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

Preliminary Report

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DISCLAIMER

1 – Background

This section contains the information regarding the purpose and goals of 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.

1.1 – Introduction

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.

1.2 – Project description

The objective of Tunnel Teams A and B is 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 will follow the guidelines that are given by the DoE in order to be eligible to compete in the competition. The turbine will be built to specific size, design, and safety requirements and care will be 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 can learn from mistakes made and improve on some of the previous design ideas. Along with having the previous turbines to acquire information from, the team also is 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 has assisted Tunnel Team B deriving the preliminary interpretation of the engineering and customer requirements.

2.1 – Customer Requirements

The DoE *CWC 16 Rules and Requirements* document [1] generates 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, while 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 consists of control of 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 (pushbutton). 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 gage and insulation thickness, with an American wire gauge (AWG) specification of 22 - 28. In addition, the team plans 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: 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 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 be supplied 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, 5 minutes will be given to remove the turbine. There are multiple test 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.

2.3 – House of Quality (QFD)

In Appendix A, the team's House of Quality (HoQ) is displayed. The currently incomplete sections are the Testing Procedures and the Design Links, due to the class not covering these points yet. 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. In the coming weeks, the team will then design testing procedures implement them, and also add design links.

3 – Existing Designs

The Tunnel Team has broken the wind turbine design down to seven subsystems: blade, structure, generator, 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 – 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.

3.1.1 – 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.

3.1.1.1 – Wind Energy Conversion System

One way to describe wind turbine controls involves a system described as a Wind Energy Conversion System (WECS). One of the four subsystems of a WECS is a pitch servo, which contains a hydraulic or electromechanical device that rotates the turbine blades side to side, based on wind direction. Controls are also needed on the power generator unit subsystem, although the specific controls are not specified. See Figure 5 for more description [2].

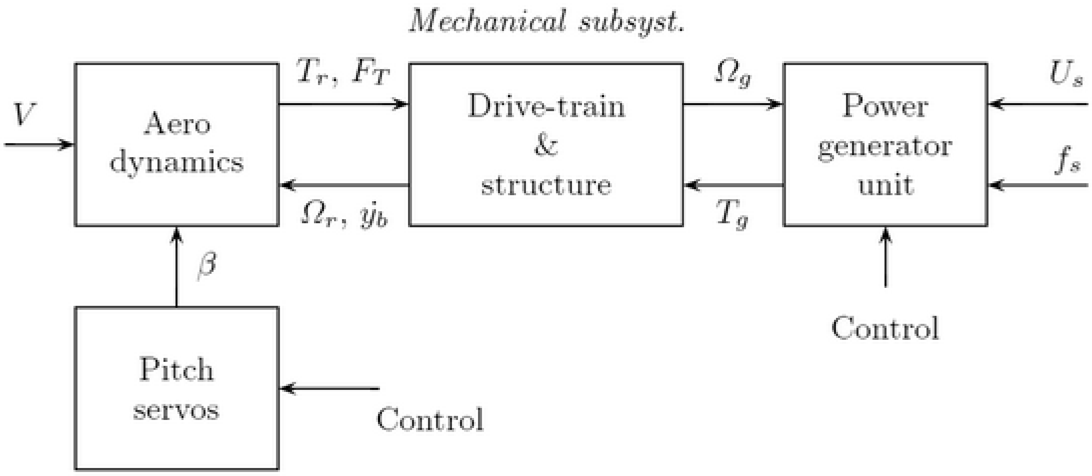


Figure 1: Block Diagram of the Subsystem Levels of a Variable Speed and Pitch WECS [3]

3.1.1.2 – Adjustable Speed Drives

Devices called adjustable speed drives (ASD) 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 [4].

3.1.1.3 – 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.

3.1.2 – 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 [6]. 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.

3.2 – 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.

3.2.1 – 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 vs the Arduino idle current draw of 50 mA [7]. The control boards for both the MSP 430 and the Arduino can be seen in Figures 2 and 3.

Figure 2: MSP430 Launchpad [8]

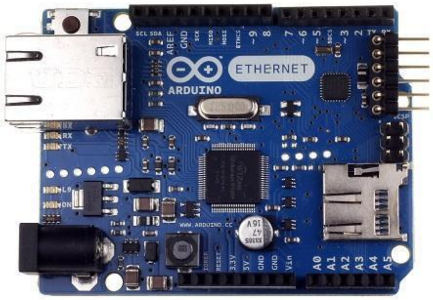


Figure 3: Arduino Control Board[9]

3.2.2 – 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.

3.3 – 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.

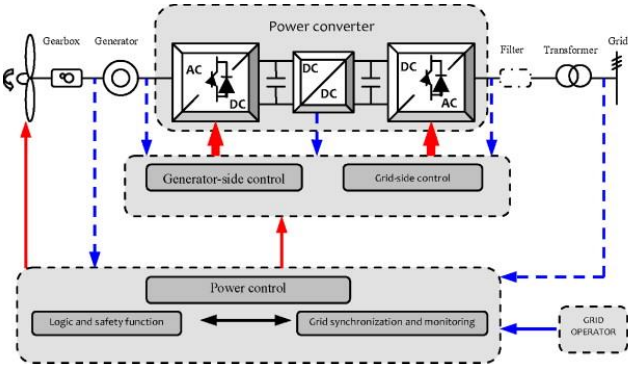


Figure 4: Power Electronics Flowchart [9]

3.3.1 – 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 provide appropriate wiring & connections.

The power curve is the graph of power vs 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 [10]. This 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.

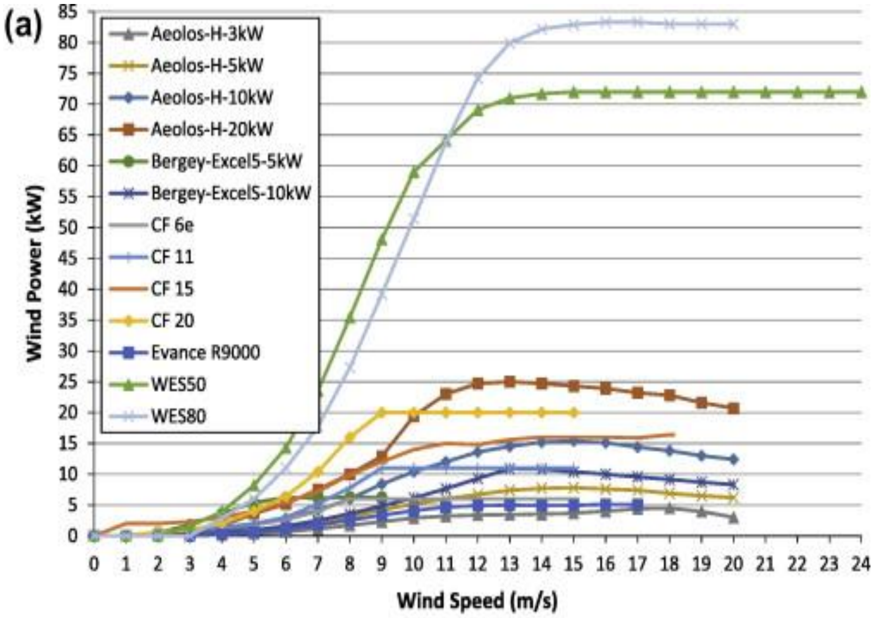


Figure 5: Power Curve for Various Wind Generators by Speed [11]

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 barking 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 ($P_{loss} = I^2R$), 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.

3.3.2 – 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.

3.4 – 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.

3.4.1 – 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.

3.4.2 – 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 (as $P = VI$). 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 [12]. However, with six diodes total, the voltage lost can range from 2 Volts to 3.9 Volts, which is 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 [13].

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. P-channel MOSFETs are most commonly used due to the relative ease of driving the gate compared to N-channel MOSFETs [14]. 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 $R_{DS(on)}$, and thus increases the power dissipated by the power switch by $P_D=I_{(L,\, rms)}^2 * R_{DS(on)}$ [15]. 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 [16].

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 [17]. 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 [17]. 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 [17].

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 require only half the inductance to get the same inductor ripple current of a SEPIC with two separate inductors [19]. 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 consolidate 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 events 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 concept 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 [20]:

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 [21].

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 [22].

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 (types of switches) 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.

The figure below 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.

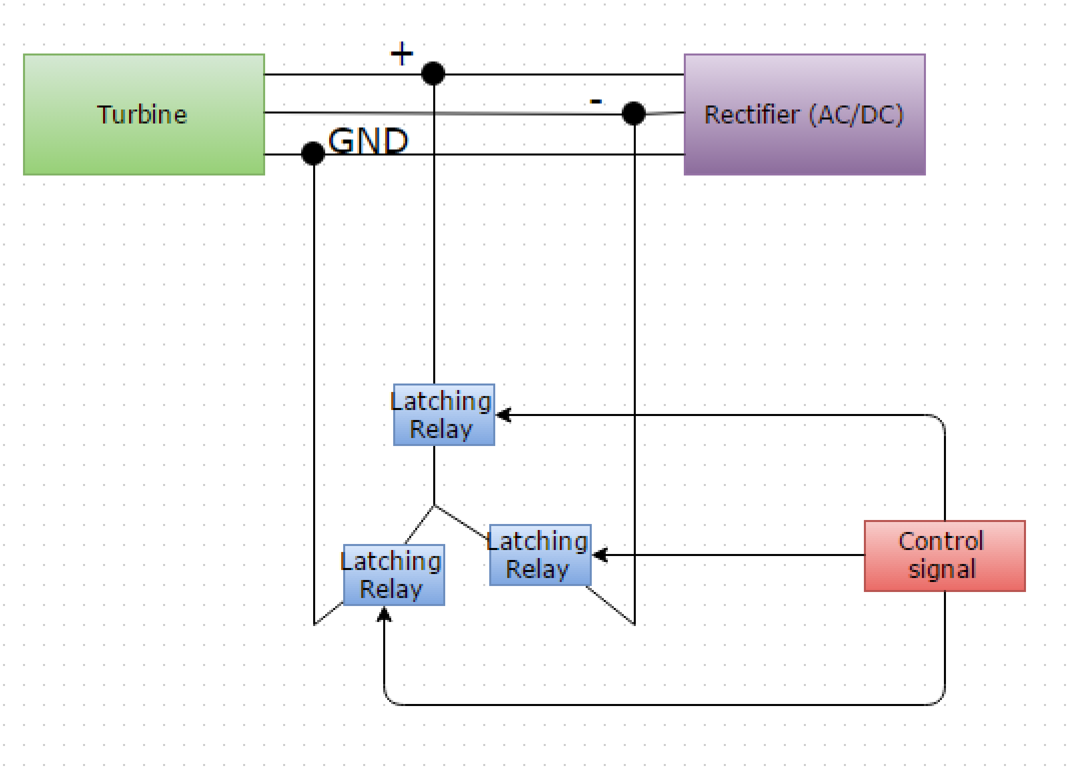


Figure 6: AC Wye-Connected Brake Configuration

4.3.2 - DC Dynamic Brake

Similar to the above 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 [23].

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 large-scale turbines. Also, competition rules only require a 10% reduction in rated (during maximum power generation) or maximum RPM [24], 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 supplied below:

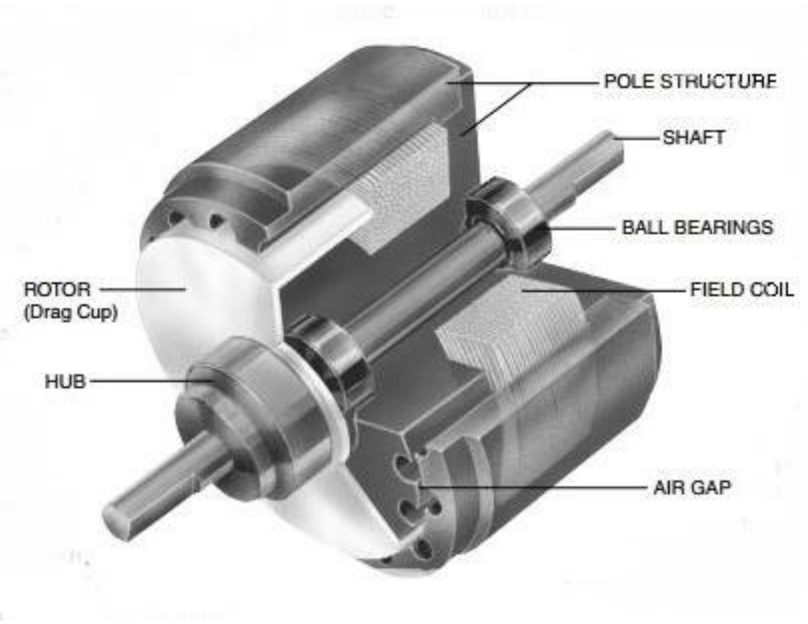


Figure 8: Hysteresis Brake [18]

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 [26]. 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 load sub-team needs to narrow its list of researched designs and choose one for the tunnel wind turbine. 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 [27].

4.4.2 - Smart Material Load

Smart materials a 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 [28]. 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 [29].

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 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 laptop on one's lap that heats up, the heat sink reduces the heat coming from the laptop.

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 doesn't have any other application, it's just a simple load. The other idea is inspired by the electric eel. Essentially it's 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 is 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 criteria 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 criteria 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 criteria 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 software design concepts a Pugh chart, found in Appendix B, was used in order to find the three strongest designs that could all be used in the final design of the wind turbine. Upon completion of the Pugh chart the team found that the designs for Built in Sensors as well as Infrared sensor beam were not strong enough ideas to implement into the final design of the wind turbine.

In order to narrow down the choice to one a decision matrix was used in order 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 3 choices. In order to narrow down the choice to one a decision matrix was used in order 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. 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 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 3 options. The decision matrix below 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	Eal 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 shouldn't 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's 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 – Schedule

See Appendix C for Tunnel Team B's calendars for November and December 2015. These calendars serve as a schedule for remaining deliverables and progress needed for the end of the Fall 2015 semester.

The team's schedule incorporates not only the deliverables for the class, but also the deliverables for the competition. The competition deliverables extend past the end of the semester, but for the time being the team is only focusing on those due before January 1, 2016. These deliverables are not just for Tunnel Team B and in fact represent the entire NAU CWC 2016 team, including the business students. All teams will then be combining their class reports into one singular report for the DoE.

In November, the team will be consistently meeting in subgroups, with all members of the Load sub-team meeting on Wednesday nights with David Willy, and the Power Electronics, Software, and Controls sub-teams meeting on Thursdays with David Willy as well. Each member also attends Friday meetings with the entire team if possible, and the Tunnel Team B Lead meets on Tuesdays with all the other Team Leads. In addition to weekly meetings, the team has slated hours on the weekends to contribute to the final report.

The remaining deliverable for the class in November is a Staff Meeting with Dr. Sarah Oman on November 16. For the CWC Project there are a number of deliverables due on November 30, including the Team's Story, the Conceptual Design Report, the Market Research, and two different personal surveys. However, the team hopes these deadlines before November 25, to avoid working over Thanksgiving Break, as most people will be busy. *In other words, Tunnel Team B is currently attempting to work ahead of schedule.*

In December, there is the Final Proposal Report and Presentation, with the presentation taking place on December 7, and the report due on December 10. Peer Evaluations are also due the same day as the report. The schedule requires all of these deliverables to be worked on at the same time as the November 30 deliverables, in addition to the CWC Technical Report due later in December. This way the team is not worrying about the various deliverables through the last two weeks of school and into the Christmas Break.

7 – Budget

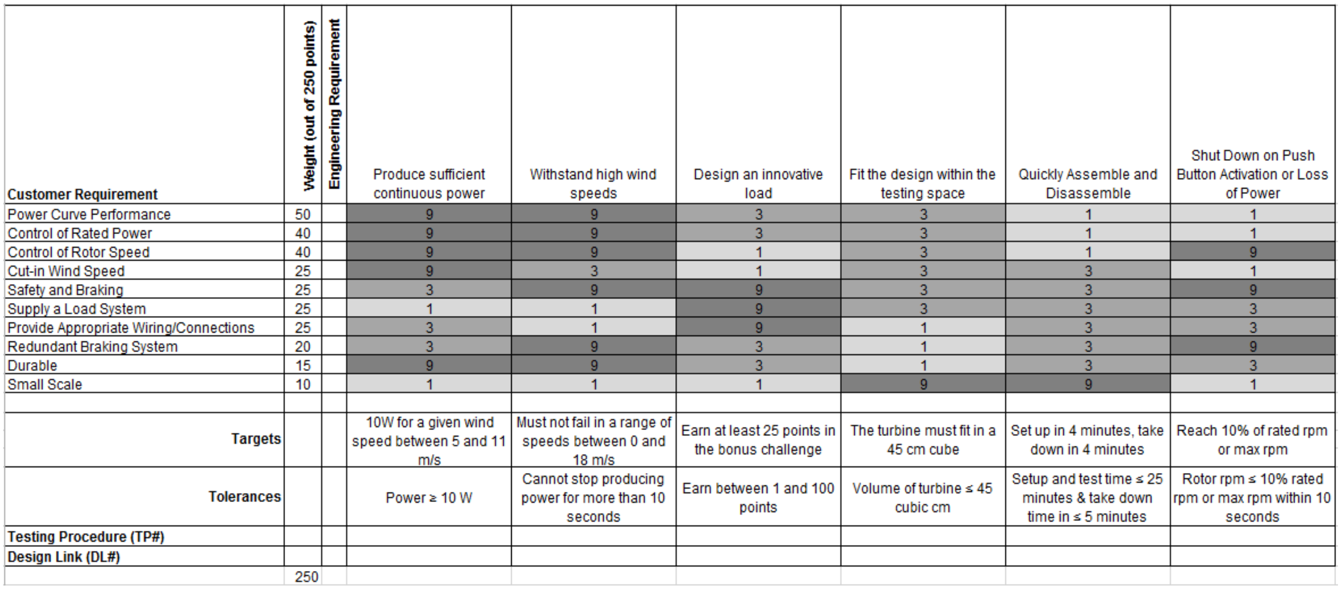
As of now, Tunnel Team B has not spent anything of its 1500.00 USD budget, which is shared with the Deployment Team and Tunnel Team A. The aim is to keep costs of manufacturing the Power Electronics, Controls, and Software under 250.00 USD, and the Load should be under 150.00 USD as well. As such, Tunnel Team B has a projected budget of 400.00 USD, in order to save portions of the budget for air travel costs to New Orleans for the tests in May, 2016.

Of the 400.00 USD set aside, approximately 42.00 USD will be sent this semester on parts to test and analyze. The team will purchase four latching relays (TE RT314A06) at 2.50 USD per unit, for a total of 10.00 USD for all of them. In addition, ten transistors (STP75nf75 MOSFETs) will be purchased, at 1.00 USD each, for a total of 10.00 USD. A spool of wire in 22 AWG (gauge) will be purchased as well, for wiring of components and connect to a standard JST RCY plug that the judges can measure voltage characteristics from. All the wire, plugs, and tape will be about 15.00 USD. In addition, a manual override button must be acquired for the push button test, which runs for 7.00 USD. All costs are initial estimates and do not include shipping, which can increase the projected costs to over 50.00 USD.

8 – Conclusion

After splitting up the Tunnel team into Teams A and B, the members of Tunnel Team B worked studiously on their respective disciplines. Each sub-team performed research in order to identify possible designs, in addition to populating Pugh charts and decision matrices with relevant criteria. Now that design selection is completed, the team will go on to proceed with the simulation and construction steps of each of the chosen designs. Throughout this process, the team will work closely with Tunnel Team A in order to design a turbine, with minimal lapses in communication due to differing design decisions.

9 – Appendix A: House of Quality



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#)								
Design Link (DL#)								
	250							

Figure 9: House of Quality

10 – Appendix B: Pugh Charts

Table 6: 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 7: 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

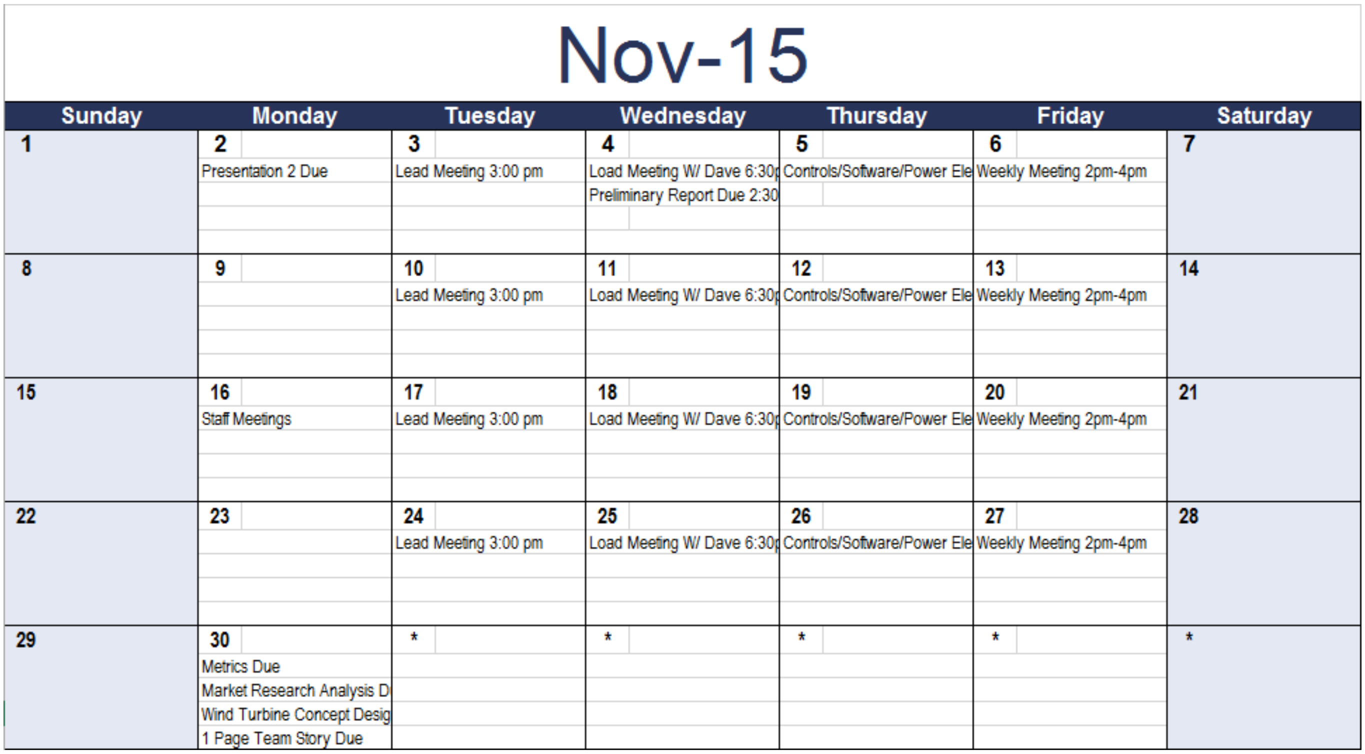
In order to eliminate the least viable ideas for brake loads, the team evaluated the concepts based on five criteria: Ease to Build, Cost, Creativity, Simplicity, Functionality. Based on these criteria, the team decided to eliminate the Smart Materials and Butterfly ideas. The team eliminated the Smart 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 8: Controls Pugh Chart

Criteria	**Webbed Feet Brake**	**AC Brake**	**DC Brake**	**Hydraulic Disc Brake**	**Pneu-matic 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.

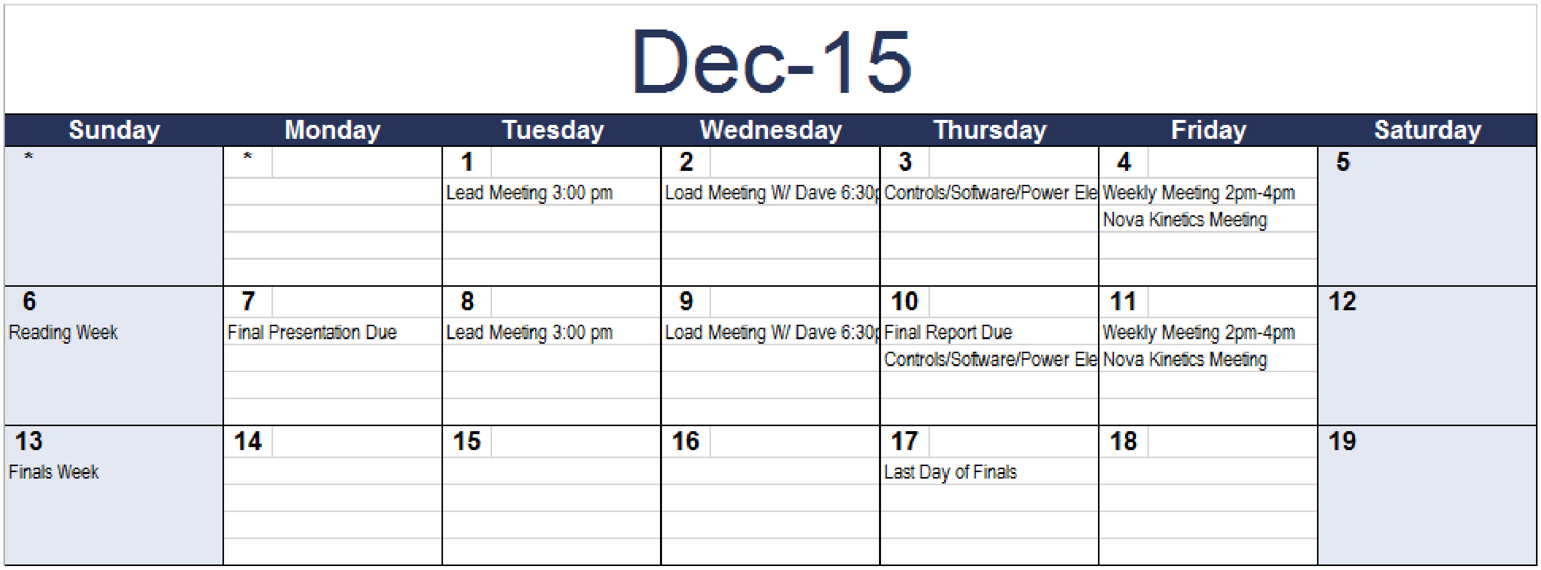
11 – Appendix C: Calendars



Nov-15

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
1	2 Presentation 2 Due	3 Lead Meeting 3:00 pm	4 Load Meeting W/ Dave 6:30p Preliminary Report Due 2:30	5 Controls/Software/Power Ele	6 Weekly Meeting 2pm-4pm	7
8	9	10 Lead Meeting 3:00 pm	11 Load Meeting W/ Dave 6:30p	12 Controls/Software/Power Ele	13 Weekly Meeting 2pm-4pm	14
15	16 Staff Meetings	17 Lead Meeting 3:00 pm	18 Load Meeting W/ Dave 6:30p	19 Controls/Software/Power Ele	20 Weekly Meeting 2pm-4pm	21
22	23	24 Lead Meeting 3:00 pm	25 Load Meeting W/ Dave 6:30p	26 Controls/Software/Power Ele	27 Weekly Meeting 2pm-4pm	28
29	30 Metrics Due Market Research Analysis D Wind Turbine Concept Desig 1 Page Team Story Due	*	*	*	*	*

Figure 10: Project Schedule for November



Dec-15

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
*	*	1 Lead Meeting 3:00 pm	2 Load Meeting W/ Dave 6:30p	3 Controls/Sofware/Power Ele	4 Weekly Meeting 2pm-4pm Nova Kinetics Meeting	5
6 Reading Week	7 Final Presentation Due	8 Lead Meeting 3:00 pm	9 Load Meeting W/ Dave 6:30p	10 Final Report Due Controls/Sofware/Power Ele	11 Weekly Meeting 2pm-4pm Nova Kinetics Meeting	12
13 Finals Week	14	15	16	17 Last Day of Finals	18	19

Figure 11: Project Schedule for December

11 – References

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