NAU NORTHERN ARIZONA UNIVERSITY

College of Engineering, Informatics, and Applied Sciences

Tunnel Turbine Technical Report

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Collegiate Wind Competition 2019

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Executive Summary

Team NAU is competing for the sixth time in the Department of Energy Collegiate Wind Competition. The 2019 team iterated on the previous year's designs with a focus on an active pitching mechanism which has yet to be successfully completed by any previous NAU team. The design constraints were derived from the competition rules and include size, power, and safety requirements.

The turbine designed by Team NAU in 2019 is a three-bladed upwind horizontal axis wind turbine that features an active pitching mechanism, passive yawing system, open nacelle with up-tower slip ring and rectifier, and buck and boost converter. In this document, the team summarized their efforts in completing the turbine design which included simulations done to evaluate the performance of the turbine, mechanical loads, and electric systems. The turbine endured thorough bench testing done for each component of the system to ensure success during full scale testing. The details of the team's yearlong effort to complete the mechanical and electrical aspects of the design are highlighted within this document. The mechanical engineer's comprehensive explanation of the technical design includes analysis of each component used for the final design of the wind turbine. A separate team of electrical engineers headed the design and production of the electrical systems for the wind turbine. The design process for the three converters is described and images of the final products are provided. A full electrical analysis was conducted to ensure cooperation between the components and verify functionality for competition. The controls and software analysis were used to determine which software would be used for the design of the turbine. Bench testing on all mechanical and electrical components demonstrated that the prototypes would perform during competition. Once all individual aspects of the design were tested, the components were connected and tested as a full system. Team NAU is still conducting testing as competition approaches. With competition quickly approaching, Team NAU is working diligently to complete all necessary testing before showcasing our complete design.

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1 Technical Design

The design objective for Team NAU in the 2019 competition was to optimize components of the wind turbine by iterating upon last year's design. The disassembly of Team NAU's previous turbine provided strong insight to the design of this year's tunnel turbine. Between faculty advising and competition rules [1], the team was able to compile a list of **Design Objectives**:

- Wind speeds up to 20 m/s
- Yaw rates up to 180°/s
- Rotor axis 60±3cm above flange
- 45-by-45-by-45 cm^3 volume cube
- Modular design
- Increased Rotor Solidity
- Integrated parts
- Reliable braking design
- Active pitching mechanism

1.1 Static Performance Analysis

The geometry of the blades was determined using the blade element momentum (BEM) theory to optimize the characteristics for discretized elements of the blade. BEM receives tip-speed ratio, blade length, ideal angle of attack, and number of blades [2]. The code was built to iterate using this theory used the inputs to determine the shape of the blade, including chord length, angle of relative wind, and twist at each section of the blade. Using a tip-speed ratio of 5, a blade length of 17cm, and an ideal attack angle of 5°, the results for blade geometry were determined and could then be exported to Q-Blade for simulations. The results that were exported to Q-Blade for the final iteration are shown in Table 1-1.

Table 1-1: Blade Geometry

Radius from root(cm)	chord(cm)	Rel. Wind direction(°)	Twist(°)
0.5	7.5	54.42	49.42
2.3	7.167	37.03	32.03
4.17	6.493	26.14	21.14
6	5.35	19.69	14.69
7.83	4.42	15.64	10.64
9.67	3.73	12.92	7.92
11.5	3.21	10.98	5.98
13.33	2.81	9.54	4.54
15.167	2.5	8.42	3.42
17	2.24	7.54	2.54

The Reynold's number for the blade geometry was calculated along the length of the blade for two primary scenarios. These scenarios were the start-up and operating conditions for the blade. The Reynold's numbers were used with resources from *airfoiltools.com* [3] to determine the airfoils that would be implemented into the blade. The team elected to incorporate three airfoils throughout the length of the blades, each having a high camber to achieve ideal lift characteristics within the low Reynold's number operating environment for the blades.

After completing the airfoil selection process, the blade geometry and airfoils were used in Q-Blade to create a 3D model to complete analysis on. The Q-Blade results showed that the turbine should output approximately 40W at an anticipated rated wind speed of 11m/s [4].

1.2 Mechanical Loads Analysis

Team NAU performed thorough Finite Element Analysis (FEA) in SolidWorks on each component of the design to achieve a safe and reliable design. As advised, the turbine was built to anticipate the failure of certain components, and therefore the turbine was designed for quick maintenance when necessary.

1.2.1 Blades

The blades were assumed to be stressed under thrust and centrifugal forces. The thrust calculation performed found that the blades achieved a thrust force of 25N. The centrifugal force of the blades was applied at an angular velocity of 5500rpm. The combined forces were applied to the blade using nylon 101 as the selected material in SolidWorks, as a substitute for the chosen carbon-fiber reinforced nylon filament. The material was chosen because it had similar strength characteristics to the filament selected by the team, aside from the modulus of elasticity. As the simulation results show in Figure 1-1, the current minimum **factor of safety is .785** due to a small stress concentration point near the blade root, circled in red in Figure 1-1. To address this concern, the team layered the printed blades with an epoxy coating, which is anticipated to increase the strength of the blades at each point. Due to the higher elastic modulus in the reinforced nylon, the team does not expect the blade to deflect to the degree that the simulation currently shows.

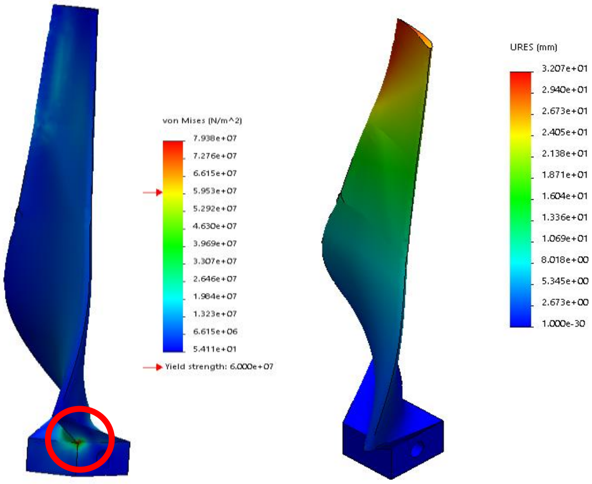


Figure 1-1: Blade FEA results

1.2.2 Hub

Each component of the hub was manufactured out of 6061 aluminum, and the FEA simulations were performed on the same material. For the hub claws, the primary force applied was the effective centrifugal force from the blades. The FEA results showed promising safety for the hub claws along with minimal deflection during operation. The minimum **factor of safety** for the claws was found to be **1.32**. The results for the claw are shown in Figure 1-2.

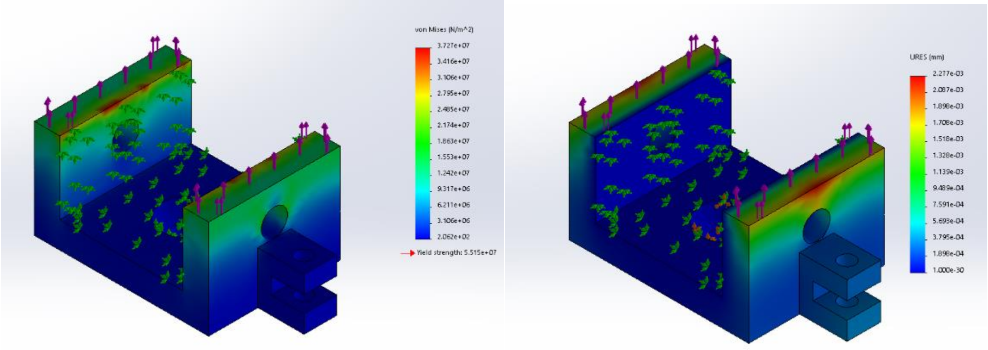


Figure 1-2: Hub Claws FEA Results

Furthermore, FEA stress and deflection analyses were completed on the main hub to determine the safety of the design. Between the claw and blade, it was estimated that the hub should withstand a maximum force of 300lbs. in the direction of each blade. The **factor of safety** of the design was found to be **1.17** for the hub at maximum rotor angular velocity. The results of the stress and deformation simulations are shown in Figure 1-3 below.

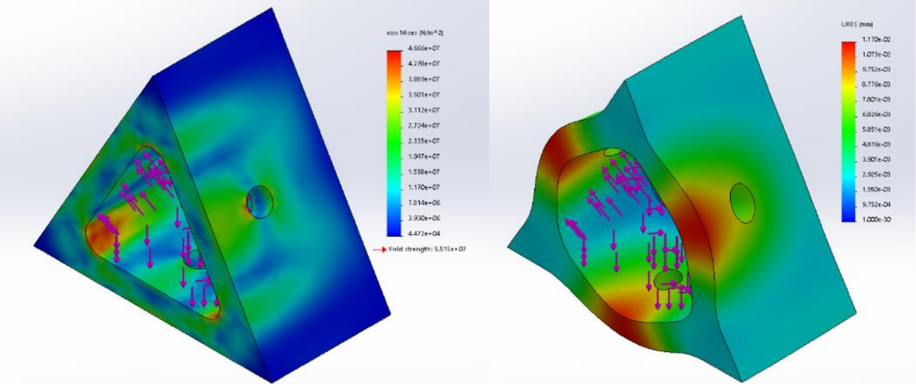


Figure 1-3: Hub FEA Results

1.2.3 Shaft

The main forces that will be seen along the shaft will be torque from the rotor and generator. Since the maximum angular velocity produced from the blades will be 5500rpm with a resulting torque of 3N-m. In order to show that the shaft design is safe enough, SolidWorks FEA was used to find out how much stress could be applied. After 5N-m of torque was applied across the shaft, it showed that the maximum stress of 351 MPa would be on the turned down section near the generator. This is most likely because it is a small diameter for a small length across the shaft. The FEA results for the shaft are shown in Figure 1-4.

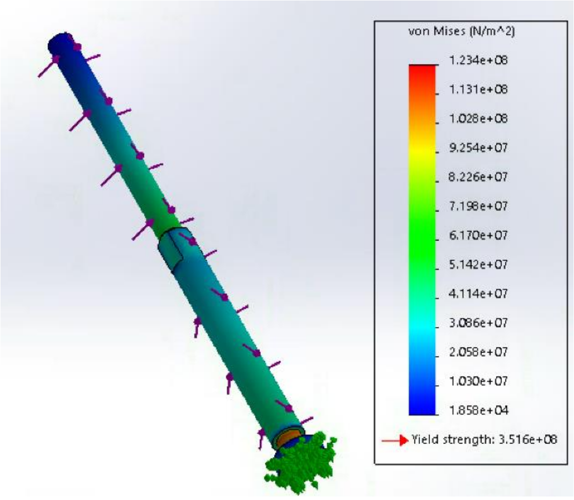


Figure 1-4: Shaft FEA Results

1.2.4 Brakes

To have a good braking system, the design was iterated on multiple times to ensure that the brakes would be reliable. The main constraints that drove the design were size, consistency, and being able to incorporate a bearing block into the design. The brake pads are standard disc brakes for a mountain bike. This was incorporated with a 6061-T6 aluminum disc, which was machined in-house. The brake pads and rotor disc were selected due to how well they work on high end mountain bikes. To incorporate this design into the turbine, a brake caliper with a bearing block was designed to hold everything in place. This was also machined out of 6061-T6 aluminum to ensure safety from the torque applied by the brake. The configuration of the brakes is shown below in Figure 1-5.

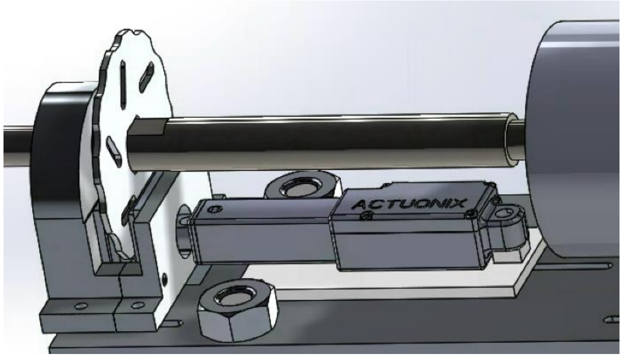


Figure 1-5: Brake Configuration

The brake force that can be applied by the linear actuator is 22N. When considering the diameter of the disc rotor and the area of the brake pads the clamping force can be estimated at 530N [5]. To ensure that the disc rotor would not sheer when that amount of pressure is applied, the actuator will gradually clamp down onto the rotor.

1.2.5 Nacelle

The nacelle was designed to house all mechanical components, as well as some electrical components. To make sure the design would be able to hold up during testing, it was machined out of 6061-T6 aluminum. A force of 35N was applied due to drag from the wind as well as the thrust force from the rotor (23N) in SolidWorks FEA. The maximum stress that is resulted from the wind and thrust is 55 MPa, which can be seen below in Figure 1-6.

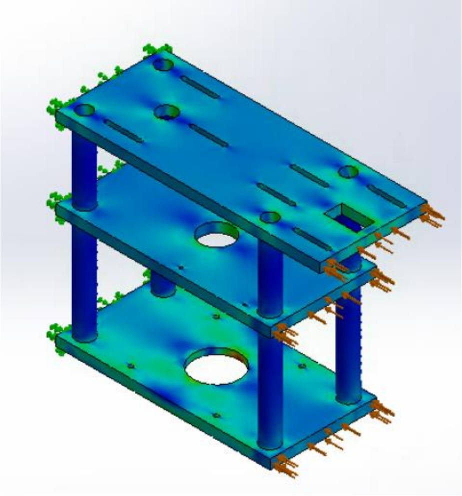


Figure 1-6: Nacelle FEA results

All the mechanical and electrical components that are mounted to the frame are using nylon insert locking nuts, star washers, and Loctite to ensure that nothing comes loose during testing.

1.2.6 Tower

During testing the tower must be able to withstand loads coming from the wind and the mechanical thrust from the blades. To ensure that the tower would be able to withstand those forces, 1018 steel was chosen. The same material was chosen for the baseplate. This would guarantee that the strength of the weldment would be equivalent on both the tower and base plate. The wind and thrust forces that are expected in the tunnel were used to calculate the yield stress, deflection, and factor of safety (shown in Figure 1-7). These results are as followed: 5.5MPa, .07mm, **46.5 factor of safety**.

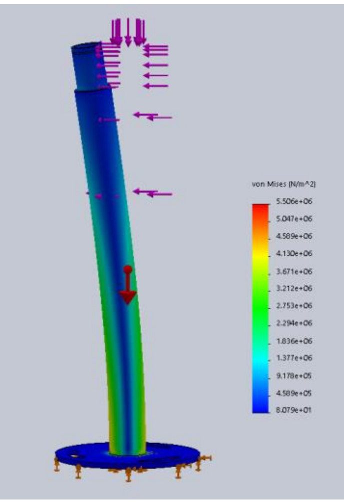


Figure 1-7: Tower FEA Results

1.2.7 Yaw System

For the competition, the yaw system is a passive system that allows the turbine to turn into the direction of the wind. For this design, a tail vane is needed to cooperate with a bearing assembly at the top of the tower.

1.2.7.1 Yaw Bearing Design

When designing the yaw bearing assembly, the main criteria was that it needed to be able to yaw at least 180º/s when in the wind tunnel. This allows for a complete change in wind direction that the turbine must adjust to. To accommodate this, two bearings with a low friction factor were used to ensure that the turbine can turn adequately. Alongside the two bearings, there is a spacer in between them to ensure the races of the bearings are not interfering with one another. An aluminum sleeve is attached to the nacelle and used as a cover for the bearings, allowing the nacelle to spin while still being supported by the tower. A figure of the design can be seen in Figure 1-8.

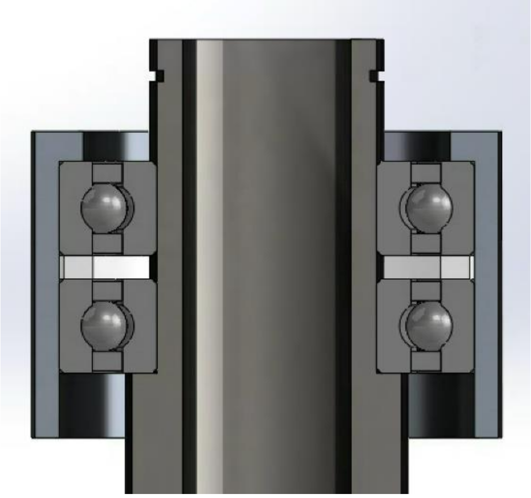


Figure 1-8: Yaw Bearing Assembly

1.2.7.2 Tail Vane Design

In order to maximize how fast the turbine can turn into the wind, it is necessary to have a tail vane with a large surface area. From this it was determined that the surface area needs to be 49cm^2. The FEA and geometry of the tail is shown in Figure 1-9.

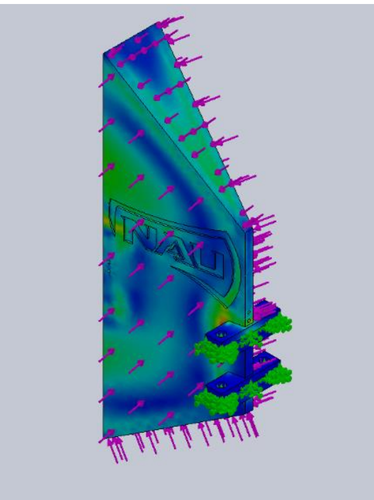


Figure 1-9: Tail FEA Analysis

2 Electrical Design

The first step in designing the converters was creating a model of each converter in Simulink. The models allowed a wide range of test voltages using different components. The simulations gave a clear picture of what components would be needed to build each converter. Below, the rectifier, buck converter, and boost converter are shown in Figure 2-1, Figure 2-2, and Figure 2-3, respectively.

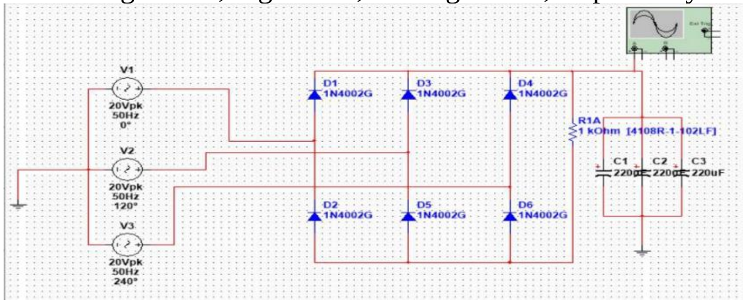


Figure 2-1: AC/DC Rectifier

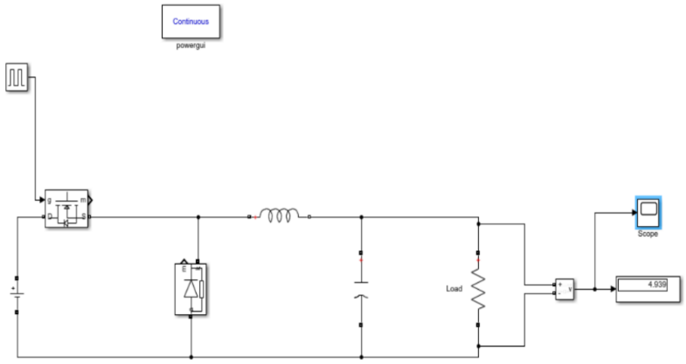


Figure 2-2: Buck Converter

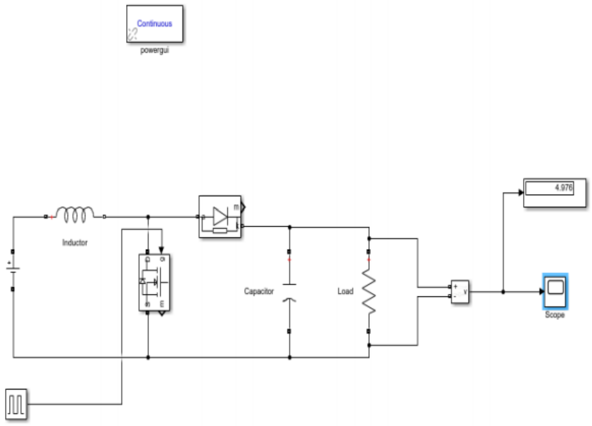


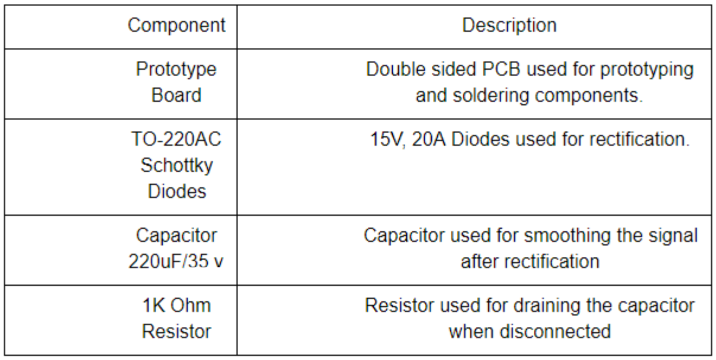
Figure 2-3: Boost Converter

Following the simulations, research was conducted to determine which components would operate under high voltage and current conditions. The components were arranged on a breadboard following the simulation diagram and tested with low voltages to verify the functionality of the circuit. The electronics were then soldered onto perf boards for higher voltage testing. The final product was soldered onto a printed circuit board for clean finish and easy replication.

2.1 AC/DC Rectifier

This passive converter consists of six high current Schottky Rectifiers, a capacitor to smooth the output signal, and a resistor to drain the capacitor when not in use. The six diodes are needed to make a three-phase rectifier. Two diodes are required for passive rectification for each phase. The rectifier works entirely passively, and all the components are soldered onto a small perf board that will be mounted up-tower to the nacelle behind the blades. The DC output from this converter will be directly connected to the input of the boost converter. In total, 5 rectifiers will be built before competition to have ready in case any components burn out during testing. While it was recommended to use a heatsink with the diodes, the team made a design decision to mount the rectifier up-tower to cool the diodes convectively. The diodes are designed to withstand up to 130 °C. During testing, the diodes never exceeded 100 °C. Although the diodes may not work at maximum efficiency at higher temperatures, the team decided a smaller, more compact rectifier would best suit the design. The specifications for the rectifier are shown below in Table 2-1, and the built rectifier is shown in Figure 2-4.

Table 2-1: AC/DC Rectifier



Component	Description
Prototype Board	Double sided PCB used for prototyping and soldering components.
TO-220AC Schottky Diodes	15V, 20A Diodes used for rectification.
Capacitor 220uF/35 v	Capacitor used for smoothing the signal after rectification
1K Ohm Resistor	Resistor used for draining the capacitor when disconnected

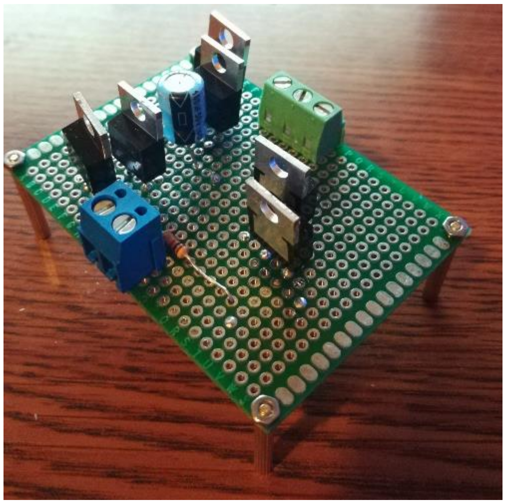


Figure 2-4: Rectifier

2.2 DC/DC Boost Converter

Testing showed that the generator and rectifier produced up to 5V while operating under 1000 RPM. The boost converter is designed to accept an input voltage between 1 and 5 volts and boost that to a voltage higher than 5V. The duty cycle is controlled through the Arduino and will always boost the voltage above 5V but never exceed 25V. The board depicted below as Figure 2-5 has a buck and a boost converter. The relays are used to switch between the converters depending on the input voltage. When under 5V the input goes to the boost converter and when over 5V the buck converter receives the input voltage. The screen displays the input voltage, output voltage, and which converter the input voltage is going to. The screen will most likely be removed before competition which is why there are also LEDs to determine which mode the circuit is operating in. The DC/DC Boost Converter specs are summarized in Table 2-2, while the constructed converter is shown in Figure 2-6 [6].

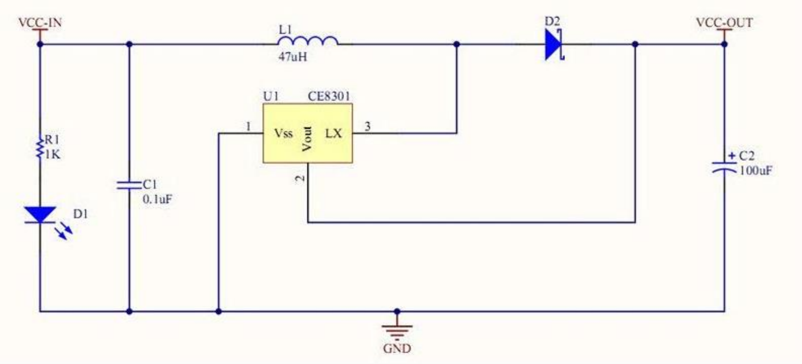


Figure 2-5: DC/DC Boost Converter One Line Diagram

Table 2-2: DC/DC Boost Converter

Comment	Description	Designator	Footprint	LibRef	Quantity
0.1uF	Capacitor	C1	0805	CAP	1
100uF	Polarized Capacitor (Surface Mount)	C2	CAP_6_5	Cap Pol3	1
LED	Typical INFRARED GaAs LED	D1	LED-0805	LED	1
	Schottky Diode	D2	SS14	D Schottky	1
47uH	Inductor	L1	INDUCTOR_6_5	Inductor	1
1K	Semiconductor Resistor	R1	0805	RES	1
CE8301		U1	SOT89L	CE8301	1

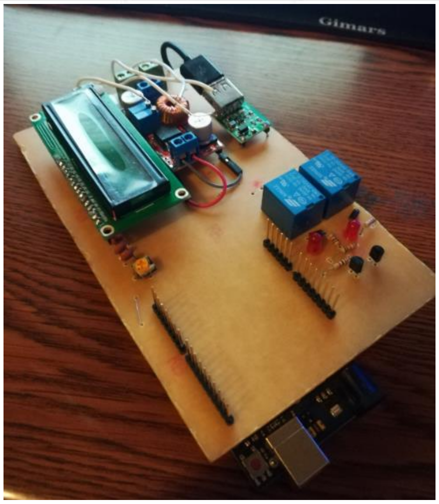


Figure 2-6: DC/DC Boost Converter

2.3 DC/DC Buck Converter

The buck converter accepts an input voltage between 5 and 25 volts. The Arduino adjusts the duty cycle to always produce a 5V output. The components for the buck converter are built to withstand up to 20A. The team experimented with many different components and were not able to get the desired results. For this reason, a pre-built buck converter was purchased and modified to suit the needs of competition. The modifications for the buck converter limited the current going into the converter with resistors and current limiting diodes. The specs for the pre-built buck converter are shown in Table 2-3 [7].

Table 2-3: DC/DC Buck Converter

Component	Description
XL4015	DC/ DC 180-KHz Buck Converter, 5 A/36 V
M7	SMD version of 1N4148 Diode
HSN3631AS	Numeric Three-Digit LED Display,
LM317	Adjustable Voltage Regulator
SS54	Schottky Diode 40 V/5 A
47 uH/5 A	Power Inductor
50K MT	Multi-Turn Preset Potentiometer 50K
LED	Indicator light
Capacitor 220uF/35 v	Capacitor used for smoothing the signal
Capacitor 100uF/50 v	Capacitor used for smoothing the signal

3 Electrical Analysis

The first component of power electronics in contact with the generator is the AC/DC rectifier. The generator is activated by spinning the blades of the turbine which will produce wild, three-phase AC voltage. This variable voltage will go directly into a passive rectifier designed to produce a steady DC voltage. The Schottky Rectifiers are designed to withstand up to 200V and 15A. While testing the rectifier on a closed circuit, the voltage never reached greater than 20V and 11A at maximum expected angular velocities. The Schottky Rectifiers reach temperatures up to 75 °C while in use. To avoid mounting a heat sink to the converter, the rectifier will be mounted up-tower directly behind the blades making use of air flow as effective convection medium. The rectified DC voltage is smoothed through a capacitor and deposited into the DC/DC boost converter. The boost converter is designed to accept an input voltage between 1 and 5 volts and output a voltage greater than 5V. The boost converter will be active while the generator is spinning under 1000rpm. Once the input voltage is greater than 5V, a relay is used to send the input voltage into the buck converter. The DC/DC buck converter is designed to accept an input voltage between 5 and 25 volts. The buck converter is controlled through an Arduino Uno that adjusts the duty cycle to produce a constant 5V output.

4 Controls Analysis and Software Documentation

The electrical engineering team started by creating simulations of the converters that would be designed for competition. Using Simulink, the three converters were designed and analyzed for what components would need to be purchased for the building of the converters. Once the parts were purchased and the circuit was built, the electrical engineers coded the Arduino Uno to produce the expected output from the system. There are two Arduino Uno's used throughout the entire system. The first Arduino is used to control the brakes and active pitching mechanism. The second Arduino is used to control the buck and boost converters which adjusts the duty cycle of the converters to produce the correct output. The brakes are controlled by a linear servo that actuates under two conditions, when the button is pressed or when there is a loss of power from the PCC. The pitching mechanism is controlled by an Arduino that activates two actuators based on voltage sensed from the voltage divider.

5 Testing

Team NAU performed bench testing throughout the design process to ensure that each subsystem would operate efficiently when integrated into a full-scale test.

5.1 Generator

The generator was tested alongside an AC/DC rectifier. A dynamometer was used to apply rotation to the generator and the rectifier received the input voltage from the three-phase generator. The generator had a known KV rating which was tested through an open circuit. By applying an increasing rotational speed to the generator, the KV rating was verified. During this test, the input voltage and amperage were recorded.

The team initially gathered data to ensure that the motor would provide ideal power characteristics using a commercial rectifier. After applying loads to the generator/rectifier set-up, power calculations were carried out to verify that the generator would not limit the team's capability of producing power. The plots of theoretical power output from the blades and bench testing are shown in Figure 5-1. Also shown in the figure is the first iteration of handcrafted rectifier to compare with the commercial rectifier originally tested.

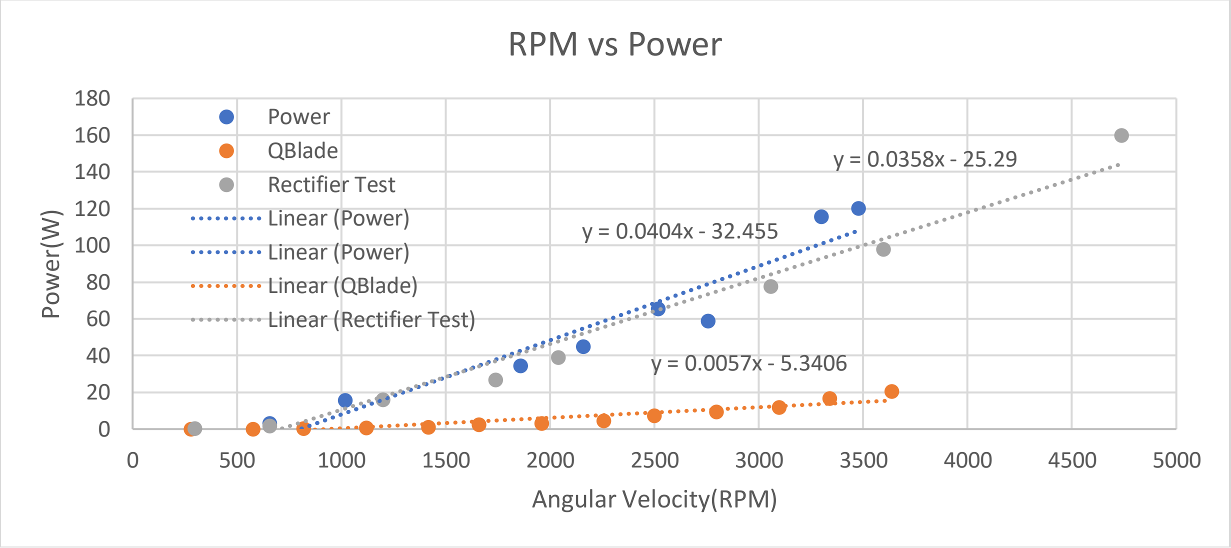


Figure 5-1: Generator Power Capabilities vs. Blades' Theoretical Output

5.2 Arduino

Arduino coding was the primary medium for Team NAU’s coding. Arduino was used in the power electronics algorithms and linear actuation for the active pitching mechanism and braking system.

5.3 Linear Actuators

A total of three linear actuators were used in the design with Arduino to perform the desired tasks in a simple way. One actuator was used for the brake system, and two are used in the active pitching mechanism with a modified remote control (RC) helicopter swashplate. For bench testing the pitching mechanism, the team wired the two actuators with a breadboard, Arduino, and input signal via button press. This bench testing is completed to ensure that the two actuators are extending and retracting simultaneously without binding the swashplate while the hub rotates. After completing bench testing with a button press, the algorithm was modified to pitch the blades automatically by using logic statements that could be easily modified for full-scale testing. For the operation of the turbine, the Arduino Uno board is programmed to pitch based on a voltage reading from the rectifier. This voltage will allow the algorithm to quantify the angular speed of the rotor and adjust the blades’ pitch angles appropriately. One Arduino Uno board will be used for both pitching and braking systems. Per competition requirements, the turbine’s brake system operates via button press and from the discharge of a capacitor when the turbine is disconnected from the PCC.

5.4 Rectifier

The rectifier was tested on both an open and closed circuit by using a dynamometer. The open-circuit test determined the maximum voltage expected, while the closed-circuit test verified the components could maintain functionality with increased amperage. The custom-built rectifier was tested against a pre-built rectifier and the results were nearly identical. The dynamometer testing set-up is shown in Figure 5-2.

Figure 5-2: Rectifier Testing

5.5 Boost Converter

The components of the boost converter were first tested using a breadboard with a low input voltage. The Arduino was used to measure the output voltage and adjust the duty cycle depending on the input voltage. The components were then soldered onto a perf board for higher voltage testing. The Arduino code was adjusted to always boost the input signal above 5V but never exceed 25V. Using a DC power supply, the boost converter was tested at a multitude of input voltages and the outputs were recorded.

5.6 Buck Converter

The testing procedure for the buck converter was identical to the boost converter. The Arduino regulated the duty cycle to always produce an output of 5V with an input between 5 and 25 volts. The buck converter was tested between its operating input range and the output was verified to always be 5V.

5.7 Entire Electrical System

The entire electrical system was tested using the dynamometer. The generator was hooked up to the rectifier. The output of the rectifier went into the boost converter. The output of the boost converter then went into the buck converter. The converter outputs were measured and recorded using a multimeter.

5.8 Mechanical Testing Procedures

The brakes have been bench tested using Arduino and all machined parts. To make sure the linear actuators can be tested repeatedly and produce the same results, there were 10 tests completed to show how much force it could apply. The results can be seen in Table 5-1 below.

Table 5-1: Brake Testing Results

Linear Actuator (g)	Linear Actuator (N)
2090	20.482
2044	20.0312
2130	20.874
2295	22.491
2122	20.7956
2262	22.1676
2291	22.4518
2390	23.422
2243	21.9814
2260	22.148

The actuator was tested using a kitchen scale that read out in grams which could then be converted into Newtons. This averaged out to be 21.68N which is just below the rated force of 22N. The braking actuator was proven by the test results to be good enough for full-system integration. This year's team made the braking system a priority to capitalize on previous team's mistakes. This was due to the brakes not disengaging from the caliper completely when the releasing clamping force. This year's design can repeatedly actuate a consistent distance without lack of disengagement.

5.9 Future Testing

Team NAU is currently manufacturing a mounting surface for a Subaru roof rack to complete field testing. At the time of submission for this report, the team was unable to complete any tests in a controlled environment due to the anticipated wind tunnel being out of commission. During testing that will take place following the submission of this document, the team will be simulating a competition run via car-mounted tests outside of city limits to ensure safety. The team is also creating a stand for an anemometer to verify the wind speeds being applied to the turbine to allow the team to tune the electronics properly. The electrical components' wires will be run into the vehicle for testing and control of the braking mechanism. After ensuring that the turbine will be capable of performing the mandatory tasks at low winds, further testing will be done at higher wind speeds to evaluate the durability of the design.

6 References

[1] C. W. Competition, "Rules and Regulations document," National Renewable Energy Laboratory, Boulder, Colorado, 2019.

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Appendix A

Appendix A-1: Exploded View