

Brigham Young University  
2021 Collegiate Wind Competition

Technical Design Report

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# 1 Executive Summary

This report was written on the challenges and successes made by the Brigham Young University Wind Energy Team. BYU applied and was accepted for the first time in the 2021 competition. Being a first year team presented many challenges as well as advantages to our team. This competition has provided the team with excellent opportunities to grow and learn. We have been exposed to the world of wind energy and have worked diligently to be able to contribute to the industry's further growth.

Challenges with being a first year team can be difficult. We had to start from the beginning and construct the tower and nacelle, parts that other teams had previously constructed and our future team will be able to reuse. We had little experience pertaining to the specific project to base our design on. However, with the challenges comes advantages. The teams that started from earlier collegiate wind competitions have made large improvements to their designs over the years. BYU's team used previous team's research to plan, design, and construct a turbine that is fit to compete in this years competition.

We were presented with new challenges this year due to COVID-19 protocols. Team meetings were virtual when possible. We divided our team into four small subgroups to avoid large groups and the risk of transmission. Having separate subgroups helped us comply with COVID guidelines as well as delegate the work appropriately. The subgroups included Mechanical, Generator, Controls, and Blade teams. Interfacing between subgroups was difficult and therefore effective communication was necessary to ensure that a piece that was constructed by one subgroup would be compatible with the others. To avoid problems, we held weekly virtual meetings and shared files containing design plans. At times, members of each team worked on projects for other subgroups to ensure the entire team was working towards the same goal.

Throughout the process our design progressed and changed as experimental results revealed where we could improve. For example, throughout the year we held mock competitions to evaluate our progress. At our first competition the cut in wind speed of our turbine was around 7.5 m/s, which was not satisfactory for our design. We decided to add a second set of blades and a rear generator with a lower startup torque which allowed us to drop our cut-in speed considerably to score more points in the competition.

We have learned to be more innovative engineers throughout the process. Most of the team is graduating but would agree that this project has been one of the highlights of our college career. We would like to thank the DOE and NREL for sponsoring this project and making it possible for us to grow our interest and skills in wind energy.

## 2 Introduction

The U.S. Department of Energy Collegiate Wind Competition challenges interdisciplinary teams of undergraduate students from a variety of programs to offer a unique solution to a wind turbine project; providing each student with real-world experience as they prepare to enter the wind industry workforce. This is the first year that BYU has been accepted to compete in the competition, and as such will be paving the way for future teams of BYU students to participate in the following years.

Although COVID-19 restrictions resulted in most meetings being online we were still able to communicate effectively so that our subsystems interacted and interfaced correctly. While the competition has been revised throughout the year our objective has always been the same. As a team our goal was to design and build a unique turbine that would earn the maximum number of points in the competition. Being a first year team we had to build everything from the start and catch up with the incumbent winners and other competitors. We based our objectives on competition requirements. Changes in our design were made in order to accrue more competition points.

## 3 Description of Design

The wind turbine that we designed is a dual rotor horizontal axis wind turbine (HAWT). The design features two sets of turbine blades, each connected to its own generator (see Fig. 1). The entire turbine can be divided into four subsystems, blades, mechanical systems, generators, and control systems. We will briefly describe the function and components of each of these subsystems.

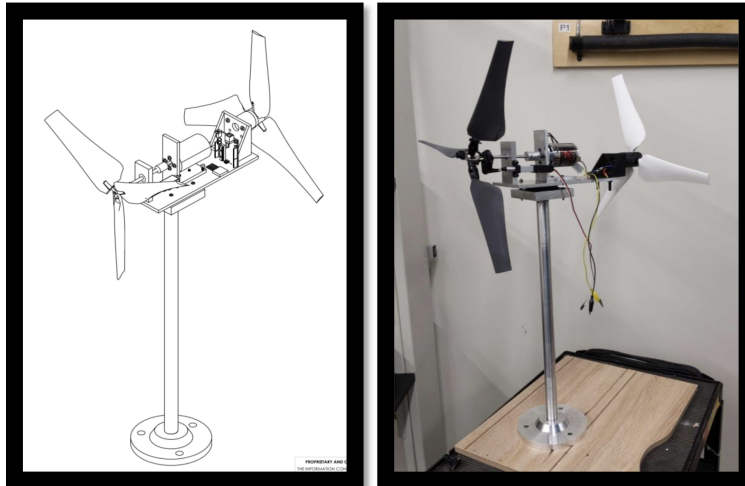


Figure 1: Side-by-side comparison of the model and physical prototype.

### 3.1 Generators and Power Electronics

From researching past reports of previous winners in the CWC we considered designing and building our own generator, however, it took some time to get our first running prototype, therefore we decided to purchase the Antigravity 5006 KV300 brushless motor that had the characteristics we were looking for in a generator with a kv of 300. A kv of 300 matches well with the optimal tip speed ratio of our blades which is designed to be around 3 (see Fig. 2).

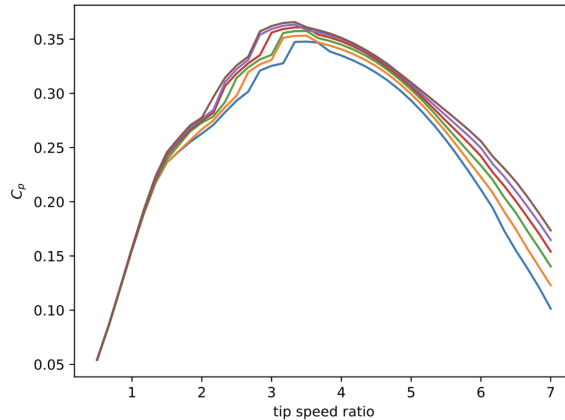


Figure 2: Coefficient of power associated with different tip speed ratios of the blades.

However, due to the primary generator’s higher starting torque, our wind turbine design also features a secondary generator which produces power during the cut-in wind speed portion of the competition. The 480 Outrunner KV960 brushless motor was chosen for the secondary generator because of its low starting torque characteristics. The low starting torque allowed for our wind turbine to begin rotating and generating power at 3 m/s.

The secondary generator will be the sole source of power generation during the cut-in wind speed portion of the competition and will run until the primary motor begins to generate power. Both generators pass through individual rectifiers which effectively convert the AC generated power to DC. After passing through the rectifier, the current passes through a variable load circuit which offers several different load resistances that the control system can use to maximize power output at different stages of the competition. A schematic of our turbine’s electrical architecture can be seen in Fig. 4.

When the resistance is high the blades rotate free but can’t provide the torque necessary to generate high power, and when the resistance is low the blades rotate slowly and aren’t able to create enough momentum to generate high power. We tested multiple resistances to the load for different wind speeds to find patterns in optimal resistances (see Fig. 3). When testing with a previous primary generator (Turnigy Aerodrive SK3 brushless motor) we noticed that the optimal resistance range was around 1.5 to 2.5 ohms. From 7 m/s to 10 m/s there seems to be a different optimal resistance for each wind speed. At 10 m/s the precision of the resistance value is important because being off by 1 to 2 ohms can result in a decrease of about 2 watts. We didn’t have resistances available in the 1.5 to 2.5 ohm range, therefore we designed the variable load controller to be able to put some resistances in parallel to get more values in the 1.5 to 2.5 ohm range. Using our current generator we reran the same test and found optimal resistances around 5.877 ohms. The variable load controller consists of a relay that controls six channels. When one of the channels in the relay is turned on then the electricity from the generator can flow through the resistor connected to that channel. By turning on a combination of resistors we are able to control the resistance more precisely.

Nearing the end of our final prototype we weren’t able to fully troubleshoot the resistance optimization portion of the code and instead set the optimal resistance to 5.877 ohms. However, next year we expect to invest more time in the optimal resistance strategy in order to maximize power generation.

We originally had planned to design our own rectifier, but since this is our first year and we were

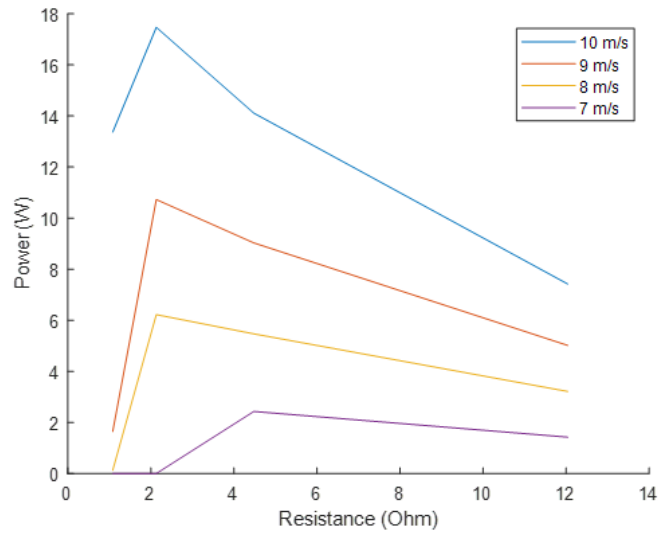


Figure 3: Power measured for different resistances to the load for different wind speeds using the Turnigy Aerodrive SK3 brushless motor.

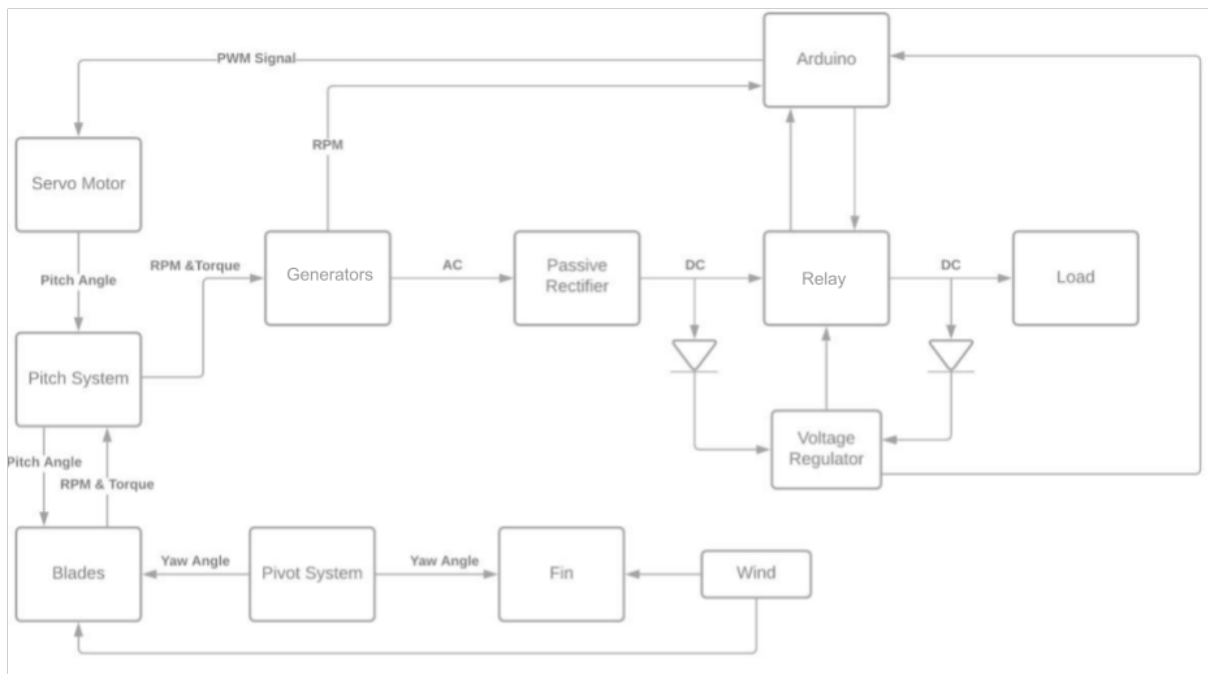


Figure 4: Illustrates the interfaces between subsystems and how the entire system interacts.

limited on time we decided to purchase and test rectifiers. Our test involved using our rectifiers with different loads. To perform this test, we used a voltmeter attached to our turbine prototype which was attached to our Variable Load Circuit and rectifier (small: IXYS FUS45-0045B, large: Micro Commercial3GBJ3516-BP). We used an oscilloscope to measure the voltage ripple.

The objective of this test was to test the big rectifier and the small rectifier against the following resistor loads: 4 ohms, 12 ohms, 26 ohms, and 46 ohms. Then calculate the power in Watts that

each of these combinations outputs (see Fig. 5).

<b>Big Rectifier</b>				
Voltage (V)				
	4 Ohm	12 Ohm	26 Ohm	46 Ohm
7 m/s	0.5	0.92	1.11	1.3
8.5 m/s	0.83	1.43	1.7	1.93
10 m/s	1.15	1.98	2.34	2.56
<b>Power (W)</b>				
	4 Ohm	12 Ohm	26 Ohm	46 Ohm
7 m/s	0.06	0.07	0.05	0.04
8.5 m/s	0.17	0.17	0.11	0.08
10 m/s	0.33	0.33	0.21	0.14
<b>Small Rectifier</b>				
Voltage (V)				
	4 Ohm	12 Ohm	26 Ohm	46 Ohm
7 m/s	1	1.46	1.79	2
8.5 m/s	1.4	2.01	2.43	2.65
10 m/s	1.77	2.52	3.04	3.29
<b>Power (W)</b>				
	4 Ohm	12 Ohm	26 Ohm	46 Ohm
7 m/s	0.25	0.18	0.12	0.09
8.5 m/s	0.49	0.34	0.23	0.15
10 m/s	0.78	0.53	0.36	0.24

Figure 5: Voltage and calculated power of the small and large rectifier across varying wind speeds and loads.

Our results in Fig. 5 indicate that the small rectifier (IXYS FUS45-0045B) is by far a better choice for power generation with almost twice the power generated compared to the large rectifier.

### 3.2 Blades

The main objective of our blade design was to provide the optimal torque to the generator in the range of wind speeds we would be operating in. In order to effectively fulfill this objective we modeled and designed blades in QBlade and CCBlade. QBlade is an open source wind turbine blade design software that we initially used to gain a general idea of how to design wind turbine blades. Once we gained a good understanding of important design variables we started using CCBlade, open source code from the BYU FLOW Lab that uses a blade element momentum method for designing wind turbine blades. The reason we switched from QBlade to CCBlade is because CCBlade can be incorporated into a process where we can use optimization methods for the design of the blades.

Penn State, the 2019 winners, provided a large amount of assistance in our blade production. For the First half of the year we used a blade that we reverse engineered from the Penn State blade. This allowed us to make large steps forward with our generator and controls without knowing a lot about turbine blades. We did eventually arrive at our own design seen in Fig. 6.

The turbine design includes two identical sets of blades for the primary and secondary generators. The primary blades are positioned on the upstream side of the nacelle while the secondary are positioned on the downstream side of the nacelle. Each rotor features three blades which were designed for the Reynolds numbers expected in the competition. The front blades drive the primary generator and produce most of the power during normal operation. The rear blades drive the secondary generator which only generates power from wind speeds between 3.0 m/s and 5.0 m/s. The blades are optimized to operate at a specific tip speed ratio (TSR) of about 3 which is the ratio of incoming wind speed to tangential speed of the blade tip (see Fig. 2).

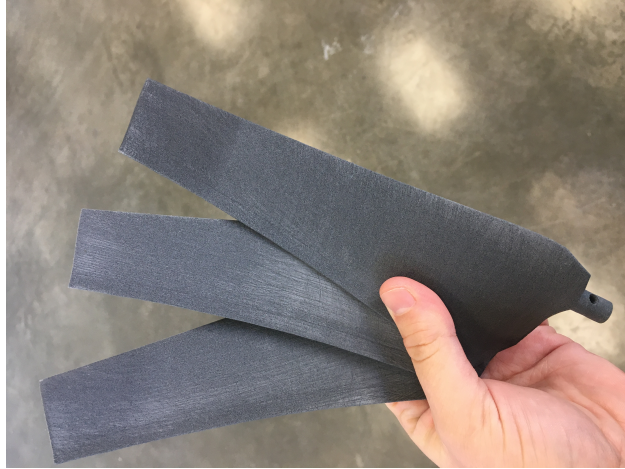


Figure 6: Current design of blades.

Figure 8 shows how the blade design fits well with the pitching system. In all of our testing the blades were able to deal with wind speeds up to 14 m/s. However, one time when we were testing the rated power function at 14 m/s and the blades broke off and shattered. We found that the blades broke at the point of connection to the pitching system. Figure 7 shows that there were several cracks that slowly propagated over time that eventually led to the failure in the blades.

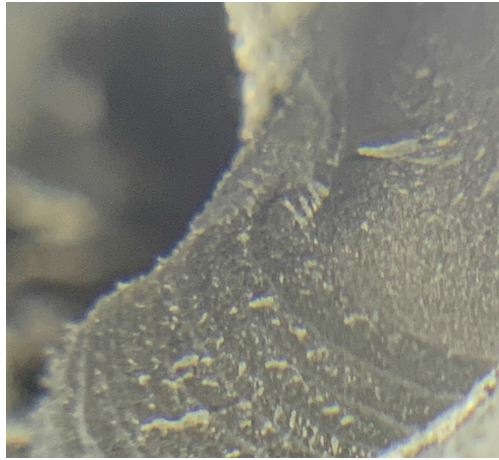


Figure 7: Closeup of where the blades failed.

The blades since have been designed to have a more fortified connection with a tighter fit and smaller through hole for the bolt that connects it to the pitching system. The previous wind turbine prototype had a slightly bent shaft which could have also led to uneven loading on the blades and caused cracking over time, especially when the blades were spinning at their optimal tip speed ratio. Our current prototype has a new shaft made of hardened steel which will reduce any vibrations and bending that can create cracks.

### 3.3 Control System

An Arduino Uno controls the several operations on the turbine by sensing the rpm of the main generator and voltage across the load. The Arduino uses the readings of rpm and voltage to

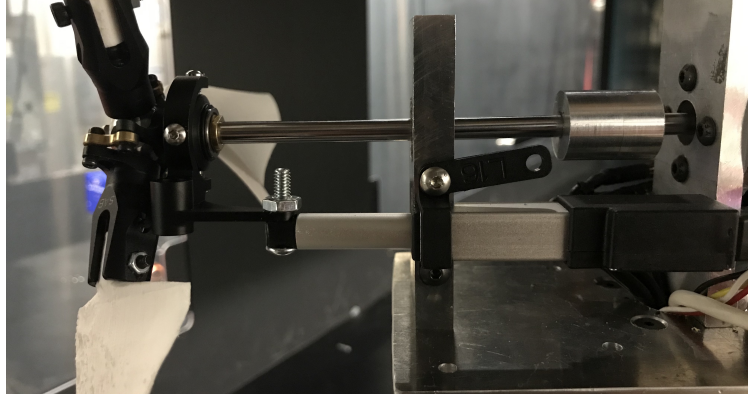


Figure 8: Assembled pitch system with blades, shaft, and linear actuator.

understand what pitch angle in the front linear actuator is needed for the front turbine, when to trigger the linear actuator brake for the back turbine, and what value to change the resistance of the load to. Figure 9 shows a wiring diagram of how we tested our controls while the wind turbine prototype was still being assembled and designed.

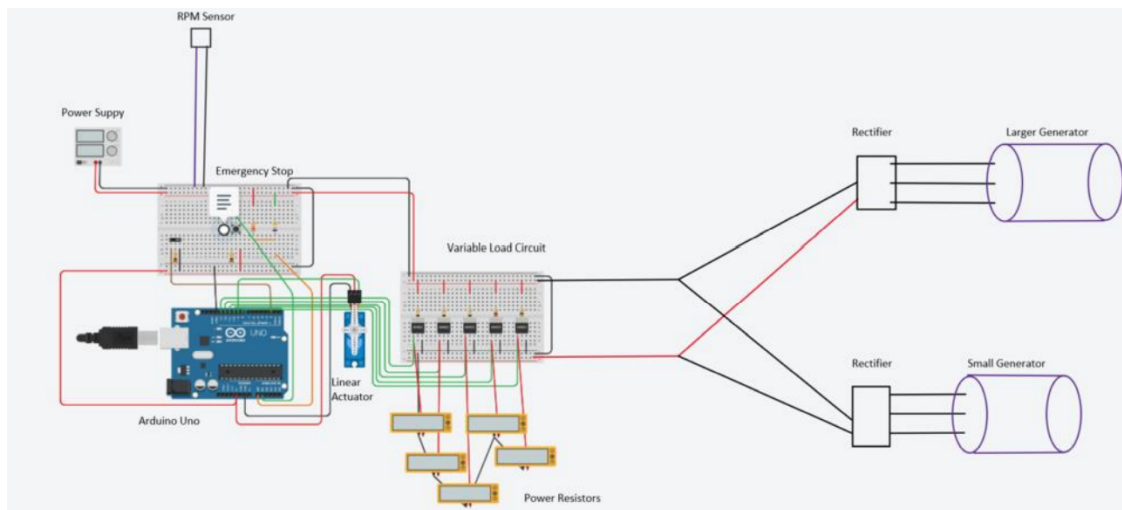


Figure 9: TinkerCAD simulation of electrical components.

At the beginning of the competition when power output is zero, the controller uses a relay switch to open the path from the secondary motor to the load. The pitch of the front blades are then periodically changed during the cut-in wind speed task. When testing to find our cut-in wind speed we noticed that if we moved the pitch of the blades back and forth we were able to achieve a lower cut-in wind speed. Therefore the front blades are pitched back and forth until they start spinning. When the wind speed reaches about 5 m/s the primary generator begins to rotate and the Arduino senses this with the rpm sensor. The signal from the rpm sensor spikes every time it sees a piece of reflective tape attached to the generator. When the rpm sensor senses an rpm above 50 the Arduino uses the relay to close the path from the secondary motor to the load and opens the path from the main generator to the load. With wind speeds between 5 m/s and 11 m/s the controller sets the pitch angle to the optimal pitch angle, turns on the brake for the secondary generator, and sets the load resistance to the optimal load resistance of 5.877 ohms. With wind

speeds above 11 m/s the controller uses PID and pitches the blades to maintain a constant power output. At any wind speed the controller provides an emergency stop (Estop) function. When the Estop button is pressed, the controller will pitch the blades to make them parallel to the wind direction and turn on the lowest resistance which effectively slows rotation to below 10% of the operational speed within 4 seconds.

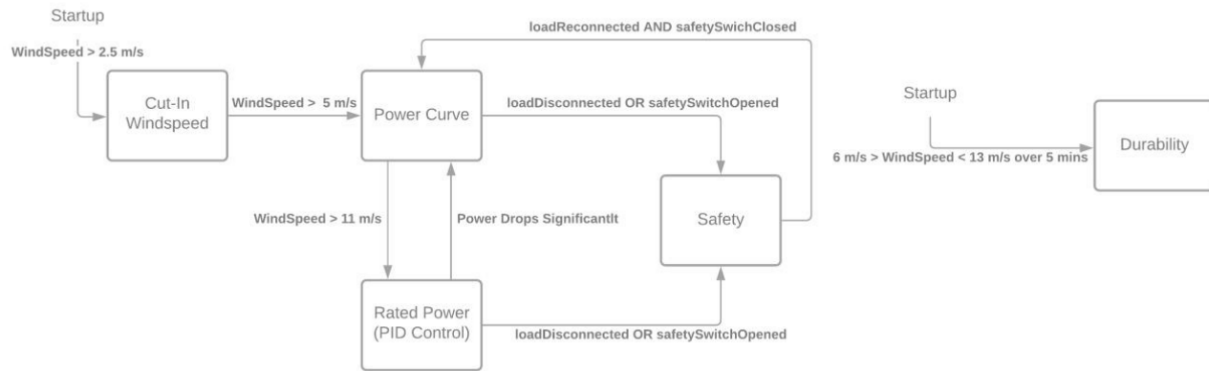


Figure 10: Control subsystem architecture diagram.

The Arduino is a constantly checking to see if the blades are still rotating with the rpm sensor and another check to see if the voltage has dropped suddenly. If the blades are still rotating and there is a sudden drop in voltage then the emergency stop function is triggered the same as when the emergency stop button is pressed. While in the emergency stop the code will watch for changes in the voltage. When disconnected from the load the voltage sensor is inconsistent and the difference in voltages sensed is never near zero. When the load is reconnected the difference in voltages level out to zero as the voltage measurements become more consistent. When the voltage measurements become consistent the code knows that the load is reconnected and the turbine returns to the pitch angle and load resistance it had before the turbine was disconnected from the load. In testing the functionality of the emergency stop code at several different wind speeds the turbine was able to sufficiently slow down and start up as designed.

### 3.4 Mechanical System

**Tower-** We designed the base plate as a circular piece that would align with the turntable in the competition tunnel. We performed a finite element analysis on the tower to ensure that it would not break during turbine testing. We assumed an even distributed load along the tower and a point load caused by the maximum allowable size of a turbine. All forces were determined based on a wind speed of 20 m/s. We found that the maximum stress was approximately 1.6 MPa and the maximum deformation was .04 mm. Our tower is made of thick walled 1" aluminum tubing. Both values suggest that the probability of our tower failing is negligible.

**Yaw system-** We elected to use a passive yaw system for simplicity. A passive yaw system allows us to output more power as it doesn't require a power source. This was accomplished with the use of a bearing and a tailfin. We used a 1" clamp-on-bearing that attached the top of the tower to the bottom of the nacelle base plate. The moment generated by the wind on the tailfin is sufficient,

even at low wind speeds, to yaw the turbine into the wind.

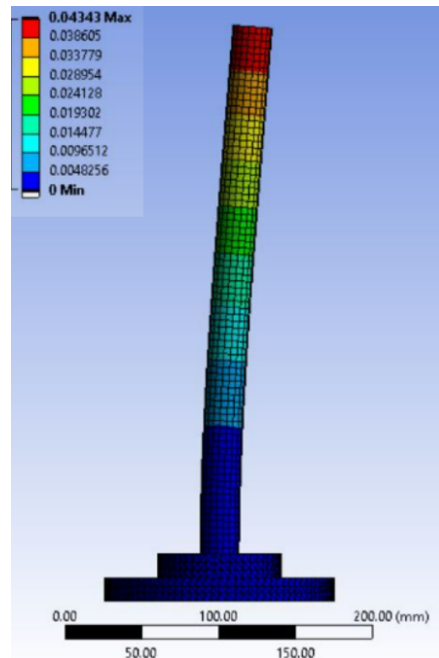


Figure 11: FEA analysis showing the deformation of the turbine tower.

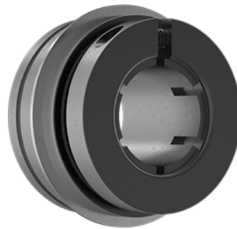


Figure 12: Clamp-on-bearing for the yaw system.

**Pitch System-** The pitch system was purchased from Goblin Helicopter. We determined that this pitch system provided all the functionality we needed so we felt comfortable getting it off the shelf. The Goblin pitch system allows for pitch of  $-30^\circ$  to  $+35^\circ$ . Within this range we were able to reach max performance as well as full brake. In testing the range of the pitch angles the front rotor was able to come to a complete stop using solely blade pitch. To control the pitch angle a linear actuator was connected to the pitch system.

**Rear Mechanical Brake** The rear blades were fixed pitch for simplicity. They were not involved in the rated power portion of the competition and were completely stopped as soon as the front rotor cuts into the wind. To shut the rear blades down we added a linear actuator with a rubber stopper that extended into our rotor. This method was simple to implement and functioned properly during testing.

**Nacelle-** The nacelle contains a metal base plate with multiple machined parts attached. We did

not use a gear box to avoid losses; our design was already optimized for the rpm's attained in the wind tunnel. The outer walls of our nacelle were 3D printed in two sections, a large front section and a shorter rear section. We attached a tailfin to the top of the rear section. The tailfin is a foam NACA 0020 airfoil cut on a CNC foam cutter. The tailfin effectively produced the necessary torque to yaw the turbine with the entire nacelle attached. Due to limited time, the front section of nacelle was not used and still remains to be redesigned. However, with only the back section of the nacelle we were able to yaw the turbine even at low speeds.

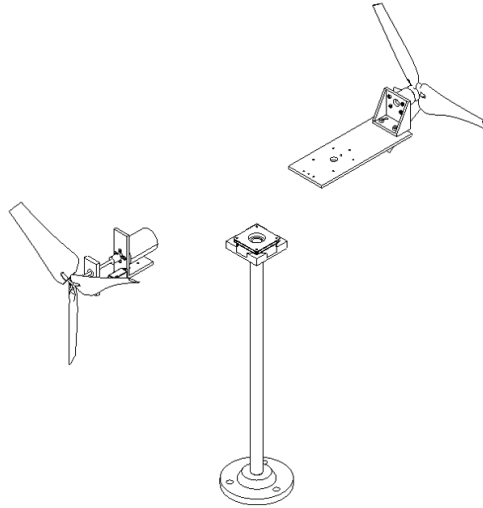


Figure 13: Turbine view exploded into three main subsystems; Tower, rear generator, and front generator.

## 4 Summary of Final Performance

### 4.1 Cut-in Wind Speed

As seen in Fig. 14, our goal is to have a cut-in wind speed below 3.0 m/s. We have achieved a cut-in wind speed of about 3.0 m/s with the secondary blades, therefore almost achieving our stretch goal and receiving a score of 20/25 in this task.

### 4.2 Power Curve Performance

According to the power curve in Fig. 15 we have a score of approximately 36.5/50 currently for our power curve task, which is around what we expected, but we plan to improve this in next year's CWC by focusing on designing our own generator. We have also achieved a peak coefficient of power of 0.24, which is lower than our lower limit and will be part of our focus in next year's competition.

### 4.3 Control of Rated Power and Rotor Speed

We have the code written to produce the same power at 11 m/s to 13 m/s by using PID code to control the pitch angle to maintain the same output voltage. The PID code tends to lead to a sharp increase in power at wind speeds between 11.4 m/s and 11.75 m/s. However, after 11.75 m/s the PID is able to control the pitch of the blades to sufficiently control the rated power. The control

Competition Task	Measure	Stretch Goal	Excellent	Good	Fair	Lower Limit	Ideal	Upper Limit
Cut-in Wind Speed	Cut-in wind speed (m/s)	$\leq 2.5$	2.5 to 3.0	3.1 to 4.0	4.1 to 5.0	NA	2.5	5.0
Power Curve Performance	Power curve score <sup>1</sup>	$\geq 50$	40 to 49	30 to 39	20 to 29	20	50	NA
	Peak coefficient of power	0.44	0.38 to 44	0.32 to .37	0.25 to .31	0.25	0.44	NA
Control of Rated Power and Rotor Speed	Power ratio <sup>2</sup>	1.00	0.90 to 1.10	0.80 to 1.20	0.75 to 1.25	0.75	1.00	1.25
	Rotor speed ratio <sup>3</sup>	$\leq 1.00$	1.00 to 1.10	1.11 to 1.20	1.21 to 1.25	NA	1.00	1.25
Safety	Ability to emergency stop and restart	(1) Stops and (2) restarts after button is pushed; (3) stops and (4) restarts after load is disconnected.	Performs all four safety tasks	Performs three safety tasks	Performs two safety tasks	Performs two safety tasks	Performs all four safety tasks	NA
Durability	Maximum survivable wind speed (m/s)	22	20 to 22	15 to 19	13 to 14	13	22	NA

Figure 14: Key success measures.

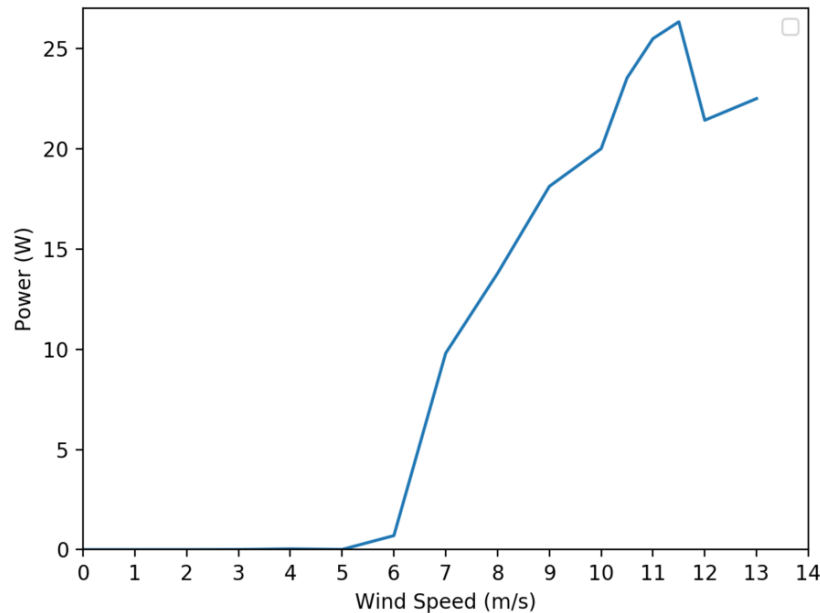


Figure 15: Power generated by the turbine over varying wind speeds.

isn't as precise as we expected but we ran out of time this year to fully calibrate it. The current rated power controls will be calibrated and worked on for our turbine in the CWC 2022. Current performance of rated power would result in a score of about 35.74/50.

Unfortunately our rpm sensor isn't accurate at high rpm and during the rated power task the rpm reading is inconsistent so we were unable to accurately measure the rpm control aspect of the rated power task.

The max voltage reached in the tests was around 14 V, which is not anywhere close to the 48 V limit. However, we still included code that when 47 V is reached the turbine will be controlled the same as if the emergency stop button had been pressed.

#### 4.4 Safety

All four elements of the safety task have been achieved. We attached an emergency stop button, that when pressed, the blades will pitch into the wind, and the resistance to the load decreases to its lowest value which increases the torque of the generator and essentially stops the blades from rotating at all wind speeds. Then when the emergency stop button is released the blades will pitch into their cut-in wind speed angle and start rotating again.

#### 4.5 Durability

The controls code used in the other tasks works for the durability task. Especially since the wind speed range for the durability task is between 6 m/s and 13 m/s. In testing this range of wind speeds in the wind tunnel the wind turbine was able to consistently generate positive power with the designed load. We attempted to build a controllable turn table for testing the yaw functionality, but unfortunately it was too unstable for the vibrations that occur at around 7 m/s. To test the yaw we offset the turbine and then turned the wind on to see when the turbine is able to redirect into the wind. Over multiple offsets the turbine was able to consistently redirect into the wind at around 5 m/s. The yawing mechanism is detailed in Fig. 12.

## 5 Commissioning Checklist

In order to safely and effectively install the wind turbine into the wind tunnel the following step will need to be followed in order:

- Take the tower piece that is connected to the base and run the six generator cables through the base of the tower to the top of the tower. Once the generator cables are run through then feed the linear actuator and rpm sensor cables through.
- Feed the cables through the hole in the bottom of the nacelle plate.
- Place the yaw mechanism over the top of the tower and tighten down using a hex wrench.
- Once nacelle is securely on the tower the base will need to be secured to the inside of the wind tunnel using the three screws provided by the CWC.
- The cables that were fed through can now be connected to their respective destinations.
- Attach the rear fin and nacelle cover to the back of the nacelle using the two larger screws and bolts that come with the turbine.
- The primary and rear blades can now be attached. Make sure the pitching mechanism screws are tightened and calibrated.
- Test for any loose screws and for tension in the cabling that could prevent the nacelle from yawing.
- Lastly, plug in the 120 VAC power source for the Arduino and check that all connections are secure in the Arduino.

## 6 Conclusion

The final model of our wind turbine is recorded in the results that we have outlined above in Fig. 14. While there is still a lot of work to be done to improve our turbine we have created a turbine that will be competitive in wind tunnel testing. The information detailed above accurately represents our progress as a team as well as suggests areas that can be improved in future designs. One year of engineering and design has allowed us to make large advances in our power output and efficiency. As time continues and as BYU continues to compete the turbine will improve.