NAU 2018 Collegiate Wind Competition

Preliminary Report

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2017-2018

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1 BACKGROUND

1.1 Introduction

The overall project goal is to build a wind turbine that will compete in the Collegiate Wind Competition (CWC), which is sponsored by the U.S. Department of Energy (DOE) and National Renewable Energy Laboratory (NREL). For the CWC, collegiate teams from around America compete against one another in three competition challenges. The competition categories listed within the CWC 2018 Rules and Requirements include:

1. Create a research supported market business plan and a conceptual-level technical development design for a marketable wind power system.
2. Manufacture a safe and reliably operating mechanical, electrical, and aerodynamic wind turbine and load design for testing in an on-site wind tunnel.
3. For the wind turbine, manufacture an electrical control system that can maintain a constant voltage feeding into a competition-provided variable-resistance load, which is conducted during the durability portion of the turbine testing (utilizing a competition-provided storage element to balance source and load energy [1].

The Northern Arizona University (NAU) CWC 2018 team is fully responsible for constructing a wind turbine and providing team transportation to and from the competition. The overall NAU team has been split up into three different teams: Market Team, Test Team A, and Test Team B. Together the two test teams will design and construct the working turbine for NAU that fits into a 45cm by 45cm by 45cm cube [1]. This report is based on the components that Test Team A is responsible for designing, which are the:

- Blades
- Drive Train
- Bearings for the Drive Train
- Generator
- Direct Current to Direct Current (DC-DC) Converter
- Printed Circuit Board (PCB).

Therefore, the goal of the overall project relevant to this report is to design and construct certain the listed wind turbine components.

This project provides hands on work experience that can be expected within the wind energy industry. Wind power at its current rate is "projected to double by 2020 and again in 2030," which means that there is a growing number of work opportunities within the wind energy industry [2]. This project builds relevant experience which is needed to fill the expanding job force within the wind energy industry.

1.2 Project Description

According to the project description on the DOE CWC website [1]:

> *The 2018 Collegiate Wind Competition will be held at American Wind Energy Association WINDPOWER in Chicago, Illinois, from May 8–10. Competing teams will design and build a model wind turbine based on market research and siting considerations, develop a business plan to market the products, and* ***test the turbines against a set of rigorous performance criteria*** *judged by a panel of wind industry leaders.*
>
> *The Collegiate Wind Competition challenges undergraduate students to design a wind turbine based on market research, develop a business plan to market the product,* ***build and test the***

> ***turbine against set requirements****, and demonstrate knowledge of opportunities related to wind farm siting.*
>
> *Teams participating in the 2018 Collegiate Wind Competition will be expected to research and design a turbine for a grid scenario with a high contribution of renewables.* ***The turbine should be able to operate in islanded mode****.*

From this description and for the scope of this report: the focus of this project is to develop safe and efficient wind turbine components. The components will be assembled within a fully designed wind turbine for testing based on the CWC requirements.

1.3 Original System

Throughout competition years, the NAU CWC team's wind turbine has had some common system structures and operations. For this report, the 2016-2017 NAU CWC team's wind turbine design is the analyzed original system. Design testing results from their design and future design considerations will dictate the use of the older turbines' components or different components for the overall system. Due to the CWC rules and requirements changing each year, the current wind turbine must be manufactured in accordance to the 2018 rules and requirements. Nonetheless, there will be some similarities to the components that have been consistent throughout the competition years. Thus, the current design will be comparable to the 2016-2017 NAU CWC team's design.

1.3.1 Original System Structure

The 2016-2017 NAU CWC team's wind turbine was a horizontal axis wind turbine (HAWT) with the tower blade dimensions set. The blades were made from carbon fiber material. The team decided on a fixed blade, stall regulated turbine with 4 blades (changing it from 3 blades used by teams from prior years). The drive train type was designed as a direct drive shaft with a disc brake for turbine speed regulation. The bearings for the drive train weren't analyzed to the extent to be expected in this report. The generator was a permanent magnet synchronous AC generator. The DC-DC converter previously used is a simple boost converter, with the board layout being done on a bread board. The PCB used last year was a simple bread board.

1.3.2 Original System Operation

The operations of the 2016-2017 NAU CWC team's wind turbine operated on fixed blades to catch the wind's energy and translate it into mechanical energy. A direct drive shaft then transfers the mechanical rotational energy into an Active Current (AC) generator that is rectified into a DC output. Then, a DC-DC boost converter steps up the power output. The PCB that holds the electronic components and acts as a signal pathway was a bread board. The use of these systems were based off of the ease of operations associated with the systems. Due to CWC requirements changing each year, our design will mirror the operation of past turbines only when allowed and/or needed.

1.3.3 Original System Performance

The performance of the 2016-2017 NAU CWC team's wind turbine was rated at 22 to 23 Watts at an 11 or 12 meters per second wind speed. The blade performance also showed a tip speed ratio of roughly 2 to 2.3 at different wind speeds ranging from 10 to 18 meters per second. The wind speed provided by the CWC will be 20 meters per second, so the performance of the turbine should be maximized between 10 to 18 meters per second, which is an acceptable range [3]. The goal of this year is to step up the wind turbine performance from last year, which translates directly with the overall design of the wind turbine.

1.3.4 Original System Deficiencies

The 2016-2017 NAU CWC competition team had problems that will be focused on for the wind turbine in current design. The tail didn't work as designed; it had to be redesigned at the competition, because there was too much wake. The PCB broke while in a team members bag on the way to the competition due to improper packaging. The brakes failed at the competition; the design wasn't adequate for the expected loads on the system.

2 REQUIREMENTS

The requirements of the design dictate how successful the performance of the design must be. The customer requirements are set by our customers (the DOE and NREL) for a satisfactory design. The engineering requirements are then derived from customer requirements and represent measurable engineering parameters in relation to design successfulness.

2.1 Customer Requirements

To design a satisfactory wind turbine, the design must meet the customer requirements. The customer requirements are based off of the DOE CWC Rules and Requirements [3] and consultation with our capstone advisor (David Willy) and past CWC competition team members. Some of the requirements were determined logically, while others were given directly. The main requirements for our design and a description of the reason why each requirement is necessary is in Table 1. Meeting these customer requirements guarantee sufficient customer satisfaction from the overall wind turbine design.

Table 1. Customer Requirements and Rationale

Customer Requirement	Requirement Selection Rationale
Power Generation	There has to be power generated by the wind turbine.
Electrical Grounding	There can be no open charge, so circuits must be grounded.
Transportability	The turbine has to be able to be shipped to and from the competition site and carried by the team.
Assembly	The assembly of the wind turbine should not be too complex, so that we can leave room for repairs.
User Friendly	The use of the wind turbine should be as easy as possible for all users, so that there is no confusion at the competition.
Safety	The turbine cannot be harmful to anyone during construction and use.
Durability	The turbine must be able to withstand relevant loading types and values without failure during use.
Maintenance	If failure occurs, the turbine should be easily accessible for maintenance.
Aesthetics	The turbine should look presentable for the competition.
Cost	The turbine cost should not exceed our project budget.

2.2 Engineering Requirements (ERs)

The engineering requirements are derived from the customer requirements or come from our customers directly. They represent measurable parameters that our design must meet or exceed. The measureable parameters are relevant to the design of each wind turbine component. All of the engineering requirements come from the CWC Rules and Requirements. Table 2 displays the engineering requirements along with a description of the reason why each engineering requirement is necessary. Meeting these engineering requirements guarantee satisfactory wind turbine performance.

Table 2. Engineering Requirements and Rationale

Engineering Requirement	Requirement Selection Rationale
Survivability Wind Speed (m/s)	The wind turbine must be able to survive winds speeds up to 22 ± 2m/s to survive competition testing.
Fit in 45cm by 45cm by 45cm cube	The wind turbine rotor must be able to fit in a cube for wind tunnel testing with a tolerance of -0.5cm.
Fit in 61cm by 122cm Turbine Door	The wind turbine must be able to be put through the wind tunnel testing turbine door with a tolerance of -0.5cm.
Electric Housing (Y/N)	There must be a housing complex for the electric components of the wind turbine equivalent to or better than the NEMA 1 standard set by the CWC.
Wire and Jacket Length from Turbine Base (m)	The length of the wire and jacket from the turbine base must be at least 1m to and from the load and at least 2m to and from the storage element with a tolerance of +0.2m.
Required Direct Current (DC) at PCC (V)	The DC value at the PCC must be at least 5V and at most 48V.
Zero State of Charge at Test Beginning (C) & (V)	The charge at the beginning of any test must be zero, so as to not expose any charge to people.
Keep Under Energy Storage Rating (V)	The rating of the output into the energy storage unit must be under 16V, or we will fail the test.
Push Shut Down on Command (Y/N)	The wind turbine must have a simple way to shut down the turbine when needed.
Bade Numbers (#)	There must be between 2 to 4 blades on the wind turbine.
Rotor Diameter (cm)	The diameter of the turbine rotor must be below 45cm with a tolerance of about -0.5cm.
Power Curve Generation between 5m/s and 11m/s (W)	The generation of power on the power curve between wind speeds from 5m/s to 11m/s must be maximized (~10 ± 2W).
Cut-in Wind Speed (m/s)	The cut-in wind speed of the wind turbine must be at a wind speed between 2 and 5m/s.
Rated Wind Speed (m/s)	The rated wind speed must be at 11 ± 0.5m/s.
Rated Power (W)	The rated power of the turbine must be at about 10 ± 2W.
Cut-out Wind Speed (m/s)	The cut-out wind speed must be at 20 ± 0.5m/s.
Tip Speed Ratio (#)	The tip speed ratio must be between 5 to 12.
Overall Efficiency (%)	The overall efficiency of the wind turbine must at 40 ± 10%.
Aerodynamic Efficiency (%)	The aerodynamic efficiency must be at 45 ± 5%.
Electric Efficiency (%)	The electrical efficiency must be at 90 ± 5%

2.3 House of Quality (HoQ)

A House of Quality (HoQ) is created from the customer requirements and engineering requirements specified from the previous two sections. The customer requirements' importance is weighted on a scale from 1-5 (with 5 being the highest importance). The engineering requirements relations to the customer requirements are weighted on a 0-1-3-9 scale (with 9 being the highest relation), and technical requirement targets at the bottom of the HoQ are targets for each engineering requirement. Note that there isn't a target value for every engineering requirement, as the target of some engineering requirements are arbitrary or different for each component we work with. The absolute technical importance (ATI) is then calculated as:

$$ATI = \sum_{i=1}^{n} [(CR\ Weight)_i * (ER\ Weight)] \quad (1)$$

Based on the ATI, the relative technical importance (RTI) at the bottom of the HoQ displays the most important engineering requirements (one being the most important). Appendix A displays the HoQ, as it is a large table.

3 EXISTING DESIGNS

The existing designs that are researched on pertain to the components relevant to this report. The components are: the blades, drive train, bearings, generator, DC-DC converter, and PCB. These components are sections of an overall wind turbine system that works in unison to produce electrical energy from rotational mechanical energy produced by the fluid wind speed energy. The blades translate the wind speed energy into mechanical energy, while the drive train transfers the mechanical energy into electrical energy through a generator. Then the DC-DC converter safely steps up the generator electrical energy to produce the necessary power by the overall system. The PCB is the bed that holds all electronics while providing a path for electronic transfer (when needed).

3.1 Design Research

Since Test Team A works on certain components of the overall turbine, research was done on only the components associated with Test Team A (the blades, drive train, bearings, generator, DC-DC converter, and PCB board).

3.1.1 Research: Blades

When looking at the turbine blades, the airfoils that are being used have a big impact on the blades performance. There are several different companies that have developed airfoils and have released the specifications for how they perform. The National Advisory Committee of Aeronautics (NACA) and the National Renewable Energy Laboratory (NREL) are biggest companies that design airfoils. The NACA 4-digit series is widely used for its simplicity in generating new airfoils. The 4-digits are represented in groups, the last two digits, first digit, and the second digit. The last two digits represent the maximum thickness of the airfoil as a percentage. The first digit represents the maximum camber of the airfoil as a percentage from 0 to 9%. The second digit is an indication of where the maximum camber is in tenths of a percent (0% to 90% in steps of 10%) [4]. The NREL series are a harder to visualize but they break up different airfoils into airfoil families. There are many other airfoils that are available for low Reynold's number (Re) flows that we will be looking at when it is time to select airfoils.

3.1.2 Research: Drive Train

The research for the shaft consisted of looking through information provided in past NAU CWC team reports and the *Shigley's Mechanical Engineering Design* textbook. The 2016 design didn't have a drive train, so they had to connect the blade hub to the generator directly. The 2017 team machined their own direct drive shaft design for the drive train out of Aluminum 7075 material, which connected the wind turbine rotor to the generator while holding a gear that acted as a disk brake. Other designs that are considered are gear boxes, which uses a gear system to increase the RPMs entering the generator to increase the power output [5].

3.1.3 Research: Bearings

Different bearing types are useful for different loading and situational applications. The 2016 NAU CWC team's bearing selection process isn't in-depth, so the research conducted for the bearings come from the *Shigley's Mechanical Engineering Design* textbook. The bearings must withstand both radial and thrust loads from the wind turbine for a short amount of hours (10 hours maximum). The selected bearings must have a static outer ring that is connected to the housing. There must be a inner ring that rolls the drive train with rollers (or balls) between the inner and outer ring. The bearing roller types dictate how well the bearings handle radial and axial (thrust) loads [5].

3.1.4 Research: Generator

One of the power electronics components that our team has to build is the generator. There are several different types of generators that can be used for this project, and all of them have different pros and cons. The main types of generators that were researched for this project were a permanent magnet AC generator, a DC generator, or a rewired AC generator that we would optimize for this project.

The first design, permanent magnet AC generator, is the simplest of the 3. It works by turning magnets around fixed coils of magnet wire. The alternating north and south poles of the magnets induce an alternating current in the wire, which can then be sent to our rectifier. For the permanent magnet generator, the advantages are that we can get a good power output and keep the generator size small. This is also the kind of generator that has been used by almost every other CWC team, so it is well established and reliable. The drawbacks are that we get a low voltage output because of the fairly high KV rating (RPM/V) from this type of generator [6].

A DC generator also works by inducing current in coils of magnet wire, but the way it does it is different. In a DC generator, the coils rotate in a fixed field. The coils are attached to a commutator, which balances the charges coming into and going out of the generator, resulting in a direct current output. The advantages of a DC generator are that it eliminates the need for a rectifier and can be built fairly easily. The disadvantages are that it is larger, requires more maintenance, and is less efficient than its AC counterpart [6].

A rewired AC generator is something we would create for this project, where we would take an AC generator apart and then try to put it back together with thinner gauge wire, which would allow us to decrease our KV rating, therefore increasing our voltage output. The advantages of a rewired AC generator are the same as the normal AC generator, with the bonus that we can get more voltage out of it since we are rewiring it to optimize it for this project. The disadvantage of doing this is that it will take a lot of careful work and if a mistake is made in the rewiring process it could ruin the generator and we would have to get a new one.

3.1.5 Research: DC-DC Converter

An important part of the turbine design is the power electronics. Our team has been assigned the task of designing the DC-DC converter. The purpose of the DC-DC converter will be to boost the output voltage of the system. There are various types of boost converters, all with specific advantages and disadvantages. As part of the research, we have looked at previous DC-DC converters used by past CWC teams. The 2017 Northern Arizona University team utilized a standard boost converter topology in their converter. Along with analyzing previous devices, we have begun researching several different types of converters. Performing simulations will help to design and optimize the DC-DC converter to best fit the wind turbine. The simulations will be conducted in the Simulink software package and this will require knowledge of the program. This has required us to watch tutorials on designing schematics in Simulink.

3.1.6 Research: PCB

The *PCB Design Tutorial* textbook describes how to choose different types of PCBs and lays out the advantages and disadvantages in the various designs [7]. According to the customer requirements and engineering requirements, the board must be durable while minimizing the overall component cost. The four types of PCBs that will be analyzed for this report are: single-side boards, double-side boards, multi-layer boards, and bread boards. The pros and cons of these designs will be mentioned in subsequent PCB sections.

3.2 System Level

The component work in which we are undertaking contributes to an overall small-scale wind turbine that will be tested within a wind tunnel. In other words, the overall system of a wind turbine can be constructed in multiple ways based on the subsystem components. The existing subsystems' that we are assigned to work on are in the subsequent 3.2 sections.

A bigger-scale but similar type of wind turbine that exhibits the relativity and applicability of our project is the GE 1.5MW Wind Turbine. The GE 1.5MW Wind Turbine is a HAWT that includes the subsystems similar to our assigned subsystems: the blades, main shaft/gearbox, generator, converter, and board for electronics. This wind turbine is being implemented into various grid networks to continue to increase the wind energy production of the planet [8].

A smaller-scale home wind turbine that exhibits the relativity and applicability of our project is the 400-Watt Wind Turbine Power Generator for 12-Volt Systems from Home Depot. It's a HAWT wind turbine with three blades that customers can use "in their own back yard" for necessary energy applications. It has all of the similar components as the turbine in which we are building. It can charge batteries, be used with an inverter to produce power for applicable electronics (like a T.V., lights, and/or power tools) [9].

Another small-scale wind turbine that exhibits the relativity and applicability of our project is the Primus Wind Power Air 40 12 Volt DC Turbine from Norther Arizona Wind & Sun. It is a three blade HAWT that works in "medium to high wind environments [10]." It too has similar components to the turbine in which we are building.

3.2.1 Subsystem Level: Blades

The blades of wind turbine are used to convert linear momentum of the wind into rotational energy of the shaft. The purpose of the blades is to generate lift causing the blades to rotate around the shaft axis. The blades are made up of different airfoils that are designed to work at different sections of the blade. The air foils need to be matched with the Reynolds number that the blade is operating at. This is important because each airfoil is designed to operate at a certain section of the airfoil and at certain Reynolds number ranges. The blades are a vital component because without them the turbine would be a giant pole in the ground.

3.2.1.1 Existing Design: Blade Material

Many of the current wind turbines for the DOE CWC have been made of carbon fiber and some type of 3-D printed material. The difference between carbon fiber and 3-D printed materials is the strength of material. Carbon fiber has mainly been used when deflection of the turbine's blades needed to be minimized and fewer number of blades were needed. 3-D printed material on the other hand were used when costs need to be low or a large number of blades were needed to be made. The application of material selection is important for the performance of the turbine. The material also greatly affects what type of airfoils that we can use. With the carbon fiber thinner airfoils are possible because molds are being used to form the blades. While thinker airfoils need to be used if the material is 3-D printed. During the 3-D printing process the tip resolution can only be so good, meaning the blade's design has to be something that the printer can handle meaning thinker airfoils.

3.2.1.2 Existing Design: Blade Types

When looking at the blade of a wind turbine the airfoils at the root (base) and tip of the blade are going to be different. In past years the teams have used the NACA 4-digit series airfoils. The reason that this series has been used is because it is easy to visually see what the airfoil is going to look like. The airfoils that are being used for the blades of the generally represent high lift airfoils. These airfoils are used for the lift that they create. The use of flat plates are not used for the turbine blades, however they are used for the tail fin.

3.2.2 Subsystem Level: Drive Train

There are two types of drive trains that will be analyzed: a gearbox and a direct drive shaft. The material of the shaft dictates its overall life based on geometrical constraints and the relevant loading factors. The necessary power requirements and the rotor rotations per minute (RPMs) dictate what type of shaft will be used for rotational mechanical energy transfer from the rotor to the generator. The material of the disk brake dictates the weight of the gear and how well the brake will work (based on the braking friction).

3.2.2.1 Existing Design: Gearbox

A gearbox is a set of connected gears within a housing whose primary function is to increase the drive train's RPM speed. The connected gears differ in size (with the smaller gear, or pinion, as the driven gear) to increase the RPM speed. The usage of a gearbox would need a more in-depth analysis on the overall drive train system fatigue (as the possibilities of failure are much higher) [5].

3.2.2.2 Existing Design: Direct Drive Shaft

A direct drive shaft connects two rotating components directly [5]. On the wind turbine, a direct drive shaft would connect the rotor and the generator. With this design, the design analysis would be much simpler and there would be a lower failure probability. Nonetheless, the RPMs going into the generator would decrease, thus decreasing the power output.

3.2.3 Subsystem Level: Bearings

The bearings allow the drive train and yawing mechanism to freely rotate while staying in static equilibrium, transferring mechanical rotational energy as efficiently as needed. The bearing housing (attached to the nacelle and/or tower) and the bearing outer ring must be connected statically. There must be rollers or balls between the outer ring and inner ring (chosen based on load applications). The inner ring will be touching the drive train or yawing mechanism in analysis, allowing it to roll as freely as possible. Based on cost, availability and application location, the bearing types at different locations may change.

3.2.3.1 Existing Design: Single-Row Deep-Groove Ball Bearings

Single-row deep-groove ball bearings have deep raceway grooves with the inner and outer rings having circular arcs of slightly larger radius than the rolling balls. They work well with high speeds and radial loads. They can handle axial loads acceptably while having low torque capacity at startup and running speeds without requiring much maintenance. Based on the application needed of the ball bearings, different numerical series can be chosen [11].

3.2.3.2 Existing Design: Tapered Roller Bearings

Tapered roller bearings are composed of the cone (inner ring), the tapered rollers, the cup (outer ring), and a cage to retain the rollers. The loads on the bearing are carried by the cone, rollers, and cup. Tapered roller bearings are good for dimensional stability, a long life, and a very durable design (they can hold all loading types very well) [12]. However, the durable design comes at a higher cost. Locations for in need of a more durable design can use tapered roller bearings.

3.2.4 Subsystem Level: Generator

The generator is what converts the mechanical energy of the blades into usable electrical energy. It does this by rotating magnets around several tightly wound coils of magnet wire. This induces a current in the wire, which can be either AC or DC based on the type of generator and the components inside of it. This voltage is then fed into our rectifier (if AC) or directly into or DC-DC converter (if DC).

3.2.4.1 Existing Design: Danish Wind Industry Association

This type of generator is the one all of the previous CWC teams have used. It is a fairly simple design, is reliable, and has a decent KV rating. The problems with this type of design are that it has a fairly low voltage output so it is hard to get a competitive voltage value during the competition.

3.2.4.2 Existing Design: Permanent Magnet Generator Design
This type of generator is much like the AC generator, but instead of the magnets rotating around the coils, the coils instead rotate inside a fixed field. The coils are then attached to a commutator, which gives a DC output. The advantages of this are that it directly produces DC current so we don't have to convert it with a rectifier. The downside is that DC generators are less efficient, larger, and require more maintenance.

3.2.4.3 Existing Design: Rewired AC Generator
This design is just a modified version of the fixed magnet AC generator. We would take an AC generator and take the current coils out so we could put new ones in with a thinner gauge wire. This would increase the number of turns which would increase our voltage. It would also take a lot of time and effort on our part though and there is no guarantee that it would significantly increase our voltage.

3.2.5 Subsystem Level: DC-DC Converter
The main purpose of the DC-DC converter is to step the input voltage up to around 48 volts. In order, to do this the system utilizes inductors, capacitors, transistors and other electrical components to achieve a higher output voltage.

3.2.5.1 Existing Design: Boost Converter
A boost converter is a simple DC-DC converter that steps up the voltage through an inductor, capacitor, MOSFET and a diode. The device would function as a switch mode supply to step the voltage up.

3.2.5.2 Existing Design: Interleaved Boost Converter
This circuit is a more complicated form, of a boost converter. It is often called a multichannel converter as it contains to channels of inductors and MOSFET's operating 180 degrees out of phase. It has a high efficiency and requires more components than a boost converter.

3.2.5.3 Existing Design: Buck-Boost Converter
This design is another variant of a boost converter, it contains additional diodes and is a bit more complicated. The overall operating principal is the same with an added feature. When the pulse width of the MOSFET transistor is below 50% it operates as a buck converter. This device would provide the ability to either step the voltage up or down based off the pulse width.

3.2.6 Subsystem Level: Printed Circuit Board (PCB)
A printed circuit board (PCB) is a carrier that connects electronic software and hardware. It is a device that needs high precision and high reliability. It is an important part in a wind turbine electrical system, because when we design and test a circuit, we need to make our circuit into a board so that we can connect generator to the DC-DC converter and all other electronics.

3.2.6.1 Existing Design: Single-Side Board
Single-side board is a very common PCB board design. Some factories use the single side boards to design some circuits within televisions (TVs) and digital versatile disc (DVD) players. Single-side boards can be obtained at a relatively low cost. However, there are many constraints on components' placement when using single-side boards, as there is a limited amount of space [7].

3.2.6.2 Existing Design: Double-Side Board
Double-side boards allows for an extra layer that electrical components can be placed on. However, the area of the board is usually smaller than that of a single-side board, because there are more tiny chip capacitors and resistors that are in use within the circuit. These chip capacitors are only used on the bottom layer to improve the circuit efficiency and reduce the error [7]. The cost of a double-side board is more than that of a single-side board, but it may be worth the extra area.

3.2.6.3 Existing Design: Multi-layer Board
There are four layers for a multi-layer board circuit design. There is the top layer, the bottom layer, the VCC layer, and GND layer. This design has the most complex circuit design out of the boards analyzed in this report, because we need to use single layer to put the VCC and GND. The usage of a multi-layer board will improve the electrical efficiency [7]. However, there is much more work associated with this design and the cost is more expensive than other board types.

3.2.6.4 Existing Design: Bread Board
A bread board is the simplest type of board in analysis within this report. It can be directly connected to the circuit. A bread board has many holes that can be directly used, but this design will increase the line resistance and decrease the output voltage. The control theory connection is very easy, because the circuit and the control can be connected [7]. The usage of the bread board is simple, but it comes at the cost of low efficiency.

3.3 Functional Decomposition
The functional decomposition for this project can be found in Appendix B, as it is a large decomposition of the wind turbine into the main components. Within the functional decomposition the different components of the turbine have been broken down into analytical terms. It also contains possible design choices that come along with each component. As shown in the functional decomposition, the main sections of the wind turbine include the power electronics (DC-DC converter and rectifier), the load (capacitor bank and batteries), the generator (AC/DC Generator), and the mechanical structure (blades, hub, shaft, yawing, nacelle, and tower). The components that this report refers to are: the blades, the shaft, the generator and the DC-DC converter.

3.3.1 Black Box Model
The wind turbine black box model shown in Figure 1 displays the necessary material, energy, and signal inputs with their corresponding outputs to translate mechanical energy into electrical energy on a wind turbine. The inputs necessary include the wind speed and direction which rotates the rotors (translating wind energy into mechanical energy) and a start, break, and stop feature for applications of these signals before and/or during operation. Then, mechanical energy is translated into electrical energy through a shaft and generator design that produces electricity and a DC-DC converter that steps up the electrical energy. The signaling output for a working turbine shows the rotor spinning and allows for working electronics when the wind turbine is on, while the rotor would be stationary and the electronics wouldn't work when it's off. The black box model helps our team understand the major material, energy, and signals associated with completing our overall goal. The necessary inputs are the building blocks of our components' functionality, while the outputs are the goals each component must work toward for proper wind turbine functionality.

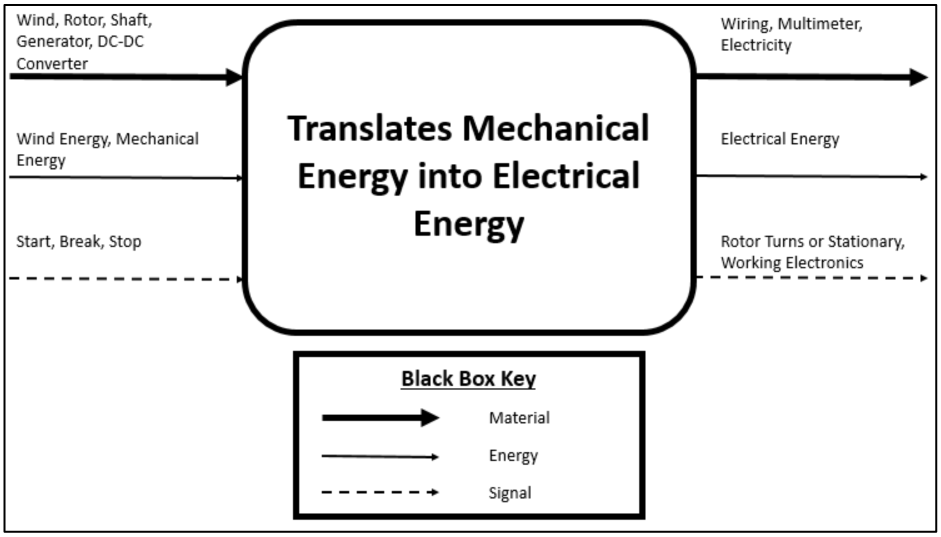

Figure 1. Wind Turbine Black Box Model

3.3.2 Functional Flow Model/Gantt Chart

The functional model is shown in Figure 2 displays what is required of the components referred to in this report. The wind flow speed is caught by the blades, which then creates kinetic rotational energy by spinning the rotor which is connected to the drive train. The drive train's kinetic rotational energy is then translated into an electrical power signal through a generator that is connected electronically to a DC-DC (boost) converter. The boost converter (which is connected to a PCB) then steps up the voltage that flows into the electrical grid.

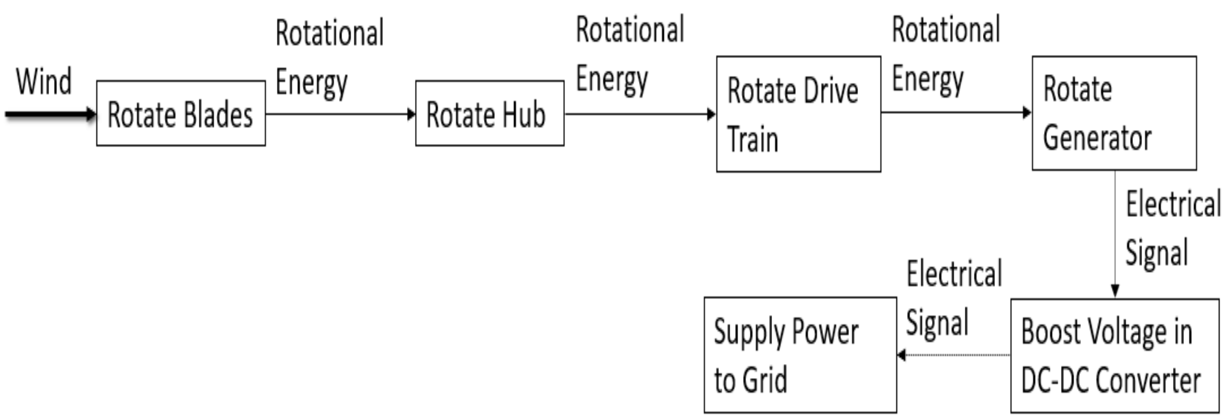

Figure 2. Functional Flow Model

Appendix C shows the Gantt Chart of the entire collegiate wind competition team. Within the headings are each teams' deliverables and a timeline for completion. Test Team A's deliverables for the upcoming 2018 term is displayed in Appendix C. The deliverables mainly consist of determining materials, ordering the materials, testing the materials, then assembling the materials on the overall wind turbine that will then be tested before the CWC in May. This Gantt chart helps us clarify our timeline to complete necessary deliverables in a timely manner.

4 DESIGNS CONSIDERED

The following sections pertain to the considered component designs for the blades, drivetrain, generator, DC-DC converter, and PCB board.

4.1 *Design: Blades*

By generating different ideas than those that have been used by existing ideas. The benefits of coming up with new ideas for the blades it is possible come up with a design that can generate more power or be more efficient.

Through the concept generation process many designs were created to increase either the performance, power, or efficiency of the blades. The first concept (shown in Figure 3) that was created was to trying to increase the Reynolds number (Re) that the blades are acting at. By increaaseing the Re there is a larger selection of airfoils that would be able to use. Therefore, potentially increaseing the power generated for the turbine's.

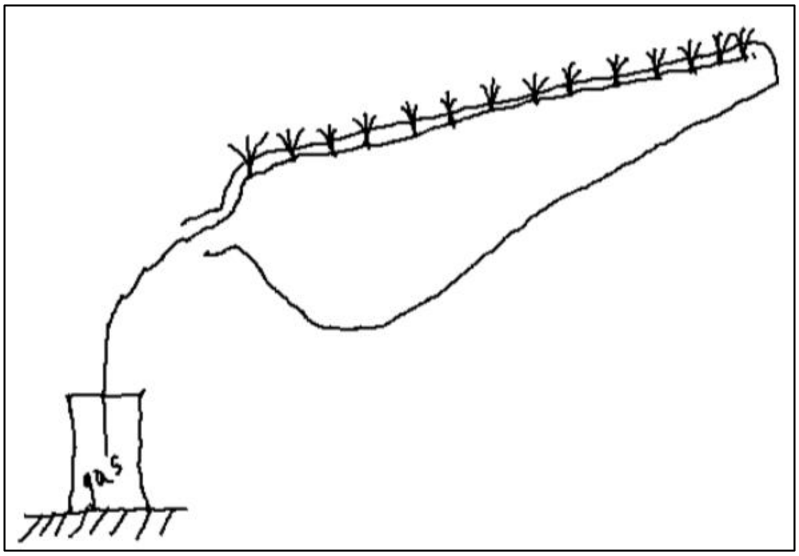

Figure 3. Fluid Nozzles to increase Reynolds number

The second design created (shown in Figure 4) was a teliscoping blade. The purpose of design was to be within the size restriction of the competition, but once the blade starts rotation and the centripital force increase the length of the blade increase the torque of the turbine, increaseing the amount of power that can be produced. Since there are a lot of forces on the turbine blades this design would need a lot of analisys to determin if the blades would survive under all the stress at higher wind speeds.

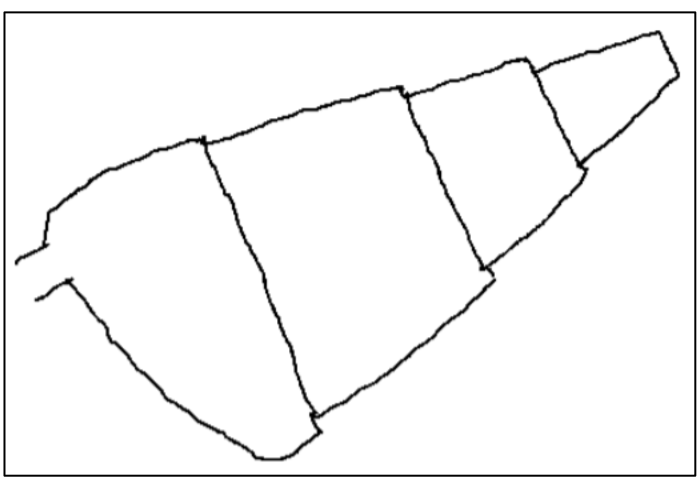

Figure 4. Telescoping Blade

The next design (shown in Figure 5) is a blade that is curved. The reason for the curve on the blade is to decrease the noice that is produced at higher revolutions per minute (RPMs) of the turbine blades. While reducing noice it increases the tip losses. With the increased tip losses the performance of the turbine would decrease and be less efficient. However, because of the shape of blades it would have an appleling factor that customers might like.

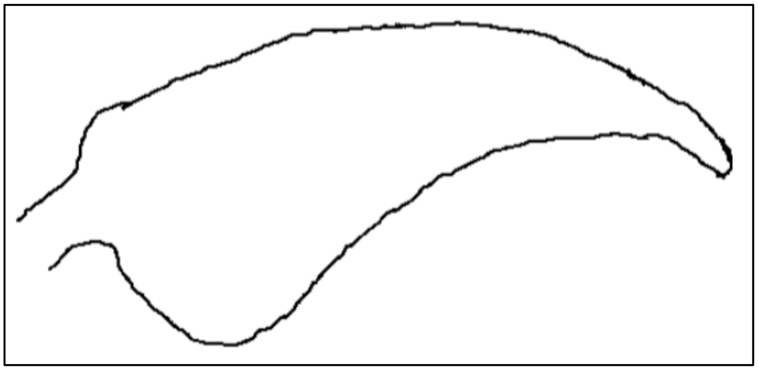

Figure 5. Curved Blade

Another design that was taken from an automotive application is the use of a shroud (shown in Figure 6). The use of the shroud would cut down on wake rotation. By cutting down on wake rotation it the blades would behave more like a betz blade. The shroud would also act as a small nozzle increase the velocity of the flow as it enters the upstream side of the blades. Since the power in the wind is equal to the curve of the velocity, the amount of power that the turbine can generate would be increased.

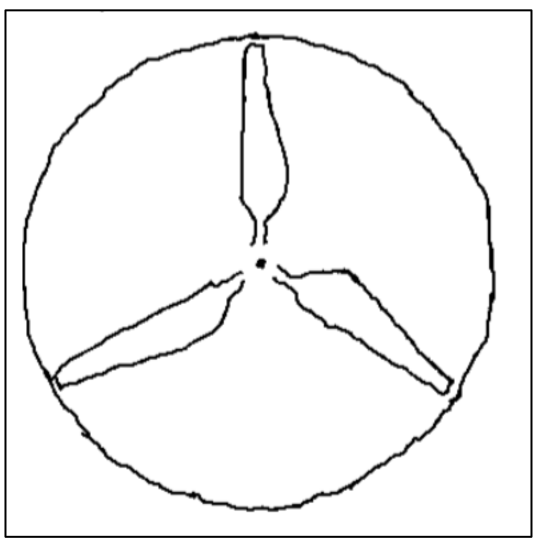

Figure 6. Blade with Shroud

A typical blade for a wind turbine (shown in Figure 7) is simple and does not require extra calculations to determine the amount of power that the turbine is producing. A normal design like this is the most commonly used. Figure 5 shows a typical blade design with a shroud aroud the turbine's blades. The circle on the outside is a shroud to direct the air through the turbine as well as avoid send the flow in the radial direction. The shroud also has the added beifits of speeding up the flow as it goes around the shroud to hopefully match the velocity of the air on the back side of the turbine blades.

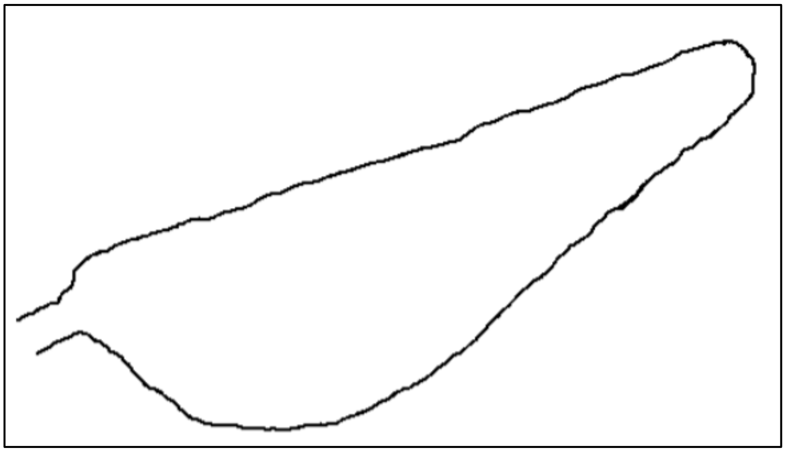

Figure 7. Conventional Blade

4.2 Design: Drive Train

There are two drive train designs in consideration: the gearbox drive and the direct drive shaft. One of these two designs will be chosen as the drive train between the wind turbine rotor and generator based on needed power requirements and design difficulty. The material of the drive train will be iteratively analyzed and chosen based on relevant fatigue factors that are based on the drive train design decision.

A simple gearbox design is shown in Figure 8. The pros of the gearbox are: an increased amount of RPMs and an increased power output. The cons of a gearbox drive include: a higher probability of failure, more complications in the overall design, and a higher overall cost.

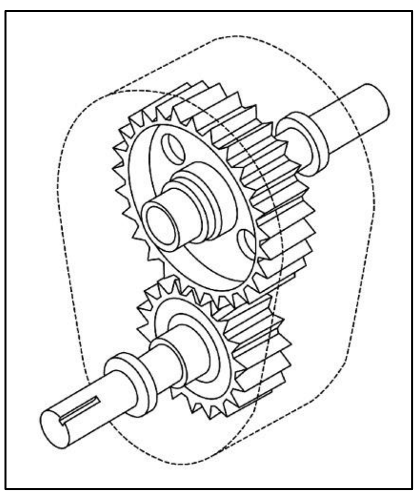

Figure 8. Gearbox Drive Train [13]

A simple direct drive shaft is shown in Figure 9. The pros of the direct drive shaft are: a lower cost design, a higher safety reliability, and an easier design to work with. The cons of the direct drive shaft are: a lower amount of RPMs for the generator and less voltage production through the generator.

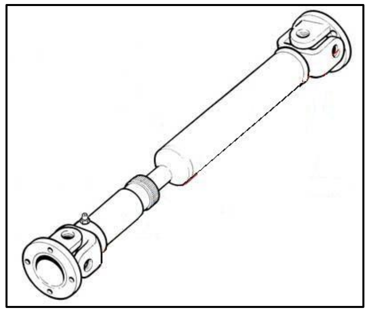

Figure 9. Direct Drive Shaft [14]

Based on the design choice: the material of the shaft has to be able to handle high loading factors from the rotor, generator, and disk brake. Therefore, the tensile strength and yield strength must be as high as possible. Aluminum is a relatively low cost metal with adequate strengths to handle the expected loads, which can be adequate for the wind turbine design.

4.3 Design: Bearings

For the drive train mechanism, the bearings to be analyzed are single-row deep-groove ball bearings and tapered roller bearings (based on iterative geometrical constraints) that will be supplied by Applied Industrial Technologies®. Since there are various application locations, either bearing may be used for each application based on the relevant loads and the overall bearing costs. Figure 10 displays a single-row deep-groove ball bearing design and Figure 11 displays a tapered roller bearing design, both from Applied Industrial Technologies® at a scale similar to what is expected for application into a small scale wind turbine.

Figure 10. Single-Row Deep-Groove Ball Bearing [15]

Figure 11. Tapered Roller Bearing [16]

On the drive train, the bearings are expected to handle both axial and radial loads when closer to the rotor, while mainly only handling radial loads closer to the generator. The bearing near the rotor will take upon most of the axial load; therefore, this location will take into consideration both bearing types. The bearings near the generator can be chosen as ball bearings, with the geometry chosen based on the iterative design process. On the yawing mechanism, the bearing will experience both axial and radial loads. Both bearing types will be analyzed for the yawing application, and based on the overall bearing life and cost, either can be chosen and tested.

4.4 Design: Generator

The first generator design we are considering is a permanent magnet synchronous AC generator. This type of generator is good because it is a simple design, small size, and provides reasonable voltage and power values for our competition. The drawbacks of this type of generator is that it requires a rectifier which adds another component to our design, and it also can't produce higher voltage values without producing a power value that is too high for the competition. Below is a Simulink model of a permanent magnet generator that has been used for testing this type of generator. This model would also be used for testing a rewired AC generator, with the specifications changing but the overall design remaining the same.

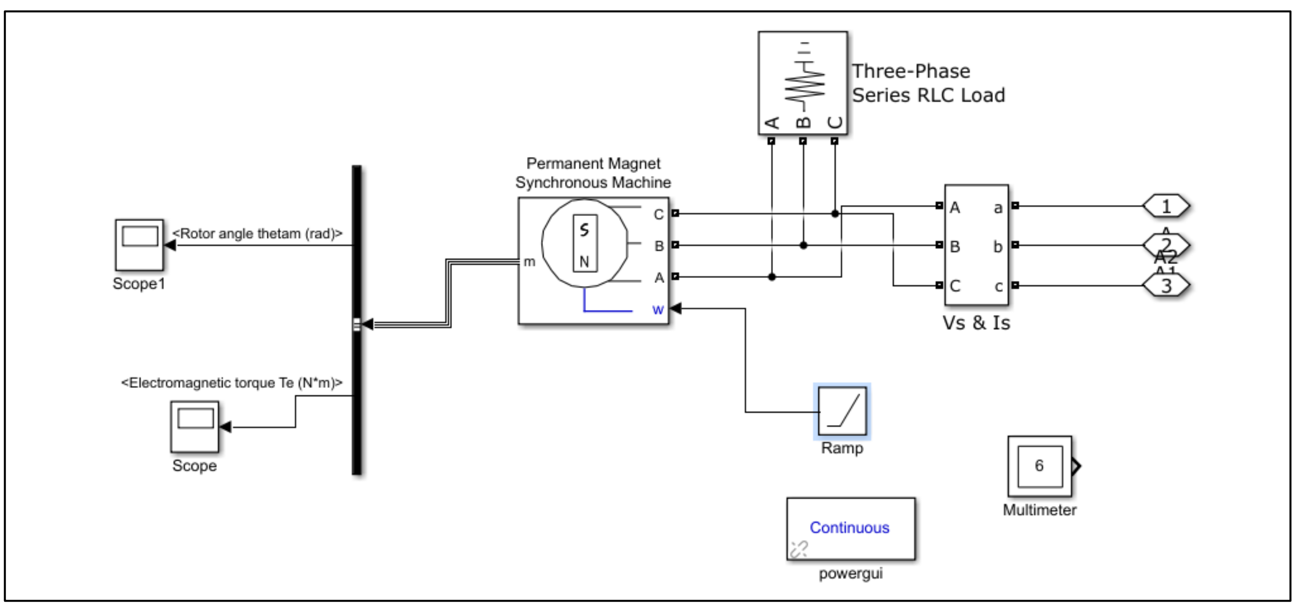

Figure 12. Simulink Generator Model

The other type of generator that was considered was a DC generator. This type of generator would eliminate the need for a rectifier, but would also be larger, less efficient, and less reliable than an AC generator. It would save us time because of not having to build a rectifier, but would not be ideal for the competition because our voltage and power values would not be as high. Below is a diagram showing a simple DC generator, with the coils rotating in a fixed field with a commutator fixing the voltage output.

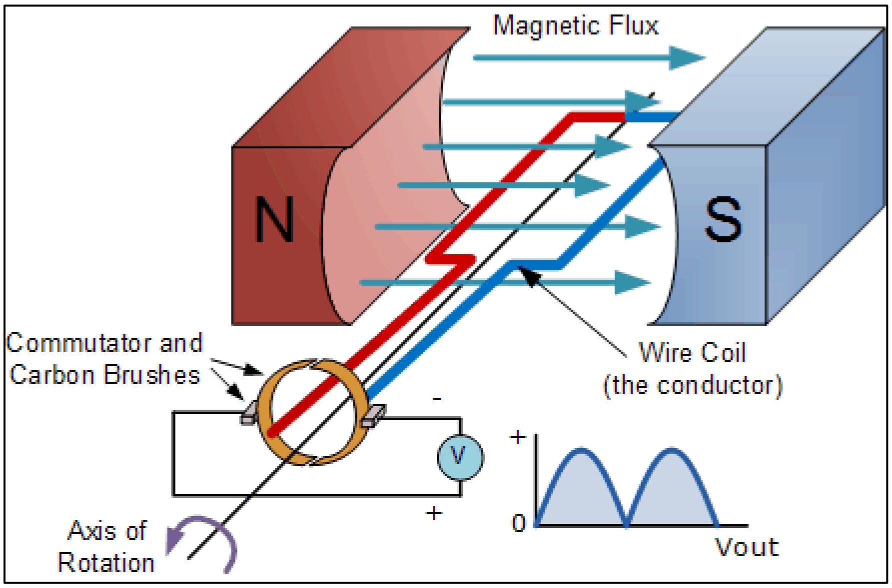

Figure 13. DC Generator [17]

4.5 Design: DC-DC Converter

In order, to decide which type of DC-DC converter to utilize for our system, we conducted research to find which converter would best match the needs of our project. Ultimately, we came up with four different designs to consider: boost converter, interleaved boost converter, flyback converter and a buck-boost converter. Upon further research, we eliminated the flyback converter because of its difficulty to implement, and that it required a transformer. Also, with the equipment available to our team we would not be able to successfully build and test the converter. The buck-boost converter could be eliminated based on premise that our system would only need to step the voltage up and it would not be necessary to step down the voltage. This left two designs remaining, from there we built two Simulink models for each converter.

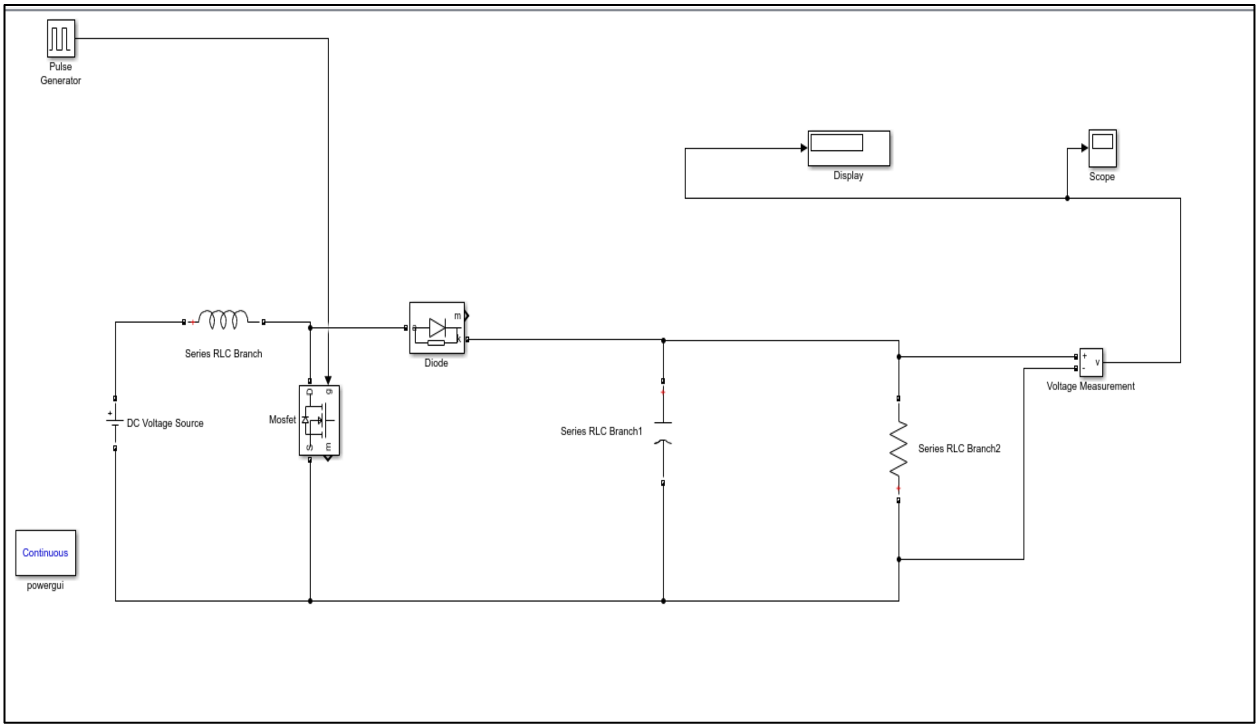

Figure 14. Boost Converter

The figure above is a schematic of a boost converter that was designed for the project. It is a simple design, which will make designing the converter relatively simple. However, it does not offer several of the advantages of an interleaved boost converter.

An interleaved boost converter or multi-channel boost converter, as seen in the schematic below would require more components than a typical boost converter; however, we believe the advantages are well worth the extra effort to implement. By having a multi-channel converter, the overall efficiency of the system would be improved along with reduced voltage ripple and shrinking the inductor and capacitor size [18].

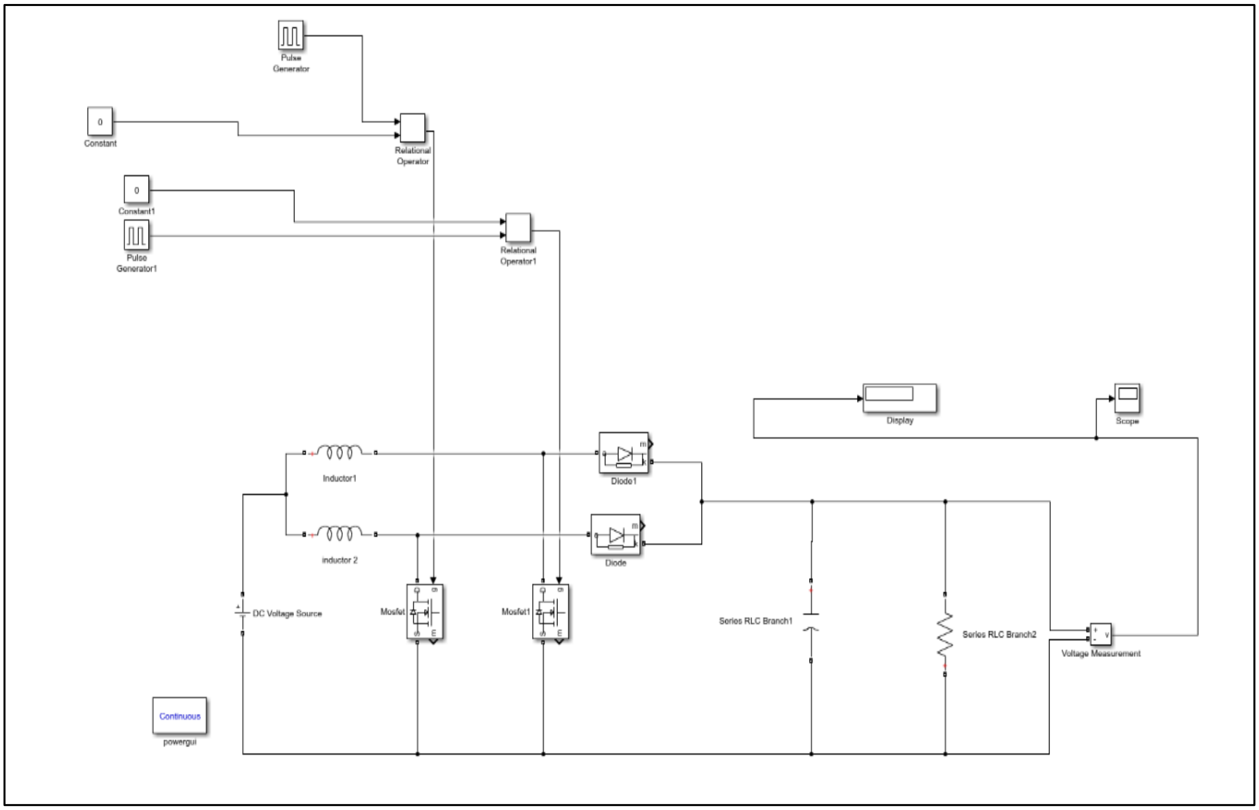

Figure 15. Interleaved Boost Converter

4.6 Design: PCB

There are different types of wiring diagrams that can be used for this project, all with their own advantages and disadvantages. The simplest diagram is a single-side board shown in Figure 16. Single-side boards are easy to repair, but the lines we use to connect components cannot cross. Double-side boards shown in Figure 17 have larger area sizes to work with, as it can house electronics on both the top and bottom layers of the boards. However, double-side boards will increase the area of the wiring, as wires must connect the top and bottom layers, which will complicate the overall PCB design. Multi-layer boards shown in Figure 18 are the most complex boards within these design considerations; they are applied to more sophisticated circuit designs. Bread boards shown in Figure 19 are the simplest designs; however, they decrease the efficiency dramatically.

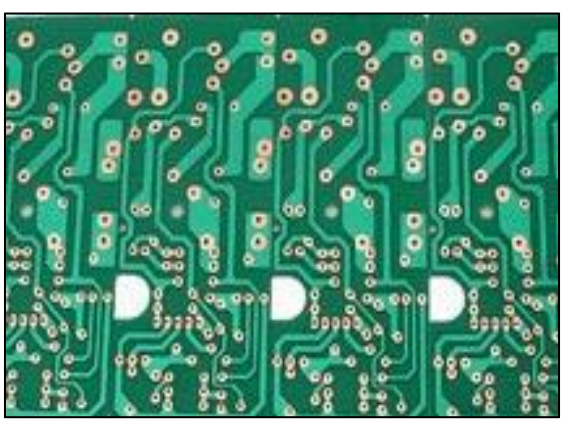

Figure 16. Single-Side Board

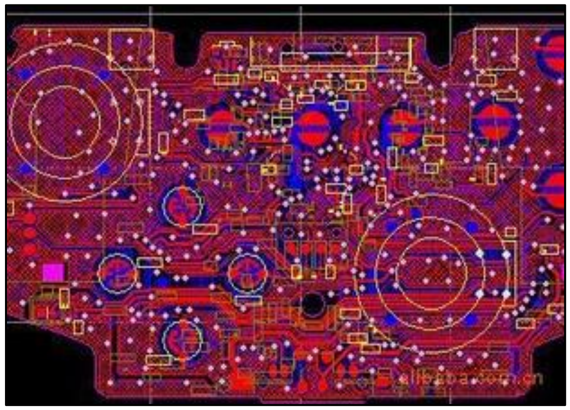

Figure 17. Double-Side Board

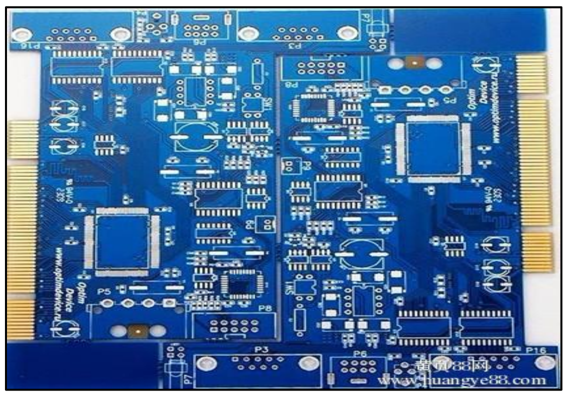

Figure 18. Multi-Layer Board

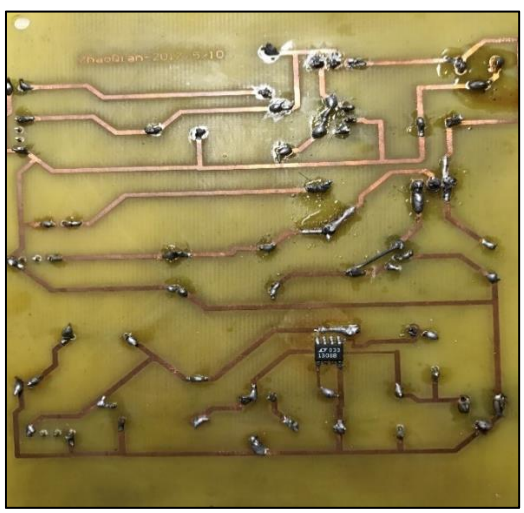

Figure 19. Bread Board

5 DESIGN SELECTED

The overall wind turbine design selection is based on the assembly of selected individual components. The components relevant to this report are selected based on logic and with the help of decision matrices; each component is selected to improve the overall wind turbine design. The blades will be conventionally made, the drive train will be a direct drive shaft, all bearings will be single-row deep-groove ball bearings, the generator will be a permanent magnet synchronous AC generator, the DC-DC converter will be a 3-channel interleaved boost converter, and the PCB will be a double-layer board.

5.1 Rationale for Design Selection

The rationale for each component selected is explained in their respective subsections.

5.1.1 Selection: Blades

After the concept generation stage of the design process, an initial design is needed to be selected. With blade design 2 and the blade length increasing, it pushes the blades outside the allowed area for the turbine; therefore, that design must be scrapped. With blade design 3, the amount of power that the turbine is going to produce, extra losses from the tip of the blades would be bad decision and would almost be impossible to recover from the losses this design. Therefore, this design was also scrapped to maximize the amount of power that the turbine can generate. After scrapping blade designs 2 and 3, a closer look at how the manufacturing of the blades would occur was needed. The diameter of fluid pipe would be extremely small to fit within the thickness of the turbine blades. For this reason blade design 4 was also scrapped. After looking at the concepts that remain, design 5 (the conventional blade) is selected as the initial design for the simplicity and reliability of the blades at higher wind speeds. No decision matrix has been used for this design decision, because all other designs considered besides the conventional blade design is obviously not feasible.

5.1.2 Selection: Drive Train

The drive train is going to be designed as a short direct drive shaft that directly connects the blades hub to the generator while providing a disk brake gear with different material. The direct drive shaft is less complicated will have less factors for failure, while providing adequate rotational momentum transfer. Table 3 below displays the decision matrix used to come to our drivetrain decision. The direct drive shaft outscored the gearbox in all categories besides the functionality aspect, as the gearbox increases the revolutions per minute entering into the generator.

Table 3. Drive Train Decision Matrix

Criteria	Weights	Direct drive shaft	Gearbox
Reliability	0.60	8	4
Size	0.05	8	6
Functionality	0.20	5	8
Ease of implementation	0.15	7	4
Total	1.00	7.25	4.9

5.1.3 Selection: Bearings

Single-row deep-groove ball bearings and tapered roller bearings bother have their own advantages and disadvantages as stated in section 4.3 in this report. For simplicity, the bearing applications on the drive train and yaw mechanism are assumed to have all locations experiencing both radial and axial loads (though the drive train locations near the generator will not experience the axial load very much). Table 4 below displays the decision matrix used for rationale on which bearing type to use for both applications based on expected geometrical constraints. As it can be seen, they both have a very similar total rating due to the expected size of the applications. However, the single-row deep-groove ball bearings cost less (in general), so they will be chosen for both applications.

Table 4. Bearings for Drive Train and Yaw Mechanism Decision Matrix

Criteria	Weights	Single-Row Deep-Groove Ball Bearing	Tapered Roller Bearing
Reliability	0.60	8	9
Size	0.05	9	7
Functionality	0.20	8	7
Ease of implementation	0.15	9	7
Total	1.00	8.2	8.2

5.1.4 Selection: Generator

For this project, we have decided to use a rewired AC generator because it will give us the best voltage output compared to the other options. Even though it takes more time and effort and there are risks involved with it, we want to have the best possible generator for the competition and we believe this is the best way to get such a generator. When we put the options into our decision matrix, it gave the same result, which is that a rewired AC generator was the best option.

Table 5. Generator Decision Matrix

Criteria	Weights	Permanent Magnet AC	DC	Rewired AC
Reliability	0.60	7	4	5
Size	0.05	5	8	5
Functionality	0.20	9	6	4
Ease of Implementation	0.15	7	8	2
Total	1.00	7.3	5.2	4.35

5.1.5 Selection: DC-DC Converter

Our initial selection, we used a pairwise matrix and a decision matrix to help select which converter to go with. The weighting from the decision matrix is based off the values determined by the pairwise matrix. From the outcome of the decision matrix, we believe an interleaved boost converter, will best fit the scope of the project. An interleaved boost converter offers several advantages: improves efficiency, reduces ripple, and shrink capacitor and inductor sizes [19]. The criteria for the DC-DC converter matrices are:

1. Reliability: The final product will need to work a high percentage of the time.
2. Ease of Implementation: Developing the DC-DC converter will require a lot of work to design. Being able to limit this work could potentially save time.
3. Functionality: The functionality is very broad, and encompasses other important characteristics like voltage ripple and device efficiency.
4. Size: The team has a limited space that the device needs to fit into.

Furthermore, in Table 6, the scale that we are using goes from one to nine. Nine being the best that a criterion can achieve and one the lowest.

Table 6. DC-DC Converter Decision Matrix

Criteria	Weights	Boost Converter	Interleaved Boost Converter
Reliability	0.60	6	5
Size	0.05	6	5
Functionality	0.20	5	6
Ease of Implementation	0.15	7	6
Total	1.00	5.77	6.01

5.1.6 Selection: PCB

The electrical board area should be minimized to decrease cost and allow for needed electric systems. It should also be easily reliable, as replacements are needed in case of failure but should be minimized. The PCB also must have good functionality, as to also minimize PCB replacements. Table 7 displays the PCB decision matrix. As it can be seen, the double-side board is the best choice for a PCB, as it offers a good balance between reliability, size, functionality and the ease of implementation.

Table 7. PCB Decision Matrix

Criteria	Weights	Single-Side Board	Double-Side Board	Multi-Layer Board	Bread Board
Reliability	0.60	5	7	6	3
Size	0.05	3	6	7	2
Functionality	0.20	4	7	8	3
Ease of Implementation	0.15	7	6	3	8
Total	1.00	5	6.8	6	3.7

5.2 Design Description

In each components' respective section, the description of their design (which will be implanted into the overall wind turbine design) is given.

5.2.1 Description: Blades

When working on specification for the blades there was a few requirements in the rules and regulations that had to be looked at. In the rules it states that the maximum entire hub must fit within a 45-cm x 45-cm x 45-cm cube. From this the maximum diameter of the wind turbine can be 45-cm. With a diameter of 45-cm the maximum blade length can be is 22.5 cm. However, this does not take into consideration the size of the hub. For the analysis and after talking another team member that is working on the hub and he needs the hub to be between 5 and 10-cm in diameter. Taking this requirement into consideration the maximum length of the blades is 20-cm. With this length and the one-two-three equation with inputs (density, diameter, and mean wind speed) the absolute maximum power that can be generated from the turbine is over 100W [3]. For that power output there are several assumptions that are being made including an ideal wind turbine, efficiency of 1, and Betz optimum blade.

For our design, we need to incorporate many factors that are not in the one-two-three equation such as tip losses, turbine efficiency's, wake loss, and drag. Also, since our blades are smaller the Reynolds number that the blades are acting at are low and special airfoils need to be used to generate the required torque needed to turn the generator. The air foils that are needed for the Reynolds numbers range are high camber or single surface airfoils.

When analyzing the performance of the wind we used a MATLAB code to deliver the primary detentions for the blades, the next step is to import those blade into a Blade Element Momentum (BEM) code in MATLAB. This code predicts the performance of the turbine with the outputs of Coefficient of Performance (CP) vs Tip Speed Ratio (TSR) and the axial induction factor and rotational induction factor. From this if the performance is close to what we are looking for, we can input the detentions and specs into Qblade. Qblade has more detailed outputs such as, power, CP vs TSR (can compare these graphs), torque vs Revolutions Per Minute (RPM), Coefficient of thrust vs TSR, power vs wind speed, and many more plots. The performance in Qblade is very graphical and not very numerical, so that the user can see how the turbine is going to change with slight variation of inputs. Table 8 is the information that is produced from the MATLAB code and is the required imports that Qbalde needs. The units on the table are meters for the first two columns and degrees for the last three columns. This is also the first part of the blade design process that we can see what the blades/turbine as a whole. Figure 20 below our current blade and Figure 21 shows the current rotor design. However, the results of our current blades shown in this section will change as the Re used in the analysis was done at 50000 where the actual Re is going to be lower.

Table 8. Outputs from MatLab. First 3 columns are inputs for Qblade

r	C	Twist_Angle	Relative_wind	Section_pitch
0.0195	0.0627	36.357	39.357	29.357
0.039	0.058253	23.537	26.537	16.537
0.0585	0.046945	16.37	19.37	9.3697
0.078	0.038081	12.08	15.08	5.0799
0.0975	0.031678	9.29	12.29	2.29
0.117	0.026987	7.3494	10.349	0.34941
0.1365	0.023449	5.9283	8.9283	-1.0717
0.156	0.020702	4.8455	7.8455	-2.1545
0.1755	0.018516	3.9943	6.9943	-3.0057
0.195	0.016739	3.3082	6.3082	-3.6918

The current airfoils that are being used are the NACA 4410, 3508, and the 3308. These airfoils were used chosen because they are similar airfoils, had a high lift at this Re. For a turbine of this size it is important that airfoils are generating a large amount lift while keeping the flow attached to the airfoil, or have these airfoils act like larger/thicker ones. Since the Re needs to be lowed the airfoils that are being used will need to be changed and even more camber is going to be needed.

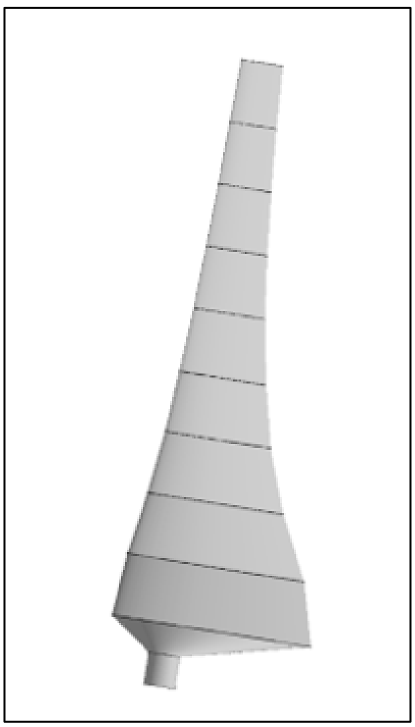

Figure 20. Current Blade Design

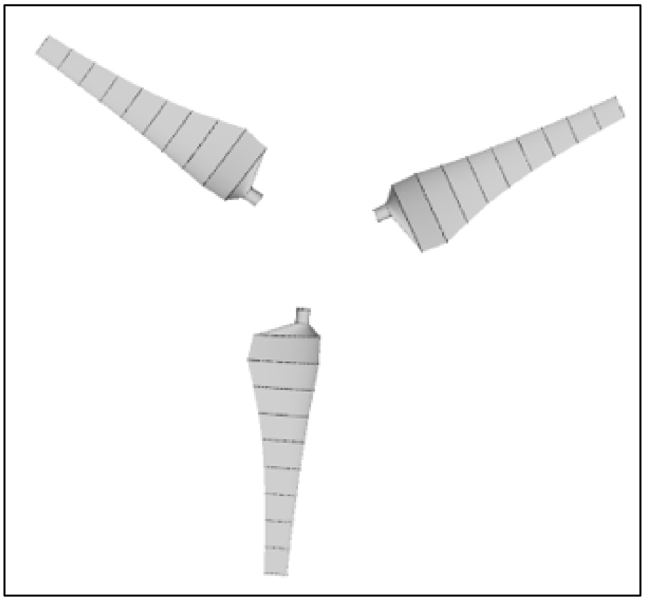

Figure 21. Current Rotor Design

With this current rotor design we can even look at the anticipated power that the rotors can produce. The main thing that should be looked at on this graph is the rated power which is the velocity of the wind that blades were designed, in this case at 10 m/s. According to Figure 22 at 10m/s the power is over 20 W. Another area of this graph that needs to be questioned is what happens as the wind speed increase the power should eventually drop off.

The current thought on the material of the blades is either carbon fiber, or a type of 3D printed martial. There are some benefits and drawbacks for both materials. For the carbon fiber some benefits are its strength the weight is very high where it is hard to layup and requires the use of molds and vacuums to harden the resin and get the great strength that carbon fiber is known for. Where 3D printed materials are easier to print, the ability to create the product almost anywhere (as long as the printer is capable of using a certain type of 3D printed material), the ability to rapidly produce prototypes, and the volume of products that could be used in the time it takes to produce a mold, prepare the mold, lay up the product, let the product cure and finally, do final touch up product. However, 3D materials a generally weaker because of the voids that made because of the printing paths. These voids are stress concentrations and the more voids or spots where the material does not fully cure or sags off the desired path during the printing process.

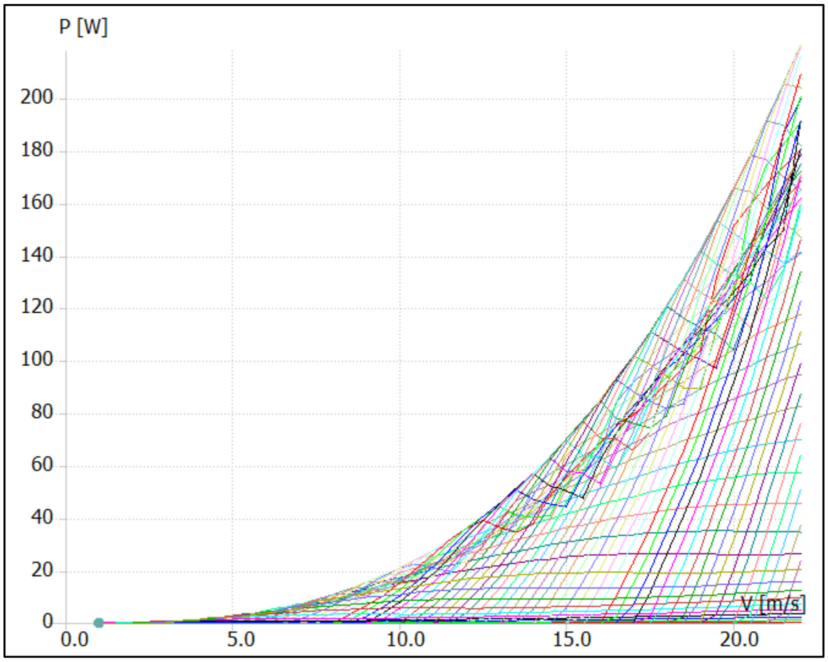

Figure 22. Power vs Wind Speed Graph

5.2.2 Description: Drive Train

The shaft that will being used in this design is a direct drive shaft. The drive train will connect the rotor to the generator transferring mechanical rotational energy to be converted to electrical energy. The shaft must be able to handle relevant loads from the rotor and the brake system without failure. Furthermore, the shaft needs to accommodate the rotor's active pitching system; which will cause more fatigue. Thus, to accommodate the needs of the design, the shaft's material must be selected based on all relevant loads and on varying geometrical constraints. Aluminum was found as the best material for this design based on its pros and cons; the pros of aluminum are: low overall cost, easy to machine and low weight. There is a con of aluminum which is hard to repair in case the drive train broken or cracked. Also, a comparison was made between different grades of aluminum, and the result turn out to be aluminum 7075 is the best one for the shaft because it's higher yield strength and ultimate tensile strength. Also, a Matlab code was created to calculate the fatigue factor of safety. This code will be used to test 7075 aluminum to check if it will satisfy this design or not; the code will be in the appendix D. The cost of two feet of 7075 aluminum is about 30 $, which is not too expensive. The rod of aluminum was found in McMaster, and it will be ordered from them to be machined. The initial geometry and dimensions of the drive train was selected; and it will be shown in the 3D model below.

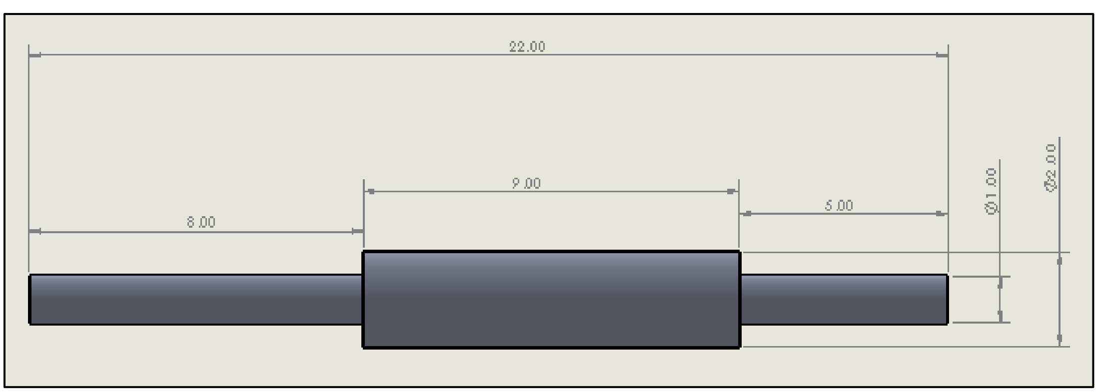

Figure 23. CAD model of the Direct Drive Shaft

5.2.3 Description: Bearings

The bearings chosen for applications on both the drive train and the yaw mechanism are single-row deep-groove ball bearings supplied by Applied Industrial Technologies®. They are the simplest designs with the lowest relative cost that works for our load and geometrical applications. Based on the preliminary drive train dimensions, the inner ring of the bearings must be at least 1cm (this can change through iterative testing). Figure 24 below shows a CAD drawing of a SKF single-row deep-groove ball bearing like what will be used for our bearing applications on the wind turbine.

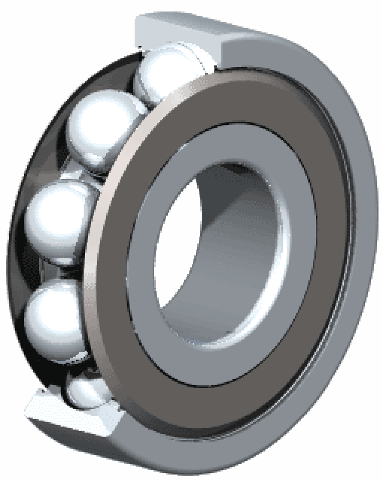

Figure 24. SKF Single-Row Deep-Groove Ball Bearing CAD Drawing [20]

5.2.4 Description: Generator

For the final generator selection, we researched many different AC and DC generators with specifications similar to the ones needed for our project. Below is a table of 10 AC and 5 DC generators with specifications that were researched for this project. All of them have KV ratings that are acceptable for this project and well as manageable sizes.

Table 9. Possible Generators

Part Number	*KV Rating*	*Diameter Size (cm)*
IF4114	*320*	*N/A*
MT4012	*340*	*4.7*
MN4012	*340*	*4.0*
P5012	*360*	*N/A*
ML3510	*360*	*4.2*
S5008	*330*	*5.75*
V4004	*300*	*N/A*
MN3510	*360*	*3.5*
D5010	*360*	*5.0*
ML3510S	*360*	*N/A*
0.60 Size Outrunner	*380*	*5.0*
X6210	*380*	*6.2*
X4108S	*380*	*4.6*

Four our final selection, we have decided to choose the SunnySky X4108s for this project. A picture of it is included below for reference. This generator was chosen due to it's good KV rating, small size, and relatively low torque, which allows for a smooth startup. It is also the generator that has been used by the majority of past CWC teams so there is a level of familiarity and confidence with it that would not exist if we decided to go with a completely new and untested generator.

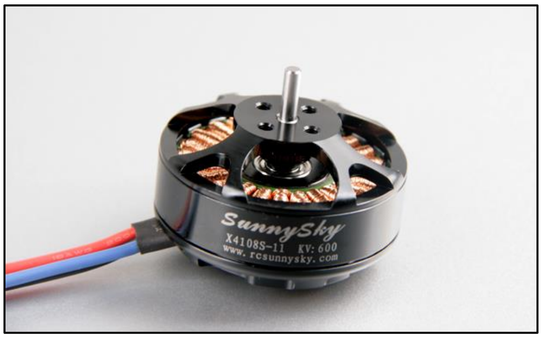

Figure 25. Sunny Sky X4108S

5.2.5 Description: DC-DC Converter

The Final design that we have decided to select is a three-channel interleaved boost converter. We feel that the benefits of using such a design outweigh the cons of requiring a more complex control theory. A three-channel interleaved boost converter steps up the input voltage to the target output voltage. For our system we will be designing all three inductor channels to have the same inductance. This is done because the small benefits gained by having differing inductances is outweighed by the added complexity to the control system and the additional microcontroller required. In the figure below, is the current schematic for our three-channel interleaved boost converter. The top section of the diagram, represents the control theory for the MOSFETS used in the circuit. The three MOSFETS connected directly after the inductors all operate 120 degrees out of phase, while the constant represents the duty cycle that the MOSFETS will be operating at. Unlike in a traditional boost topology, we have replaced the diodes with MOSFETS that operate inversely to the MOSFET on the same channel as them. For example: when MOSFET11 is high, MOSFET1 will be low.

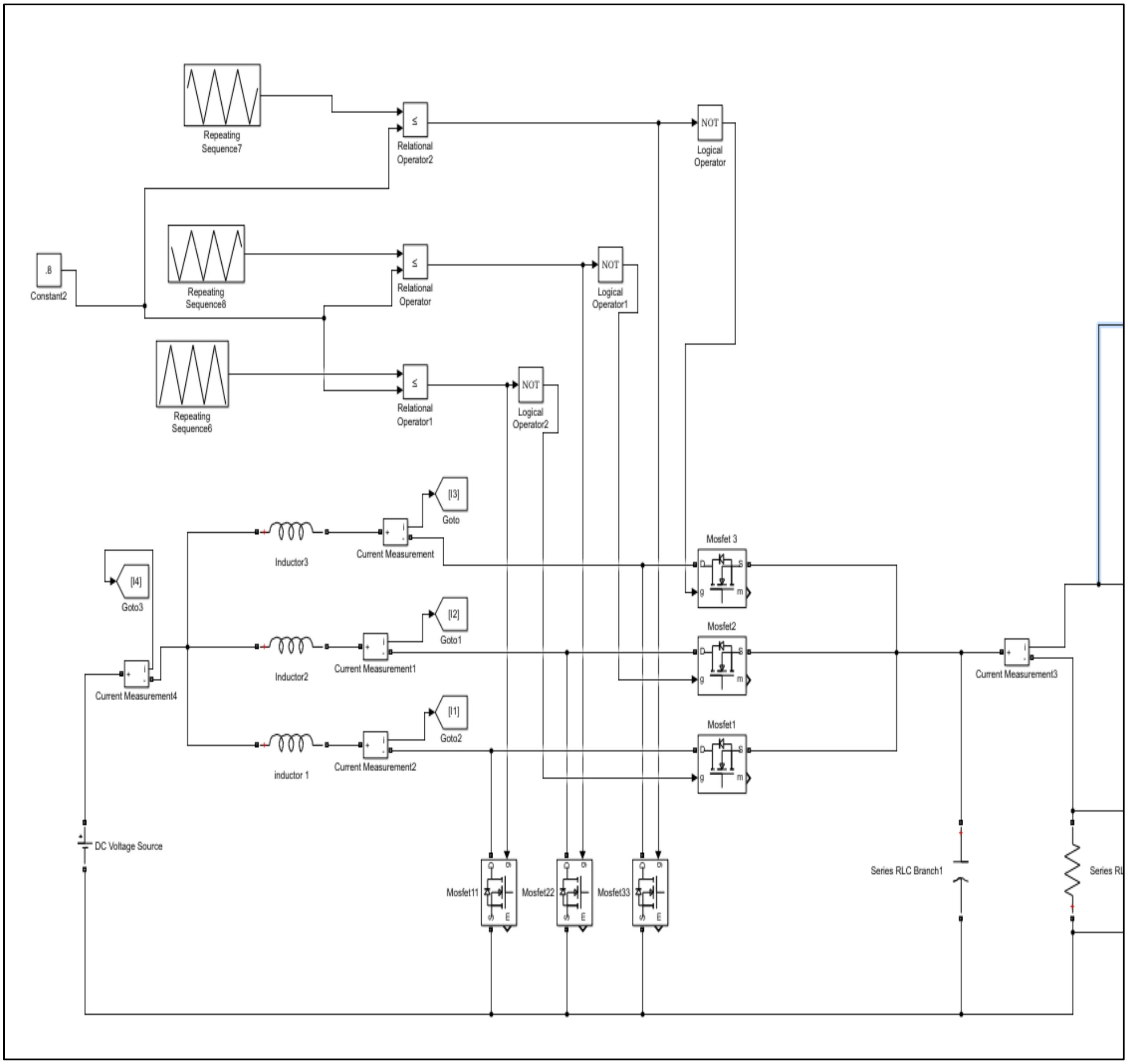

Figure 26. Three-Channel Interleaved Boost Converter

5.2.6 Description: PCB

Beside the board layout selection, components selection is another important part in PCB. The most significant parts are Inductor selection and MOSFET selection. There are two main types of inductor cores that can be chosen for the wind turbine boost converter: magnetic power core and magnetic ferrite core. The advantages of magnetic powder core are low temperature which means that can be worked in a low temperature. It also can apply to switching circuit, but the cost is more expensive than powder core. For magnetic powder core, it has a low loss at high frequency circuit, but the core needs to add some air gap to improve the efficiency. In order to obtain the output parameters, there is an inductor selection tool can help us to determine the specific value that can meet the requirements.

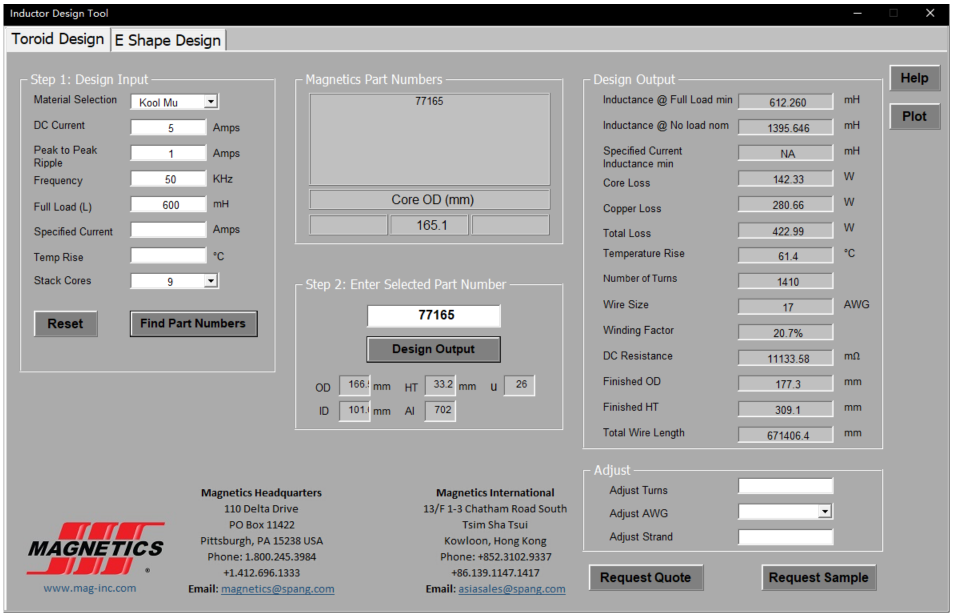

Figure 27. Inductor Selection Tool [21]

MOSFET selection, there also has a MOSFET selection tool, based on the boost converter simulation, the current and voltage can be figure out. Then the selection tool can select the correct MOSFET which can meet the requirements. The material of MOSFET is also important. For our wind turbine boost converter, there need 6 MOSFET, three of them need to use silicon-carbide, this material has a higher efficiency and frequency. Another three MOSFET can use the gallium-nitrite which is cheaper than silicon-carbide.

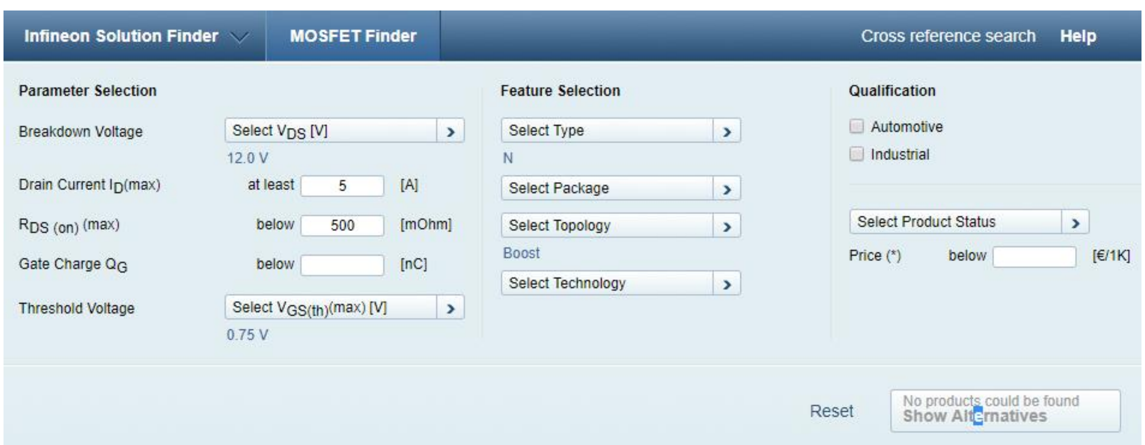

Figure 28. MOSFET Selection Tool [22]

6 PROPOSED DESIGN

Shown below in Figure 29 is the current assembly for both test teams. This assemble is just an initial collaboration from both test teams. After compiling all the part files into this assembly a few dimensional errors arose and need to be changed in the part files and recompiled. After the CAD package is compiled and completed each of the parts are going to begin being manufactured. Certain components within the assembly are going to be iterated on as much as possible to achieve the best solution for the project. From the CAD file it is also clear that how components are being connected need to be reconsidered or thought of how each component is going to be secured to each other.

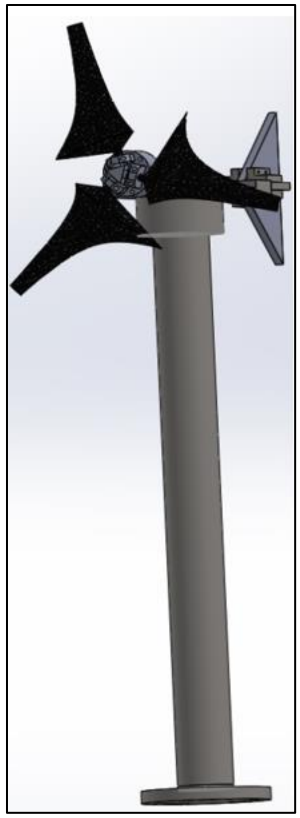

Figure 29. CAD Image of Overall Wind Turbine Design

6.1 Proposed: 3 Carbon-Fiber Blades

The material of the blades is still being determined however the current design has them as carbon fiber because of how thin the airfoils are. With the material still trying to be decided, a closer look at different material properties is needed. Shown in Figure 30 is the current airfoil and is shown in carbon fiber. Carbon fiber has a high Modulus of Elasticity but has a slow setup and production time. Different types of 3D printed/plastic materials are also being looked at. Some benefits for this type of material are its production time, and ability to create a large number of blades at one time. Some deficiencies for this type of material are voids are easily formed during printing or molding, also the low Modulus of Elasticity. The cost for a 50" wide piece of fabric per linear yard costs $17.99 but decrease if five or more linear yards are bought. To go with the fabric an epoxy resin is needed. The cost for a 3:1 two-part epoxy resin that is 1.33 gallons costs $69.99. A decision on final material will be made before the end of the semester. Early is January the material will be ordered. From January until the end of February the blades will continue to be iterated and tested. The final turbine assembly is expected to be put together and tested at the end of March and early April.

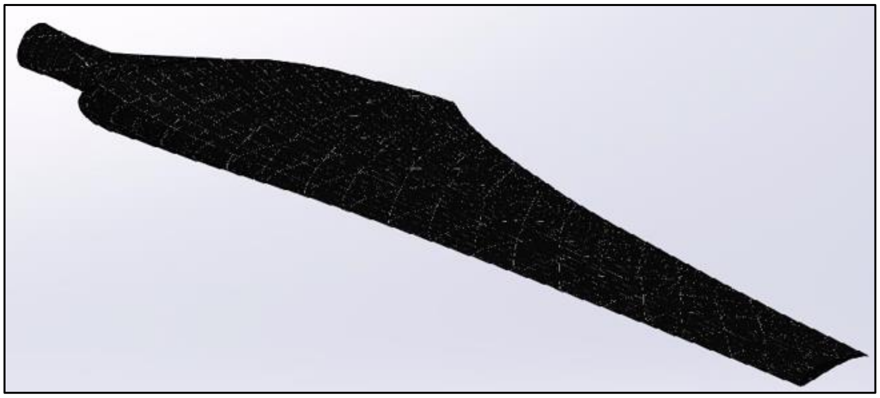

Figure 30. Current Blade Design

6.2 Proposed: Direct Drive Shaft

Aluminum was found as the best material for this design based on its pros and cons; the pros of aluminum are: low overall cost, easy to machine and low weight. There is a con of aluminum which is hard to repair in case the drive train brakes or cracks. Also, a comparison was made between different grades of aluminum, and the result turn out to be aluminum 7075 is the best one for the shaft because it's higher yield strength and ultimate tensile strength. Also, a Matlab code was created to calculate the fatigue factor of safety. This code will be used to test 7075 aluminum to check if it will satisfy this design or not; the code will be in the Appendix D. The cost of two feet of 7075 aluminum is about $30. The rod of aluminum was found from McMaster-Carr, and it will be ordered from them to be machined. The material will be ordered in the beginning of January; and it will take about two weeks to be delivered. Machining will be done upon material retrieval until a geometry acceptable for the constraints set by the wind turbine design is found (which is expected to be in early April).

6.3 Proposed: Single-Row Deep-Groove Ball Bearings

The proposed bearing designs are single-row deep-groove ball bearings with an inner ring diameter of 1cm for the drive train and a larger diameter to be determined through iterative testing for the yawing mechanism. The ball bearings are able to handle all relevant expected loads while offering a relatively low-cost price. For the drive train, one bearing will be placed near the rotor and two in between the largest drive train diameter and the generator. For the yawing mechanism, one large bearing will be placed in between the tower and the nacelle for proper rotation. The geometries of all the bearings will be tested iteratively within the load rating MatLab calculator code (shown in Appendix E) and physically to find the best fit.

6.4 Proposed: Permanent Magnet Synchronous AC Generator

For the final generator design, it will be a permanent magnet synchronous AC generator. The expected to acquire the generator is very low, only about $30 to $40. There are no components to actually be built for the generator, so next semester will consist mostly of testing the generator and generating power curves so that the team designing the blades will know what tip speed ratios and rotational velocities to design for. For the schedule, the majority of next semester (about 2-3 months) will be spent on generator testing. The rest of the time will be spent on acquiring the generator at the beginning of the semester and assembling it onto the turbine at the end of the semester.

6.5 Proposed: 3-Channel Interleaved Boost Converter

To implement the interleaved boost converter from simulation to physical hardware will require a collaboration from both teams. The first step will to gather all the required components: six gallium nitride FETS, three inductors, one capacitor, and an Arduino Nano. The next step will be to size the components and order all the parts except for the inductors. We will make our inductors based off the inductor selection design process. The inductor design selection process involves calculating the current passing through each inductor, determine a core type and the number of turns required. The three inductors will all have the same value. The next step will be to create the control theory for the FETs using the Arduino Nano. From there we will create a circuit on a breadboard and test it. Once the board has been tested and changes made if necessary. We will design our own PCB and have it printed at a location in Phoenix. The goal is to have all the testing and design done by the end of the semester and have the board ordered and printed over winter break.

6.6 Proposed: PCB Inductors and MOSFETs

For PCB design, board layout selection, inductor design, and MOSFET selection must be completed. The double-side board has a suitable size for the expected wind turbine boost converter geometrical constraints and the design can carry some surface mode components that will be needed to use in the boost circuit. For the inductor design, a magnetic powder core is the better choice than magnetic ferrite core, the two inductors in consideration. The power core can be applied to the switching circuit, and it also has a better DC bias which can improve electrical efficiency. The exact inductor can be selected using the inductor selection tools, which can figure out any output parameters that the wind turbine may need.

For the MOSFET selection, there are 6 MOSFETs that are needed for use in the boost converter circuit. For circuit functionality, 3 MOSFETs need to use silicon carbide material, because it has the highest possible efficiency from a higher frequency. The other 3 MOSFETs can implement gallium nitrite material, because these 3 MOSFETs are used to dump the voltage for voltage regulation. A high efficiency for these MOSFETs is not necessary, and gallium nitrite material is much cheaper; therefore, it is better for our team to reduce the expenses.

At the beginning of the next semester, we must order the components. Then, all the electrical engineering major team members need to build the PCB, which should take two-three weeks. Afterwards, the board will be sent to a professional manufacturer. Upon retrieval of the professionally manufactured PCB, we will test the board before implementing it onto the wind turbine. Once the test is consistently successful, we will assemble the board with wind turbine for the assembly test and then the competition in May.

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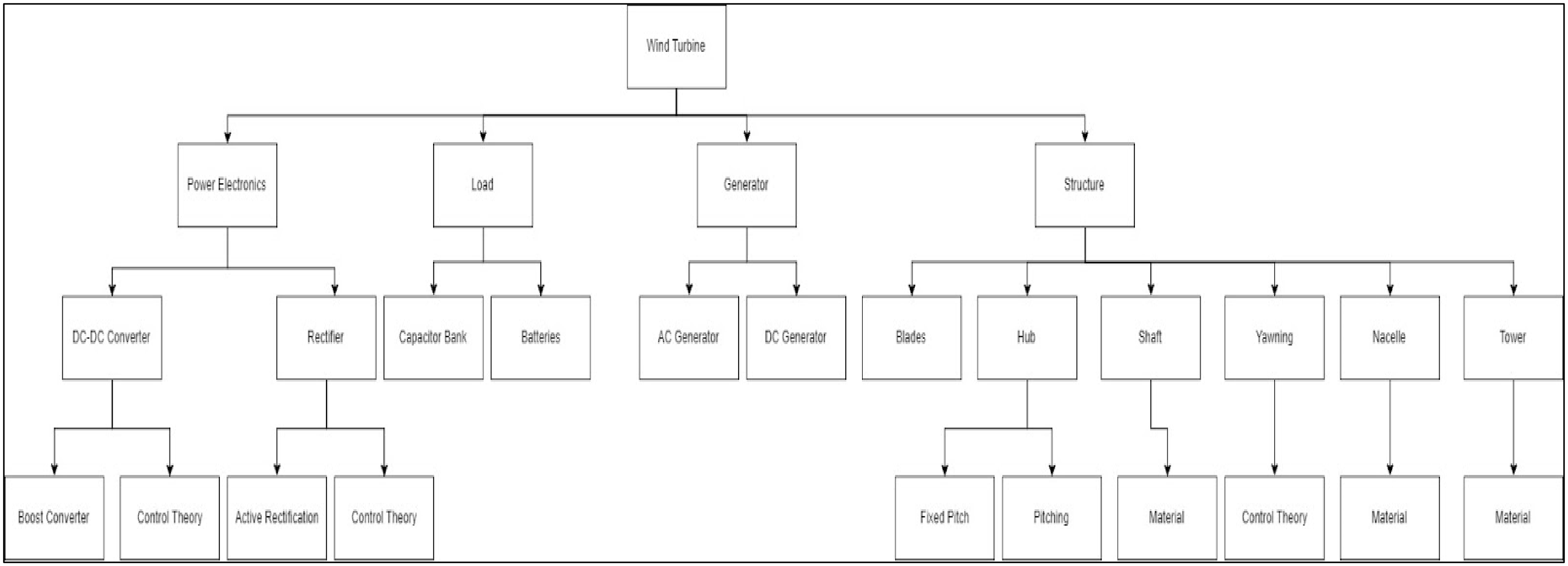
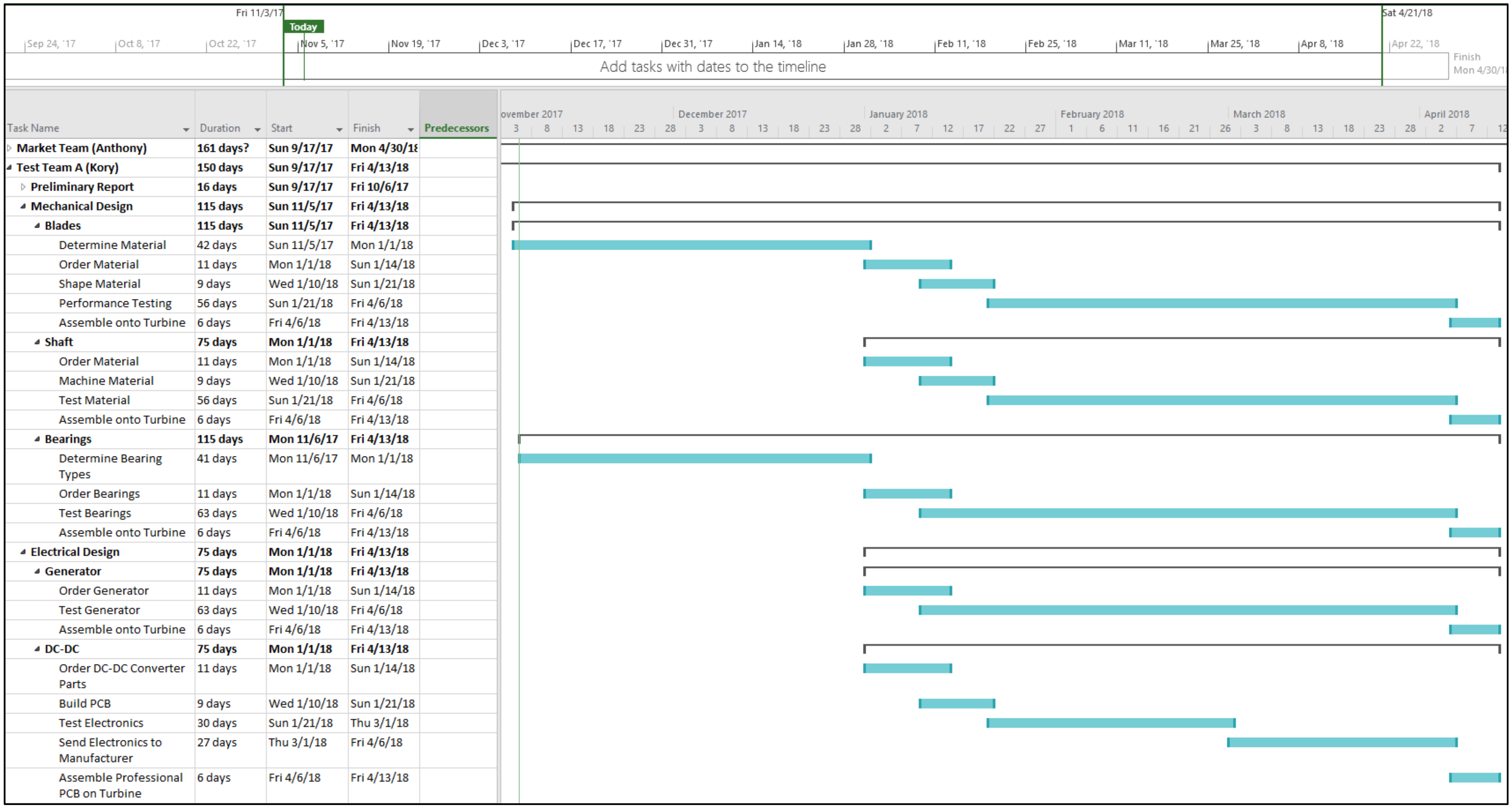
APPENDIX A: House of Quality (HoQ)

System QFD		Technical Requirements																			
Customer Needs	Customer Weights	Survivability Wind Speed (m/s)	Fit in 45cm by 45cm by 45cm cube	Fit in 61cm by 122cm Turbine Door	Electric Housing (#)	Wire and Jacket Length from Turbine Base (m)	Required Direct Current (DC) at PCC (V)	Zero State of Charge at Test Beginning (C) & (V)	Keep Under Energy Storage Rating (V)	Push Shut Down on Command (Y/N)	Blade Numbers (#)	Rotor Diameter (cm)	Power Curve Generation between 5m/s and 11m/s	Cut-in Wind Speed (m/s)	Rated Wind Speed (m/s)	Rated Power (W)	Cut-out Wind Speed (m/s)	Tip Speed Ratio (#)	Overall Efficiency (%)	Aerodynamic Efficiency (%)	Electrical Efficiency (%)
Power Generation	4.5	9	9	9	3	9	9	1	9	1	9	9	9	9	9	9	9	9	9	9	9
Electrical Gounding	1.0	0	0	0	9	9	9	9	3	3	0	0	3	1	1	1	1	0	3	0	9
Electric Wire Distribution	2.6	0	1	1	9	9	3	9	1	1	0	0	3	3	3	3	3	0	3	0	9
Transportability	4.0	3	9	9	3	3	1	0	0	3	3	9	3	3	3	3	3	3	9	9	3
Assembly	4.2	3	9	9	9	3	3	0	1	9	9	9	9	9	9	9	9	9	9	9	9
User Friendly	3.0	1	9	9	9	1	1	9	9	9	3	3	9	9	9	9	9	3	9	9	3
Safety	2.0	9	0	0	9	9	3	9	9	9	1	9	9	9	9	9	9	3	1	1	3
Durability	4.8	9	3	3	3	1	3	1	3	3	9	9	9	9	9	9	9	9	1	1	3
Maintenance	3.9	9	3	3	9	3	1	3	9	3	9	9	9	9	9	9	9	9	9	9	3
Aesthetics	2.7	1	1	1	3	1	1	0	1	1	3	3	3	3	3	3	3	3	1	1	3
Material Resources	9.0	9	9	9	9	1	3	3	3	3	9	9	9	9	9	9	9	3	9	9	9
Technical Requirement Targets Tolerance		0.5	-0.5cm	-0.5cm	0	+0.2m	-5V	C	-3V	Y	#	-0.5cm	+2W	- 2m/s	0m/s	1kW	4m/s	-2,+1	4%	-19%	5%
Technical Requirement Targets		22	Fit	Fit	≥NEMA 1	1m (2x), 2m	48V	0	16V	Y/N	2 to 4	45cm	10W	5m/s	11m/s	2kW	25m/s	7	20%	59%	90%
Absolute Technical Importance		248	254	254	279	147	131	125	175	161	269	309	314	312	312	312	312	219	278	267	253
Testing Procedure (TP#)		N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

APPENDIX B: Functional Decomposition



APPENDIX C: Gantt Chart



Task Name	Duration	Start	Finish	Predecessors
Market Team (Anthony)	**161 days?**	**Sun 9/17/17**	**Mon 4/30/18**	
Test Team A (Kory)	**150 days**	**Sun 9/17/17**	**Fri 4/13/18**	
Preliminary Report	**16 days**	**Sun 9/17/17**	**Fri 10/6/17**	
Mechanical Design	**115 days**	**Sun 11/5/17**	**Fri 4/13/18**	
Blades	**115 days**	**Sun 11/5/17**	**Fri 4/13/18**	
Determine Material	42 days	Sun 11/5/17	Mon 1/1/18	
Order Material	11 days	Mon 1/1/18	Sun 1/14/18	
Shape Material	9 days	Wed 1/10/18	Sun 1/21/18	
Performance Testing	56 days	Sun 1/21/18	Fri 4/6/18	
Assemble onto Turbine	6 days	Fri 4/6/18	Fri 4/13/18	
Shaft	**75 days**	**Mon 1/1/18**	**Fri 4/13/18**	
Order Material	11 days	Mon 1/1/18	Sun 1/14/18	
Machine Material	9 days	Wed 1/10/18	Sun 1/21/18	
Test Material	56 days	Sun 1/21/18	Fri 4/6/18	
Assemble onto Turbine	6 days	Fri 4/6/18	Fri 4/13/18	
Bearings	**115 days**	**Mon 11/6/17**	**Fri 4/13/18**	
Determine Bearing Types	41 days	Mon 11/6/17	Mon 1/1/18	
Order Bearings	11 days	Mon 1/1/18	Sun 1/14/18	
Test Bearings	63 days	Wed 1/10/18	Fri 4/6/18	
Assemble onto Turbine	6 days	Fri 4/6/18	Fri 4/13/18	
Electrical Design	**75 days**	**Mon 1/1/18**	**Fri 4/13/18**	
Generator	**75 days**	**Mon 1/1/18**	**Fri 4/13/18**	
Order Generator	11 days	Mon 1/1/18	Sun 1/14/18	
Test Generator	63 days	Wed 1/10/18	Fri 4/6/18	
Assemble onto Turbine	6 days	Fri 4/6/18	Fri 4/13/18	
DC-DC	**75 days**	**Mon 1/1/18**	**Fri 4/13/18**	
Order DC-DC Converter Parts	11 days	Mon 1/1/18	Sun 1/14/18	
Build PCB	9 days	Wed 1/10/18	Sun 1/21/18	
Test Electronics	30 days	Sun 1/21/18	Thu 3/1/18	
Send Electronics to Manufacturer	27 days	Thu 3/1/18	Fri 4/6/18	
Assemble Professional PCB on Turbine	6 days	Fri 4/6/18	Fri 4/13/18	

APPENDIX D: Shaft Fatigue Analysis MatLab Code

```
%Shaft Fatigue Analysis MatLab Code
d = input('Enter the diameter: ');
Sut = input('Enter Ultimate Tensile Strength: ');
Sy = input('Enter Yield Strength: ');
Sep = (1/2)*Sut; %S'e<1400MPa
a = 4.51;
b = -0.265;
ka = a*((Sut)^b);
kb = 1.24*(d^(-0.107));
kc = 0.59;
Se = ka*kb*Sep;
Ma = input('Ma: ');
Tm = input('Tm: ');
kt = input('kt value: ');
kts = input('kts value: ');
q = input('q value: ');
qs = input('qs value: ');
kf = 1+(q*(kt-1));
kfs = 1+(qs*(kts-1));
A = sqrt(4*(kt*Ma)^(2));
B = sqrt(2*(kfs*Tm)^(2));
ns = 1/(((8*A)/(pi()*Se*d^(3)))*(1+(1+((2*B*Se)/(A*Sut))^(2))^(1/2)))
```

APPENDIX E: Bearing Catalog Load Rating MatLab Code

```
%Bearing Catalog Load Rating code for bearing selection
%Assumptions on Report Paper apply to this code%Assumed Values
a = input('a Value for bearing: '); %Cylindrical and Tapered Roller
R = 0.99; %Reliability
V = 1; %Rotation factor
x_0 = 0; theta = 4.48; b = 3/2; %Weibell model used
a_f = input('Application Factor: ');
L_D = input('Desired Life (hrs): ');
L_R = input('Rated Life (hrs): ');
L = input('Length of Shaft (m): ');
n_D = input('Shaft Angular Speed (rev/min): ');
R_D = sqrt(R)
x_D = L_D*n_D*60/(L_R)
%Rotor parameters analysis
%Load relevant values from Rotor
Ta_R = input('Tangential Force from Rotor (N): ');
Ra_R = input('Radial Force from Rotor (N): ');
Th_R = input('Thrust Force from Rotor (N): ');
%Bearing A Load Analysis with respect to the Rotor
x1 = input('Distance from Rotor to Bearing A (m): ');
Fr_AR = input('Reactive Load for Bearing A (N): ');
%Bearing B Load Analysis with respect to the Rotor
x3 = input('Distance from Rotor to Bearing B (m): ');
Fr_BR = input('Reactive Load for Bearing B (N): ');
%Catelog Entry Analysis with respect to the Rotor
K = input('K Factor initial guess: ');
FaeR = input('External Thrust (N) from Rotor: ');
Fi_AR = 0.47*Fr_AR/K
Fi_BR = 0.47*Fr_BR/K
if le(Fi_AR,Fi_BR+FaeR)
    Fe_AR = 0.4*Fr_AR+K*(Fi_BR+FaeR)
    Fe_BR = Fr_BR
end
if gt(Fi_AR,Fi_BR+FaeR)
    Fe_AR = Fr_AR
    Fe_BR = 0.4*Fr_BR+K*(Fi_AR-FaeR)
end
C10_AR = a_f*Fe_AR*(x_D/((x_0+(theta-x_0)*(1-R_D)^(1/b))))^(1/a)
C10_BR = a_f*Fe_BR*(x_D/((x_0+(theta-x_0)*(1-R_D)^(1/b))))^(1/a)
%Brake parameters analysis
%Load relevant values from Brake
Ta_B = input('Tangential Force from Brake (N): ');
Ra_B = input('Radial Force from Brake (N): ');
%Bearing A Load Analysis with respect to the Brake
x2 = input('Distance from Brake to Bearing A: ');
Fr_AB = input('Reactive Load for Bearing A (N): ');
%Bearing B Load Analysis with respect to the Brake
x4 = input('Distance from Brake to Bearing B: ');
Fr_BB = input('Reactive Load for Bearing B (N): ');
%Catelog Entry Analysis with respect to the Brake
FaeB = input('External Thrust (N) from Brake: ');
Fi_AB = 0.47*Fr_AB/K;
Fi_BB = 0.47*Fr_BB/K;
if le(Fi_AB,Fi_BB+FaeB)
   Fe_AB = 0.4*Fr_AB+K*(Fi_BB+FaeB);
   Fe_BB = Fr_BB;
end
if gt(Fi_AB,Fi_BB+FaeB)
    Fe_AB = Fr_AB;
    Fe_BB = 0.4*Fr_BB+K*(Fi_AB-FeaB);
end
C10_AB = a_f*Fe_AB*(x_D/((x_0+(theta-x_0)*(1-R_D)^(1/b))))^(1/a)
C10_BB = a_f*Fe_BB*(x_D/((x_0+(theta-x_0)*(1-R_D)^(1/b))))^(1/a)
```