Voltage Drop	40%	3	**8**	5
Power Draw	30%	4	**7**	4
Complexity	20%	8	**4**	2
Cost	10%	6	**5**	3
Total	100%	5.4	**6.6**	3.9

The active rectification with MOSFETs design was the best design by a small margin, scoring a little over 1 point more than the passive rectification with Schottky Diodes design. The MOSFETs have a much lower voltage drop, so they score higher than all the other categories and use less power when operating as well. They are not the simplest design, nor the cheapest, but overall the points favor the MOSFET design over others.

5.1.2 – DC/DC Conversion

The buck-boost, flyback, and SEPIC DC/DC converter topologies were considered for implementation in the design by scoring them individually with regards to the following criteria and their associated relative weighting. For low power applications, the differences in power losses and efficiency between each topology are negligible and thus, efficiency holds a relatively low criteria weighting. Due to clear restrictions on the dimensions of the design, the ability for the DC/DC converter to easily fit within the nacelle is paramount to success and thus size holds a relatively high criteria weighting. Whichever DC/DC converter that is chosen must be designed, simulated, and ordered within certain time restrictions, thus the complexity of the chosen design must not be such that it would hinder the ability of the team to stay on schedule.

Additionally, most of the added components and features of the SEPIC, for example, provide benefits that are not as advantageous to this application as they would be in other more large scale or precision applications. Most important to consider is the power range. This includes the range of input voltages, output voltages, and output current. For the moment, the range must be wide enough to pair well with both the generator and load rated power values that are still to be determined. Each criterion is rated on a scale from 0 to 10, with ten being the best, and 0 being the worst.

Table 2: DC/DC Conversion Decision Matrix

Criteria	Weight	**Buck-Boost**	Flyback	SEPIC
Efficiency	15%	**4**	8	8
Size	25%	**8**	6	4
Cost	10%	**8**	7	6

Complexity	20%	**8**	7	5
Power Range	30%	**8**	4	2
Total	100%	**7.4**	6.0	3.9

Using the aforementioned criterion as a guide, it has been determined that the buck-boost topology will be used for the DC/DC conversion of the design. The buck-boost topology is the basis upon which almost all other DC/DC topologies are designed, and as such has the fewest components, which results in the lowest cost, and also the greatest ease of design. From researching off the shelf versions of each topology, the team found that the buck-boost converter also has a relatively good range of rated power. Efficiency is the only criterion found to be lacking for the buck-boost topology, but as mentioned the efficiency of the converter is not of great concern.

5.2 – Software

In order to narrow down the choice to one a decision matrix was used to see which would be the best design to implement in the overall system. The criterion was separated into four categories with the most important being power draw, braking and responsiveness. The wind turbine that is to be designed by the tunnel team is a low power system and it is because of this power draw had the highest weight. Braking and responsiveness both had an equal weight because it was found both were equally needed in the controls aspect of the system.

Table 3: Software Decision Matrix

Criteria	Weight	LoP and Push Button Together	**PID and PWM**	Arduino Sleep Library
Power Draw	35%	6	**5**	7
Braking	25%	7	**8**	5
Responsive	25%	6	**8**	6
Difficulty	15%	6	**5**	8
Total	100%	6.25	**6.5**	6.4

After using the software Pugh chart found in Appendix B, the designs were narrowed down to three choices. The wind turbine that is to be designed by the Tunnel team is a low power system and it is because of this power draw had the highest weight. Braking and responsiveness both had an equal weight because it was found both were equally needed in the controls aspect of the system. After scoring each design in the criterion listed, the team found that the PID and PWM design would be the best fit for the overall system.

5.3 - Controls

After eliminating the webbed feet and two disk brake concepts by way of the Pugh chart in Appendix B, the team used a decision matrix to finalize one concept as the most viable. The team used the same five criteria used for the Pugh chart. Power consumption was weighted most important in the decision matrix due to the power curve performance test in the competition. The power drawn away from powering the load needs to be minimized in order for best turbine performance with this test.

The team rated complexity as second most important due to its association with reliability. The more complex a brake system, the more likely that it might not work in competition. This possibility would greatly hurt the team's performance on the safety test.

Braking power, cost, and size did not have as much impact on the evaluation of the final three concepts as the previous criteria. For braking power, this was because the turbine RPM only needs to be reduced by 10% of the maximum or rated RPM -- measured by the team -- during the safety test. Size and cost are still important due to turbine size and budget limits, but are simply not as high of a priority as the other criteria.

Table 4: Controls Decision Matrix

Criteria	Weight	**AC Brake**	DC Brake	Hysteresis Brake
Power Consumption	35%	**9**	7	5
Complexity	25%	**7**	9	6
Size	10%	**8**	9	4
Braking Power	20%	**7**	6	9
Cost	10%	**9**	9	6
Total	100%	**8**	7.7	6.05

After completion of the decision matrix, the AC Brake concept was evaluated as the optimal idea for a turbine brake system. The main reason for this is due to its lower power consumption requirements -- the brake only needs to connect wires, and does that immediately next to the turbine, minimizing power loss. Latching relays can be used to accomplish the toggling of these electrical connections, as the mechanically operated switches only require power at the moment of opening and closing of their switch mechanism.

Tunnel Team B will use a different mechanism as a redundant brake system. The different mechanism will operate independently from the primary brake system, allowing for the redundant brake to supplement the primary brake in the event of primary brake failure. This mechanism could consist of a DC brake which uses a MOSFET transistor as a switch to connect or disconnect the two wires of the DC portion of the turbine output.

5.4 - Load

After using the load Pugh chart in Appendix B the team selected three options. The decision matrix in Table 5 is graded on four criteria: cost, simplicity, creativity, and functionality, as in whether the load serves a function other than itself.

Table 5: Load Decision Matrix

Criteria	Weight	**Diversion Load**	Heat Sink	Eel Discharge
Cost	30%	**8**	8	6
Simplicity	30%	**8**	9	5
Creativity	20%	**7**	4	9
Functionality	20%	**8**	5	7
Total	100%	**7.8**	6.9	6.5

For load, the two most important criteria were cost and simplicity because in the long run, the load should not have the most money or time spent on making it. If the load is simple there can be more time spent on the more complicated parts of the turbine. The diversion load was the obvious best option because its design on paper was simple, and the materials to make it are cheap and plentiful. It is also more creative than a heat sink. Since the diversion load has a battery bank it can be used to power anything hooked up to the load for the bonus challenge such as the display monitor discussed earlier.

6 – Implementation

The team worked on creating the components in the workspace shared with Tunnel Team A. Both teams operated within the Sustainable Energies Laboratory (Building 74), also known as the “Solar Shack”. As each team progressed in their construction, members changed their designs to assure that each component fulfilled the Engineering Requirements set at the beginning of the project.

6.1 – Design Updates

Tunnel Team B has changed some aspects of the design, between the beginning of the second semester and the start of testing. The major changes were in the layout of the electrical components, the controls system, and the load portion.

6.1.1 - Layout

Figure 9 shows the layout of the electrical components, as well as the turbine itself. First up is the Turbine, connected directly to the AC Brake, which the Arduino Zero controls, and the manual shutdown switch. Next is the AC/DC converter, also known as the rectifier. The rectifier takes the unregulated AC power from the generator, then uses some diodes to change the properties of the power from AC to DC.

The rectifier has been changed from an active design to a passive one, to better ensure that it works and will not fail due to faulty coding. The unregulated DC power then goes into the DC/DC Converter, which corrects the imperfections in the power signal, turning unregulated DC power into regulated DC power.

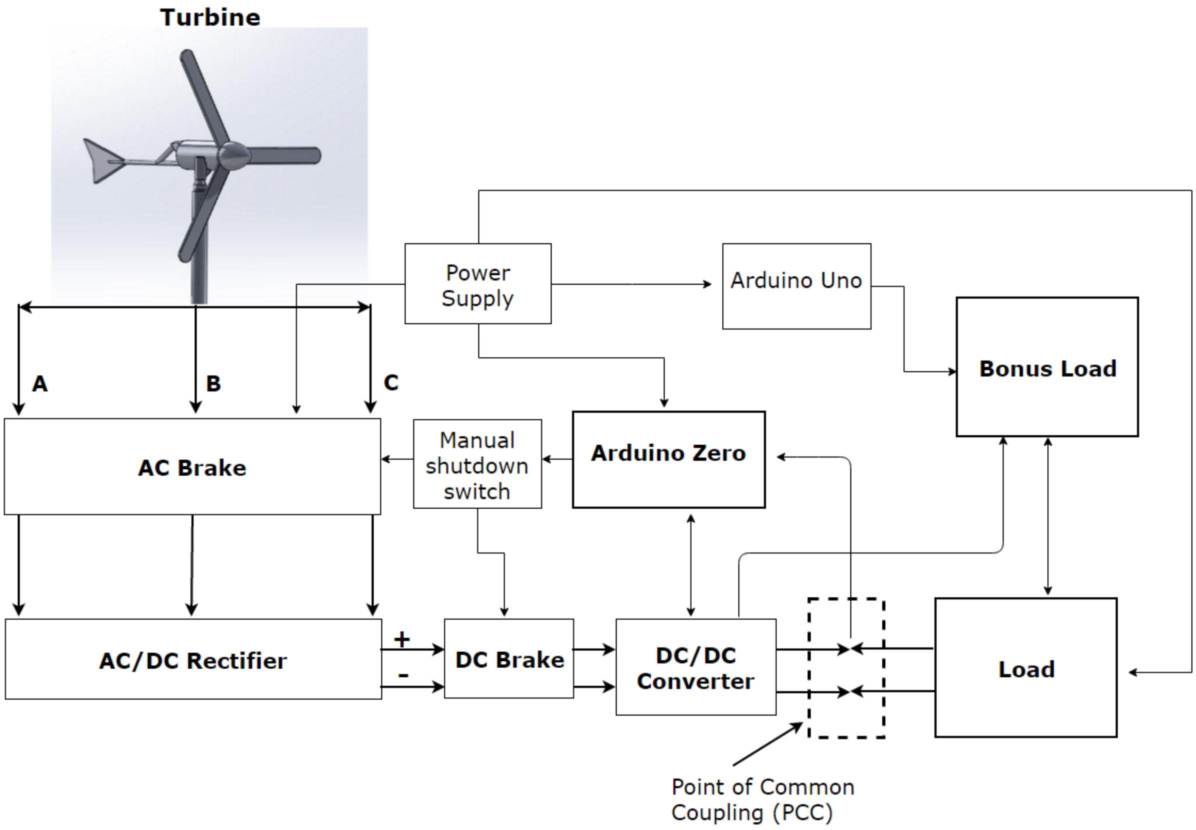


Figure 9: The current layout of the turbine's electrical components.

The output power then goes into a shunt, an electrical device meant to assist in the measurement of current, then the Load. Between the load and the DC/DC converter there is a DC Brake, which is a redundant braking system meant to activate in case of a failure in the AC Brake. The Arduino is the controller for all the other systems, and gives instructions to both of the brakes, as well as the DC/DC converter. The Load is where power is safely dissipated, and the Point of Common Coupling (PCC) is the point at which the distinction is made between what is inside the wind tunnel, and what is outside the wind tunnel. Note that, according to the Rules and Regulations document, it is acceptable to have connections between objects inside and outside of the wind tunnel [1].

Tunnel Team B has made some changes to the above Figure since the progress presentations at the beginning of the semester. Looking from left to right, the first change involves the task of manually braking the turbine. For the sake of clarity, the team has been thinking about this task in terms of a push button, whereas the competition requirements define the associated hardware as a competition-provided normally closed switch typical in safety applications for industrial equipment [1].

The most recent block diagram also reflects the team's plans of using pulse-width modulation (PWM) regulate the DC/DC converter's power output to the load, as well as turbine RPM. The team is planning on using this same principle for the “soft” DC brake. These two functionalities can be seen between the Arduino Zero and DC/DC converter block, as well as the Arduino Zero and Redundant DC Pulse Brake blocks, respectively.

Lastly, Tunnel Team B has made the point of common coupling (PCC), the point at which the load is ultimately connected to the turbine, easier to visualize on the block diagram. The Arduino Zero will both be powered by, and will sense data from the load, but will accomplish this task through the PCC, and not the load itself. The link between the Zero and the PCC displays this feature. The load has also been changed to a basic resistive load in the form of an adjustable power resistor.

6.1.2 - Controls

Although the design used has an AC brake to shut down the turbine, the team significantly changed its design. Instead of using MOSFET transistors to connect the three wires coming out of the turbine (reducing turbine RPM dramatically), Tunnel Team B used electromechanical relays to accomplish this function. Although relays use more power than MOSFETs, they allow for electrical current to flow both ways, unlike most MOSFET transistors. This is essential for an AC brake, because the AC current produced directly from the turbine is bi-directional.

Tunnel Team B has also implemented a redundant DC brake. This brake was not designed for shutting down the turbine (90% reduction in RPM), but as a redundancy in case the DC/DC converter fails to limit turbine RPM and power, in the Control of Rated Power task. Like a MOSFET transistor, the IGBT acts as a switch, toggling an electrical connection between the outputs of the DC/DC converter, reducing turbine RPM as a result. The team decided to use an IGBT because of its increased durability in high power applications.

6.1.3 - Load

The team went through four iterations when designing the bonus load, which is a representation of the Deployment Team’s design for their marketable turbine. In the first iteration, the team created a CAD model of a scaffolding tower that was a scaled-down model of a full telecommunications tower. The 3D printer used could not print the scaffolding legs as thin as the model was, so another iteration was designed. This one changed it from a scaffold tower to a monopole tower that could be printed. The third iteration added a box beneath the tower that could house the electronics controlling the bonus load, as well as some LEDs. As voltage output of the turbine increases, more LEDs turn on, to represent the signal strength of the tower. The fourth and final iteration added a small 3D-printed turbine to the top of the tower, in order to better link the design to the deployment strategy. Figure 10 shows the CAD Model of the Bonus Load, with the LEDs removed.

Figure 10: The Bonus Load CAD

6.2 – Manufacturing

Tunnel Team B finalized all purchase orders necessary to begin the manufacturing process, and most of the pieces were delivered by early February. Tunnel A and B shared many of the components, such as copper wire, to help aid their testing process for the generator, as well as the testing of the rectifier. The AC/DC rectifier and IGBT transistor for the DC brake needed heatsinks to dissipate excess heat caused during high wind speeds, and a number of options are being tested for the rectifier; a mechanical fan as well as a vanned aluminum block are slated for testing in the coming weeks. However, the block needs to have the rectifier secured onto it, and a device to secure it in place is under construction.

For software, the team considered two tasks. One is the hardware and the other is the overall software needed to control the turbine. For the hardware side, mounts and a casing for the Arduino have been considered in order to both protect the microcontroller as well as the connections for the input/output lines. The other task was the software used to control the wind turbine; this is not just in reference to the controls (controls will be the most significant) but also within in the load should the load team design a load to compete for bonus points. The code for the controls is going to be written in stages to ensure individual operation. Upon completion of each stage the entire code will then be compiled into one mastered code and tested for each scenario that will be judged in the competition

6.2.1 – Controls

Manufacturing and testing of Tunnel Team B’s brake systems involved three major steps. The first step was low current testing of components on a breadboard, with soldering the remaining electrical connections. The team used an Arduino Uno and DC power supply as power and control sources, with a sample motor as a model, but spinning it by hand at low speeds. The other two major steps involved perfboard manufacturing, and testing in the wind tunnel, making assembly changes as necessary. The team manufactured and tested the perforated board brake circuit in pieces, so as to more easily debug faulty hardware and software setups.

6.2.2 – Load

The Load sub-team worked on a concept for the bonus challenge, which is mentioned in the competition Rules and Regulations document. It states that a team will receive bonus points during testing if their load can drive an auditory or visual device that links to the business plan developed by the deployment team [1]. As the deployment team focused their efforts on the concept of a wind turbine providing alternative power to a telecom tower in India, the Load sub-team focused their efforts into reflecting the signal strength of the antennae through a number of small LEDs to show a scale of this strength. In Figure 11, the prototype of this display is shown in detail, with some (but not all) of the LEDs lit up to display a signal power below maximum.

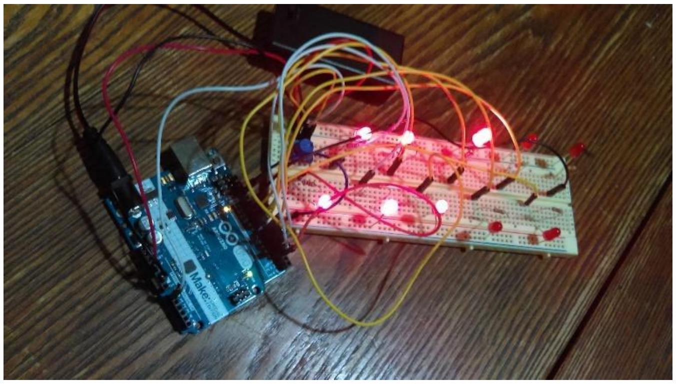


Figure 11: The bonus challenge prototype, controlled by an Arduino microcontroller.

6.2.3 – Power Electronics

The Power Electronics sub-team finished securing the rectifier to the heat sink, and then focused on the completion of the DC/DC converter. Once the final simulation of the DC/DC converter was approved by both faculty advisors, the team assembled it using the correctly-rated parts. At that point, both the rectifier and the DC/DC converter were placed onto separate perfboards and secured to the turbine, and connected to the rest of the systems to submit for testing

6.3 – Design of Experiment

The team designed each of the following experiments to test and show the hard work of each team member. While not all experiments have three variables capable of testing, each was assigned by our faculty advisors or approved of by them as important to the advancement of the team's construction or knowledge.

6.3.1 – Experiment One: AC Brake vs. DC Brake

Concerning controls, Tunnel Team B first tested the AC brake design under low current conditions by hooking up three 24 V relays to a power supply, and verifying that when activated and connected to a sample motor, the motor relays reduce motor speed significantly. The team accomplished this verification by rotating the motor by hand, and observing significant changes in resistance to motion. Figure 12 shows the resultant hardware configuration shown in Hardware Review 1.

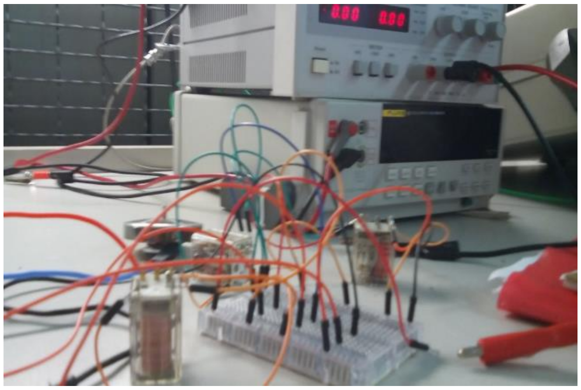


Figure 12: Initial prototype for the AC Brake.

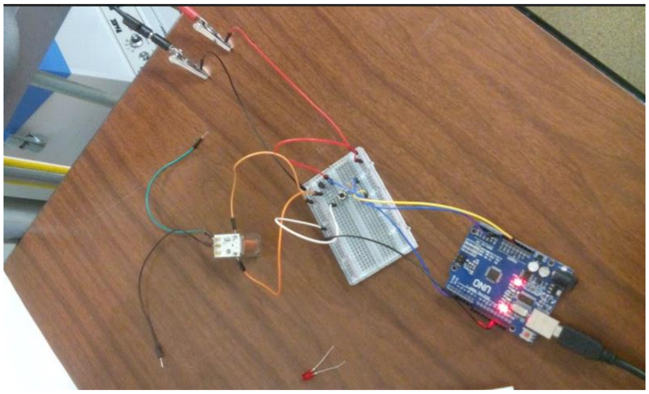


Figure 13: A relay driven by a push button.

After this first task, the team worked on opening and closing a single relay by pushing a button, and accomplishing electronic control through the Arduino Uno. Figure 13 illustrates this testing step. The team had some difficulty in accomplishing this step, due to improper wiring. Upon re-wiring, and moving around and replacing certain components, the team was able to get the relay to open and close effectively. The team also had to make sure to turn the power supply up to an adequate voltage to power the relay. Tunnel Team B was able to make progress by combining the last two tests by hooking up three relays to Arduino-button control, and the corresponding motor. This configuration allowed for activating the relays upon the push of a button, which connected the motor wires together, and significantly reduced hand-spun motor rotational speed. See Figure 14 for this testing setup.

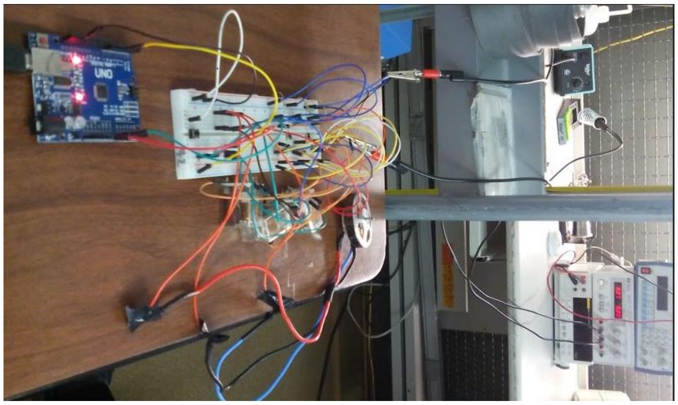


Figure 14: Three relays on a push button, with a motor attached.

6.3.2 – Experiment Two: Heat Sink Testing

The rectifier used in the testing device shown in Figure 15. The yellow, red, and white wires connect directly to the rectifier. The heatsink connected to the rectifier is not intended for use with that device, as it is a salvaged laptop fan. Instead, a larger, unpowered heatsink was obtained from the Solar Shack and the rectifier was secured against it. Once the team acquires the components for mounting the rectifier to its own circuit board, it can run a test to determine the gain in efficiency compared to the previous design.

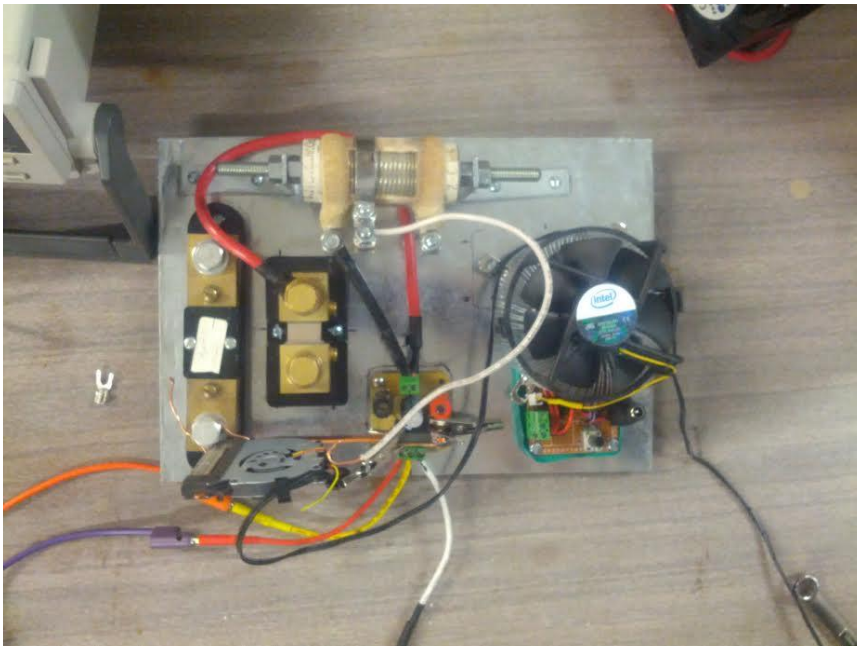


Figure 15: The testing device for the electrical components, shared with Tunnel Team A.

In order to do this, the team will run the same test that Tunnel Team A ran to calculate the generator's Power Curve, which involves running the generator at a set RPM long enough to measure the voltage, current, and power output through the large cylinder at the top of Figure 15. By measuring these three values across an RPM range, the team can calculate the increase or decrease in efficiency between the two heatsinks, to determine if the passive, unpowered heatsink is more effective. The results of this test will allow both Tunnel Teams to proceed further, especially in regards to getting the design inside the local wind tunnel in Flagstaff for proper testing.

7 – Testing

With the design changes necessary for testing complete, the team worked with their mechanical counterparts to test each component. Testing was primarily performed either in the Engineering Building (Building 69) or in a wind turbine provided in town. Here are the tests for each sub-team and the results of each test.

7.1 – Controls

Tunnel Team B first tested the dynamic AC brake (without the addition of the DC brake) for functionality in the Flagstaff wind tunnel at wind speeds ranging from 5 to 20 m/s. The team used an anemometer to measure wind speed, and monitored AC and DC open-circuit voltages for safety reasons. The team judged a successful instance of braking by visually observing the reduction in RPM upon activating the brakes. If this reduction was significant enough to eliminate the blur seen in fast-moving blades, the braking instance was successful.

The anemometer did not work correctly for the first test, so the team estimated wind speed by observation. The AC brake was able to successfully achieve turbine shutdown (90% reduction in RPM) up to an estimated 10 m/s wind speed. As a result, the team connected the DC brake in line with the AC brake, in order to increase braking power.

For the second tunnel test involving the use of both the AC and DC brakes, the team was able to successfully measure wind speed with the anemometer. It should be noted that the team also implemented the DC brake with 4 transistors instead of just 1, in order to increase braking power by decreasing the electrical resistance between the positive and negative terminals of the rectifier. Although the brakes activated at all wind speeds up to 20 m/s during this test, the team only observed successful turbine shutdown from all wind speeds up to and including 12 m/s, after which the brakes were not able to significantly reduce RPM. Wind speeds above 15 m/s were not recorded for this reason. Table 6 displays these results.

Table 6: Open Circuit Brake System Test Results

Wind Speed (m/s)	**AC Voltage (V)**	**DC Voltage (V)**	**Brake?**
5.1	0	0	N/A
5.6	2.78	3.65	Yes
6.9	3.9	5.35	Yes
8.6	5.2	6.8	Yes
9.9	6.1	8.3	Yes
11.7	7.3	9.8	Yes
12.7	8.1	11	Yes
13.9	8.9	12	No
15.1	9.9	13.3	No

Both the AC and DC brakes met the competition requirement of achieving turbine shutdown within 10 seconds, as this shutdown occurred in 3 to 4 seconds. However, since braking did not occur at wind speeds greater than 12 m/s, the brake system did not meet the competition requirement of being able to achieve turbine shutdown up to 18 m/s wind speeds. This is still possible with AC and DC dynamic brake systems, but the electrical resistance involved in activating both types of brakes would need to be further decreased enough to allow significantly more energy to be fed back into the generator.

In addition, Tunnel Team B was able to achieve turbine shutdown with a manual shutdown switch similar to the competition-provided switch. The load disconnect braking implementation involved using the Arduino Zero to send a small amount of electrical current through a path in the PCC, that would result in a voltage drop measurable by the Arduino. This voltage drop became 0 V upon load disconnect, as no current would flow through the disconnected load.

Lastly, to fulfil the Engineering Requirement of Quick Assembly and Disassembly, Tunnel Team B used terminal blocks and pin header connectors to make secure, but not permanent electrical connections between components. The team also used JST-RCY connectors to connect the competition-provided shutdown switch to the turbine. The aforementioned electrical connectors allowed the team to set up the electrical side of the turbine within a fraction of the 25 minute competition tunnel testing limit.

7.2 -Load

Tunnel team B first tested the load in the lab of the engineering building. The load was an adjustable power resistor with a declared range of 0.1 ohms to 0.8 ohms. In the lab the team tested the range with an ohmmeter and the results confirmed the range of resistance as advertised. Tunnel team B then took the load to the wind tunnel and connected it at the point of common coupling and set its resistance to 0.8 ohms. The power resistor was kept at the point of common coupling during the testing of other components in the tunnel and was able to safely dissipate the power throughout operation of the turbine.

The testing done on the load gave a better understanding of the Produces Sufficient Continuous Power, Design an Innovative Load, and Quick Assembly and Disassembly Engineering Requirements.

7.3 - Power Electronics

Since the beginning of testing, the team needed to make a number of updates and design changes. A resistor was added to the Rectifier board because the power stored within the capacitor was not discharging fast enough. The resistor changed the time to discharge from over 10 seconds to under 2 seconds, a vast improvement in the safety of our teammates who will be at the competition.

The two major power electronics components, the Rectifier and DC/DC Converter, were tested individually at first, then together later. This was done to catch any bugs and remove them before the linked design made finding said bugs incredibly difficult.

Of the two, the Rectifier was bench-tested first to assure that the wiring was correct and that the voltage output related to the voltage input. The concept behind this was that by measuring the AC input, and the DC output, the amount of voltage lost to the diodes inside the rectifier. The team had difficulty approximating the voltage drop until it was realized that some of the wires were incorrectly labelled. After replacing the wires and labelling them correctly, the voltage drop checked and found to be just over one volt. In order to get more accurate readings, the rectifier was connected to the output of the generator, with sensors before and after the rectifier to measure voltage. The drop in voltage was more precisely calculated out to 1.25 volts.

Next, the rectifier was connected to the load, so that current could freely flow through the components. By measuring the voltage and current, one can multiply them together to get power. By comparing the input power and output power, one can see the power losses across the rectifier, and as a result calculate the efficiency. The Rectifier's power losses scale up with the amount of power in the circuit, so a percentage of efficiency calculation was used instead, giving a 95% efficiency rating. With the AC and DC brake in place, the efficiency drops to 85% due to the power required to hold the brakes open.

With these tests, the rectifier helped meet the Produces Sufficient Continuous Power and Quick Assembly and Disassembly Engineering Requirements. Testing the power losses shows that the power will be continuously generated, and the short change that added the resistor to aid power dissipation assists in the disassembly procedures.

Initial bench testing of the DC/DC converter was conducted using an off the shelf boost converter that was purchased online. The boost converter is rated for input voltages between 3 and 35 volts, 9 amperes input current, 6 amperes output current, and an overall output power rating of 65 watts. The purpose of this testing was to not only create a benchmark upon which future prototypes would be compared against, but to also confirm that the off the shelf converter would serve as a suitable backup.

The converter was subjected to steady state testing using a DC power supply to simulate the input power from the rectifier, a 10 Ω power resistor connected to the output leads to simulate the load, and a digital multimeter (DMM) to measure the voltage drop across the resistor. Proper performance of the converter was confirmed by first supplying it with 4 volts from the DC power supply and then adjusting the potentiometer that controls the output voltage so that the converter output 8 volts. The input voltage was then reduced to just below its minimum input voltage rating to confirm the minimum input voltage required for proper operation. The input voltage was then stepped up by 0.5 volt increments and output measurements were taken each step along the way, as can be seen in Table 7. The outcome of this testing confirmed that without further adjustments to the potentiometer, the off the shelf boost converter successfully regulated the output voltage within the range of expected input voltages and thus would make a suitable backup.

Table 7: DC/DC Converter testing.

Input Current (A)	Input Voltage (V)	Output Voltage (V)		Input Current (A)	Input Voltage (V)	Output Voltage (V)
0.22	3	2.68		0.77	6.5	8.02
1.61	3.5	7.99		0.72	7	8.02
1.34	4	8		0.68	7.5	8.03
1.17	4.5	8		0.63	8	8.03
1.04	5	8.01		0.57	8.5	8.08
0.94	5.5	8.02		0.61	9	8.58
0.85	6	8.02		0.62	9.5	9.08

The results of this test help in fulfilling the Produces Sufficient Continuous Power and Withstand High Wind Speeds Engineering Requirements.

7.4 - Software

State 1 through 3 are both controlled through the Arduino Zero as well as the DC/DC converter. In order to test the overall functioning of the software with respect to state 2 and 3, there were 3 separate tests that needed to be performed. The controls of state 1 - 3 are dependent on the DC/DC converter and as such the range limits for controls operation needed to be continually fined tuned in order to best match the overall performance of the DC/DC converter.

The first test was to make sure that state 1 was appropriately waiting for the necessary input for the DC/DC converter to operate efficiently. In order to do this the duty ratio needed to be measured and compared to an expected value of 50%. While at 50% the DC/DC converter input voltage is equal to the DC/DC converter's output voltage. While in this state it allows the wind turbine's RPM to increase without it being disrupted by the converter. With this test the wind speed, output voltage, and duty ratio needed to be recorded.

After reaching an appropriate output the next test that was performed was in relation to state two. While in state two the program on the Arduino Zero needed to increase the duty ratio to a max of 91% in order to ramp the output voltage to the level that was needed in order to reach the power output power needed for competition. The way this was done is to have the output voltage of the converter constantly compared with a reference voltage stored within the master control program of the Arduino Zero. With this test the wind speed, output voltage, and duty ratio needed to be recorded.

At the point where the output voltage of the DC/DC converter was higher than the reference voltage stored on the Arduino Zero, the testing moved to the third test. While in the third state we need modulate the output power of the turbine. In order to do this the Arduino Zero needed to lower the duty cycle of the PWM control to below 50%. The controls are dependent on the output voltage of the DC/DC converter, therefore, the duty cycle needed to drop continuously in order to give us a stable output voltage from the DC/DC converter. With this test wind speed, output voltage, duty ratio, and percent error needed to be recorded. The point of state 3 is to keep the output voltage at a constant value so a percent error needed to be recorded in order to see the control efficiency of this state.

The tests performed for the software controls of the wind turbine were performed in order to see how well this designed matched up with what was required through both customer and engineering requirements.

The customer requirement specific to software were: power curve performance, control of rated power, and control of rotor speed. The engineering requirements specific to software were: produces sufficient continuous power and withstanding high wind speeds.

Looking first at the customer requirements; the power curve performance is the combined operation of states 1 - 4. Because there is a lower bound set within the code the turbine the team was able to get up to its cut-in wind speed without being interrupted in any way. While optimizing output power the wind turbine is in state 2. The way the team tested for this requirement was through the testing of state 2. There is a max put on the controls of 91%, however, because the program climbs to this max duty ratio quickly the team is able to the reach turbine's rated power sufficiently enough such that team met the required produced power. State 3 testing handles the modulation of the output power; because the controls are output dependent, it constantly changes the duty ratio giving a constant output power minus the percent error. State 4 of the power curve is handled through the testing of the brakes

The Engineering Requirements for the control of rated power as well as control of rated speed are directly related and are tested through state 3 testing. While in state 3 the controls are constantly looking at the output voltage and changing the duty ratio in order to keep the output voltage at a constant value. Because it was possible to control the output power through this method the RPM of the turbine was also being regulated. This is simply because the controls were only allowing so much power to be produced forcing the turbine blades themselves to remain at a constant rotational speed.

Looking at the Engineering Requirements; the testing focused on the power curve performance can also be related to the production of sufficient continuous power. It is required to produce 10W of power within a speed range of 5 - 11 m/s, therefore, when performing the state 2 tests it was also checked that the 10W was reached within this wind speed.

The tests for state 3 are set to see how well the controls of the turbine are to keep the DC/DC output voltage constant after we reach the rated voltage. This test was designed specifically for the Engineering Requirements but it also allowed the team to meet the expectation of withstanding high wind speeds.

8 – Schedule & Budget

8.1 – Schedule

Tunnel Team A, Tunnel Team B, and Deployment Team worked together on combining their schedules into one simple calendar. The semester calendar covers the following:

- Midpoint Presentation: March 7, 2016
- Hardware Review 2: March 21, 2016
- Staff Meeting 2: April 4, 2016
- Presentation Walkthroughs: April 18, 2016
- UGRADS Presentations: April 25, 2016 to April 29, 2016
- Final Paper Due: May 6, 2016
- AWEA/CWC Conference: May 23, 2016 to May 25, 2016

In addition, all members of the combined teams meet Wednesdays every week, in order to collaborate with both of our faculty advisors and each other for two hours. Tunnel Team A and Tunnel Team B both meet each Saturday for three to four hours in order to boost productivity and communication as well, so that no one is left in the dark about what their fellow engineers are doing.

8.2 – Budget

Tunnel Team B's update budget is just over the expected $500, coming to a total of $549.39 USD. The team used their ability to acquire many spare electrical components from CEFNS Room 236 to keep costs lower, as well as avoid costly mistakes with expensive and slow-to-arrive parts. Figure 16 shows the budget in full.

Name of Part	Part Number	Name of Supplier	Unit Price	Quantity	Total
STMicroelectronics STP75NF75Power MOSFET	B00W1587O8	Amazon	$4.55 (5 pcs)	2	$9.10
45 Amp Anderson Powerpole Connectors	B00HZ9A0FY	Amazon	$11.85 (10 sets)	1	$11.85
JACKY LED 32.8 ft. (10 m) 22 AWG Extension Cable WIre Cordfor LED Strips	B00QTC0RAQ	Amazon	$6.99	1	$6.99
Grand General Back 10 AWG Primary Wire	B00INVF468	Amazon	$12.99	1	$12.99
Red Electrical Tape .75 in. x 66 ft. UL/CSA	B003ZWHSKK	Amazon	$4.75	1	$4.75
JST Male/Female Connectors 200 mm 22 AWG Wire	B00EZH8P9W	Amazon	$3.98 (20 pairs)	1	$3.98
STMicroelectronics STD52P3LLH6Power MOSFET	497-15464-1-ND	DigiKey	$1.37	10	$13.68
ECOSPARK 2 IGNITION IGBT	FGP3040G2_F085-ND	DigiKey	$2.32	10	$23.24
TE Connectivity 1432873-1 Power Relay	PB2034-ND	DigiKey	$3.77	6	$22.62
TE Connectivity VCF4-1000 Relay Socket	PB232-ND	DigiKey	$1.96	6	$11.76
2 3/4" x 3 11/16 " Perfboard with Pads (tax: $0.77)	N/A	Radioshack	$4.49	2	$9.75
Arduino Zero: 48pins LQFP, 3.3V	ATSAMD21G18	DigiKey	$49.90	2	$99.80
Power Sonic AGM Battery 6V 2.8AH	POWPS-628F	Batteries Plus	$21.99	1	$21.99
Boat RC Heli Watt Meter DC 60V 100A Digital LCD Display	B00RFDV87E	Amazon	$14.50	1	$14.15
Tantalum Capacitor - Solid Leaded	TAP157K016CCS	Mouser	$5.75	4	$23.00
Fixed Inductor	1140-390K-RC	Digikey	$7.65	3	$22.95
Protoboard	854-SB4	Mouser	$5.50	4	$22.00
Boost Converter	SMAKN® LTC1871	Amazon	$19.20	1	$19.20
IR LED/detector	N/A	Radioshack	$4.35	2	$8.69
RES ADJ .80 OHM 300W 10%	AVE300-.08-ND	DigiKey	$16.17	1	$16.17
Mounting Kit	HEIKIT1030300E293	Digikey	$9.10	1	$9.10
Expedited shipping	N/A	DigiKey	$66.97	1	$66.97
Gel Superglue	N/A	Home Depot	$5.38	1	$5.38
3 pc file set	N/A	Home Depot	$7.59	1	$7.59
Heatsink Self Adhessive (Shipping: $2.45)	HEATSINK_23MM_C28	Cutedigi	$3.40	4	$16.05
Adjustable Booster Module (Shipping: $1.52)	NZ0049601	GearBest	$7.81	2	$17.14
MOSFET n-channel 30V (shipping: $7.99)	STP160N3LL	Mouser	$1.13	4	$12.51
MOSFET 60V (shipping: $7.99)	SUP90P06-09L-E3	Mouser	$5.60	5	$35.99
				**GRAND	$549.39

Figure 16: The current operating budget of Tunnel Team B.

By the end to the semester, last minute expenses such as replacement parts for the DC/DC converter and the new load design as well as expedited shipping drove the team's end total to be higher than anticipated. Note that there was still room in the budget due to deployment teams low spending.

9 – Conclusions

Now that the semester has ended, those attending the competition later this May have started to practice for the various presentations and tests that will occur. During this time, the team members not attending the competition have reviewed the project and considered what could make the next year's team do ever better. Here are seven questions, and their answers, which facilitate this review process:

1. **Did the team complete the mission?**

   The team worked together to create an electrical system that fulfilled the initial problem statement, as well as the Engineering Requirements.

2. **Which aspects of project performance (dev. time & cost, product quality, manf. cost) were most positive?**

   The best aspects of project performance were the development time, where the time worked together to speed up the development and selection of the components, and the costs, as generous team members donated components and pieces they already had for both development and manufacturing.

3. Which aspects of project performance were most negative?

The product quality in the early stages was not of professional quality, and the team spent more time than it allocated increasing the quality and meeting the customer requirements.

4. Which tools, methodologies, and practices contributed to positive (or negative) aspects of performance?

The team did not spend enough time meeting together in the first semester of the project, which put us behind for the second semester. However, the team's drive for success and willingness to excel assisted our efforts in catching up.

5. What problems did the team encounter?

The team's designs needed to be revisited often, delaying testing days and interfering with other classes. In addition, there were some interpersonal issues that resulted from miscommunication issues, or some teammates attempting to assume authority over certain deliverables before clearing it with a faculty advisor.

6. What specific organizational actions can be taken to improve performance?

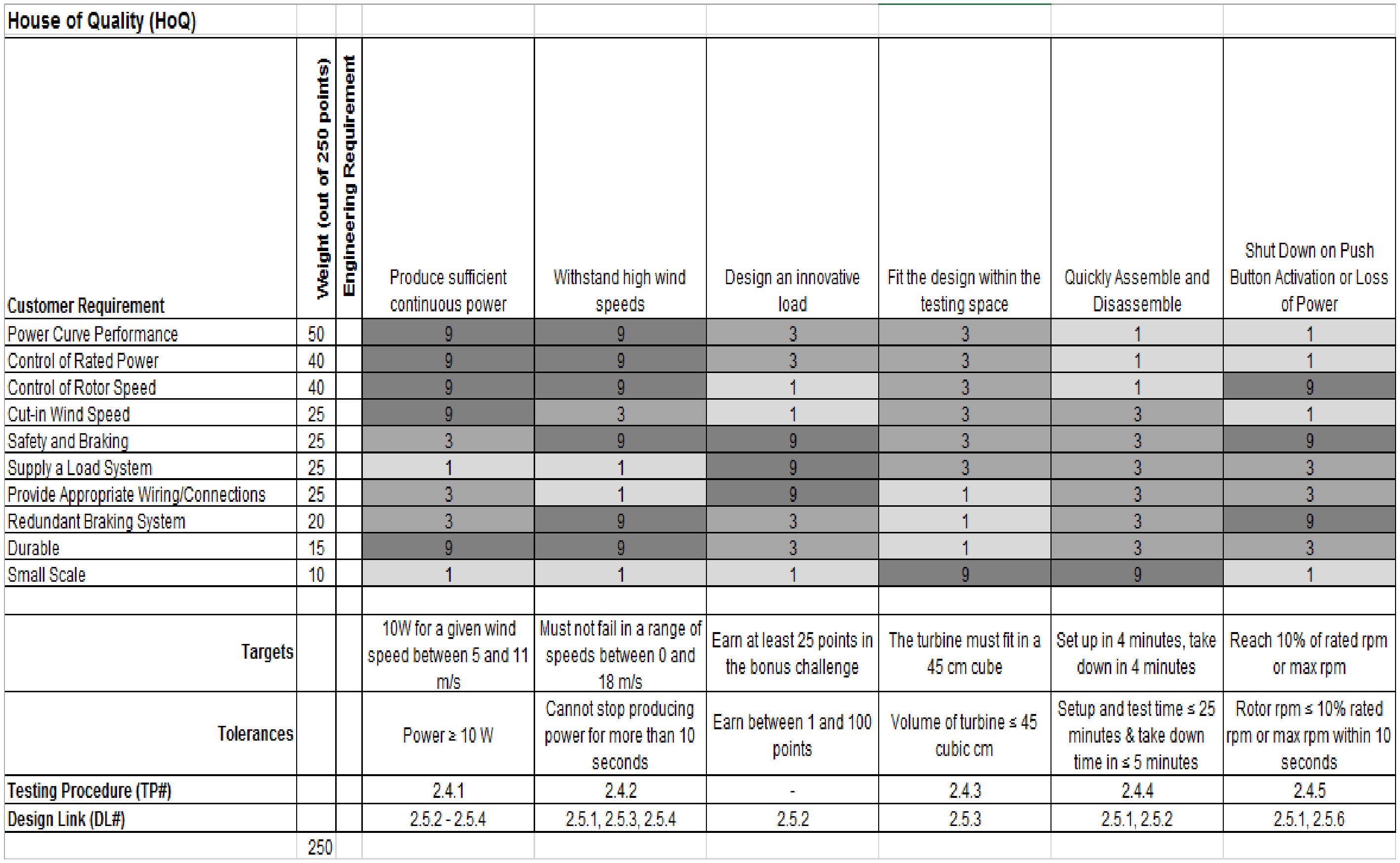
Regular meeting times and meeting minute turn-ins are necessary for success, with the job of taking minutes rotating between team members. Once-a-week meetings are acceptable, but bi-weekly meeting times are ideal. Also, more time to meet with the mechanical team is ideal.

7. What specific technical lesson were learned?

Teams need more time for meetings, and trying to get an entire team to meet at the same time is difficult. Each member needs equal weight and responsibility in the team to keep every part of the project progressing along at the same pace.

With the reviewing done, the team passed these answers along to the faculty advisors, hoping that next year's team would be able to improve upon the mistakes made by this team, and perform even better.

10 – Appendix A: House of Quality



House of Quality (HoQ)

Customer Requirement	**Weight (out of 250 points)**	**Engineering Requirement**	Produce sufficient continuous power	Withstand high wind speeds	Design an innovative load	Fit the design within the testing space	Quickly Assemble and Disassemble	Shut Down on Push Button Activation or Loss of Power
Power Curve Performance	50		9	9	3	3	1	1
Control of Rated Power	40		9	9	3	3	1	1
Control of Rotor Speed	40		9	9	1	3	1	9
Cut-in Wind Speed	25		9	3	1	3	3	1
Safety and Braking	25		3	9	9	3	3	9
Supply a Load System	25		1	1	9	3	3	3
Provide Appropriate Wiring/Connections	25		3	1	9	1	3	3
Redundant Braking System	20		3	9	3	1	3	9
Durable	15		9	9	3	1	3	3
Small Scale	10		1	1	1	9	9	1
Targets			10W for a given wind speed between 5 and 11 m/s	Must not fail in a range of speeds between 0 and 18 m/s	Earn at least 25 points in the bonus challenge	The turbine must fit in a 45 cm cube	Set up in 4 minutes, take down in 4 minutes	Reach 10% of rated rpm or max rpm
Tolerances			Power ≥ 10 W	Cannot stop producing power for more than 10 seconds	Earn between 1 and 100 points	Volume of turbine ≤ 45 cubic cm	Setup and test time ≤ 25 minutes & take down time in ≤ 5 minutes	Rotor rpm ≤ 10% rated rpm or max rpm within 10 seconds
Testing Procedure (TP#)			2.4.1	2.4.2	-	2.4.3	2.4.4	2.4.5
Design Link (DL#)			2.5.2 - 2.5.4	2.5.1, 2.5.3, 2.5.4	2.5.2	2.5.3	2.5.1, 2.5.2	2.5.1, 2.5.6
	250							

Figure 17: House of Quality

11 – Appendix B: Pugh Charts

Table 8: Software Pugh Chart

Criteria	**Baseline - Built in Sensors**	**Infrared Sensor Beam**	**LoP and Button Algorithms**	**PID and PWM Algorithms**	**ARD Sleep Library**
Responsive	D	+	+	S	+
Power Draw	A	-	S	+	+
Cost	T	-	+	+	+
Difficulty	U	+	S	-	+
Braking	M	S	+	+	-
Sum of +	N/A	2	3	3	4
Sum of -	N/A	2	0	1	1
Sum of S	N/A	1	2	1	0

Of the five criteria selected for this Pugh Chart, each was chosen for their relation to the various engineering and customer requirements. Responsiveness is necessary for controlling the various power electronic switches, Power Draw is necessary for reducing impact on the turbine's Power Curve performance, Cost must be low for the team's budget, Difficulty can cause problems with implementing it and causing failures due to human error, and Braking is a major requirement for Tunnel Team B. The sub-team chose the Built in Sensors design as the Datum because it was simple, yet average. The Datum and the Infrared Sensor Beam were both dropped, as the Datum could not outperform the three best categories, and the Infrared Sensor Beam's cost was considered far too high for such a small scale.

Table 9: Load Pugh Chart

Criteria	**Diversion Load**	**Smart Materials**	**Heat Sink**	**Butterfly**	**Eel Discharge**
Ease to Build	D	-	+	-	-
Cost	A	-	+	-	-
Creativity	T	+	-	+	+
Simplicity	U	-	+	-	-
Functionality	M	S	-	-	+
Sum of +	N/A	1	3	1	2
Sum of -	N/A	3	2	4	3
Sum of S	N/A	1	0	0	0

In order to eliminate the least viable ideas for brake loads, the team evaluated the concepts based on five criteria: Ease to Build, Cost, Creativity, Simplicity, Functionality. Based on these criteria, the team decided to eliminate the Smart Materials and Butterfly ideas. The team eliminated the Smart Materials idea because it is too expensive and complex to produce. The team eliminated the Butterfly idea based on low scores throughout the Pugh chart.

Table 10: Controls Pugh Chart

Criteria	**Webbed Feet Brake**	**AC Brake**	**DC Brake**	**Hydraulic Disc Brake**	**Pneumatic Disc Brake**	**Hysteresis Brake**
Power Consumption	D	+	S	-	-	-
Complexity	A	+	+	S	S	+
Size	T	+	+	-	-	-
Braking Power	U	+	-	+	+	+
Cost	M	+	+	-	-	-
Sum of +	N/A	5	3	1	1	2
Sum of -	N/A	0	1	3	3	3
Sum of S	N/A	0	1	1	1	0

In order to eliminate the least viable ideas for brake systems, the team evaluated the concepts based on five criteria: Power Consumption, Complexity, Size, Braking Power, and Cost. The Webbed Feet Brake served as the datum idea, as flaps on blades imply high complexity, but less power consumption than other designs. Tunnel Team B eliminated the two disk brake ideas, as they both use more power than any of the other concepts, and are complex to design and use reliably. The team also eliminated the Webbed Feet Brake idea, because it is a more complex (and less reliable), and costly idea, as compared to the other ideas.

12 – Appendix C: Control Flowchart

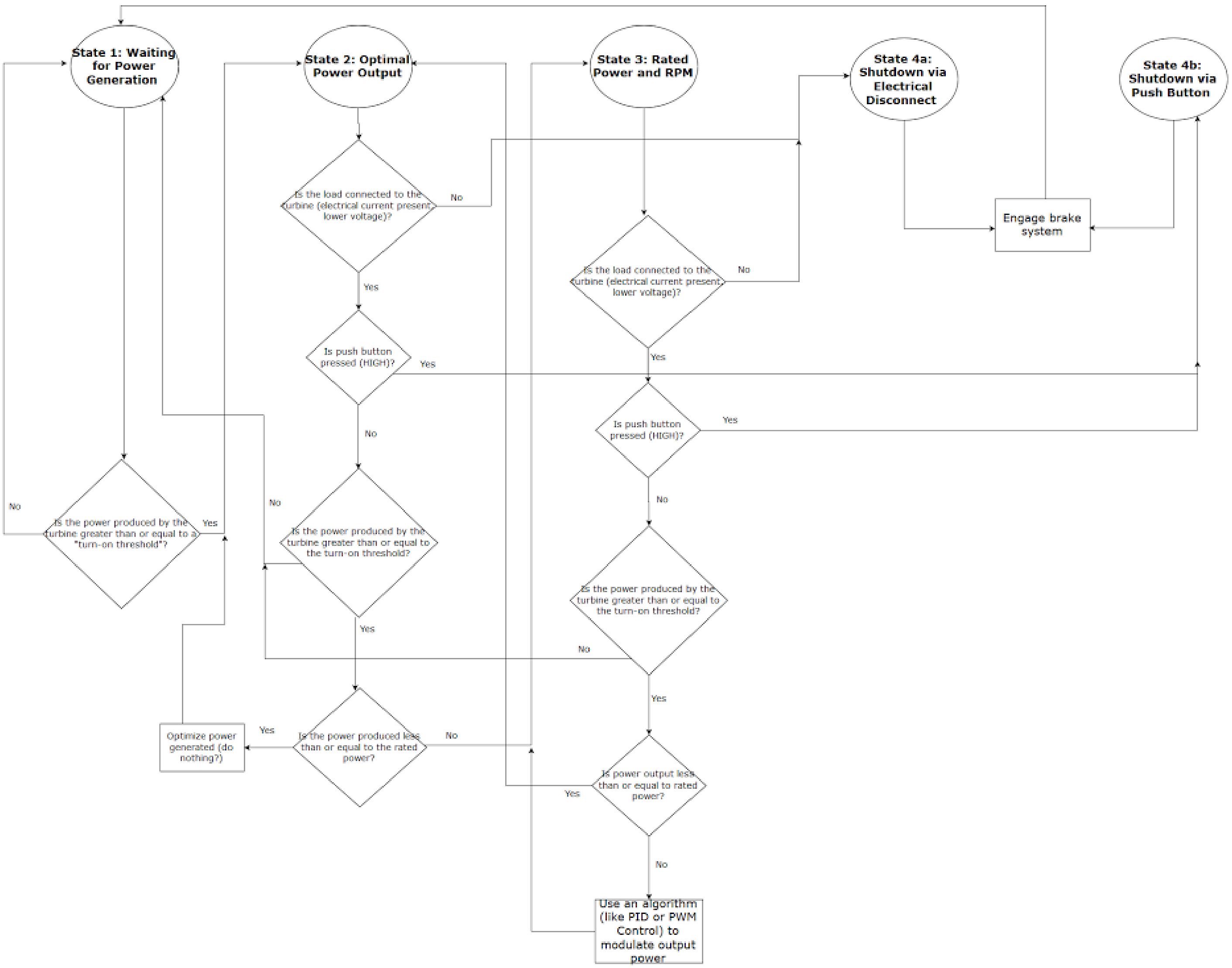


Figure 18: Step-by-Step Flowchart of the Turbine States (Involving Regulation of Turbine Power)

13 – Appendix D: Miscellaneous Calculations

Tables 9 to 12 illustrate how Tunnel Team B determined the maximum current theoretically produced by the turbine. The team used this current to verify the viability of selected electrical components for use on the turbine brakes. Table 10 displays the first step in this calculation as calculating the maximum power extracted from the wind by the turbine.

Table 10: Theoretical Maximum Power Extracted from Wind by Turbine

	Cp, Coefficient of Performance	Rho, Air Density (kg / m^3)	R, Blade Radius (m)	V, Velocity of Wind (m/s)	**Pmax, Maximum Power Extracted From Wind (W)**
	0.3	1.225	0.225	25	**456.627731**
Comments:	Assume .3	Assume sea level air density	Assume maximum blade radius allowed in competition	Maximum wind speed	Pmax = Cp * .5 * rho * pi * (R ^ 2) * (V ^ 3)

Table 10=1 illustrates the next step in calculating this theoretical maximum current: calculating the Volts per RPM ratio (V / RPM) of the selected motor (rewired as a generator).

Table 11: V/RPM Ratio of Selected Motor

	KV of Motor (RPM / V)	Ce, Efficiency of Motor Re-wired as a Generator (Coefficient)	**V / RPM Produced as Generator**			
	380	0.9	**0.002368421053**	=	**2.368421053**	**mV / RPM**
Comments:	KV of selected SUNNYSKY X4108S motor	Jeremy Cook's estimate	V / RPM = Ce * (1 / KV)			

Next, the team calculated the maximum RPM of the turbine, shown in Table 12.

Table 12: Maximum RPM of Turbine

	TSR, Tip Speed Ratio	V, Velocity of Wind (m/s)	R, Blade Radius (m)	**Fmax of Turbine (Hz)**	**Maximum RPM of Turbine**
	7	25	0.225	**123.787178**	**7427.230678**
Comments:	Current chosen TSR	Maximum wind speed	Maximum blade radius [1]	Fmax = TSR * V / (2pi * R)	RPMmax = 60 * Fmax

Then, the team used the previous calculations to determine the maximum theoretical current produced by the turbine, presented in Table 13 This helped the team determine the viability of the STMicroelectronics

STP75NF75 N-channel Power MOSFET and STMicroelectronics STD52P3LLH6 P-channel Power MOSFET for use in the turbine brake system and other turbine components.

Table 13: Maximum Theoretical Current Produced by Turbine

	Vmax, Maximum Voltage Generated By Turbine (V)	**Imax, Maximum Current Produced by Turbine (A)**
	17.5908095	**25.95831255**
Comments:	Vmax = (V / RPM) * RPMmax	Imax = Pmax / Vmax

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