BYU Collegiate Wind Competition

Turbine Design Report

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Faculty Advisors
Andrew Ning (Associate Professor)

Student Team Leaders
Carson Townsend
Ariel Cable

Blades Team
Kevin Steele
Amanda Dame
Jacob Child

Foundation Team
Ariel Cable
Garrett MacKay
Ezekiel Jensen

Controls Team
Jacob Numbers
Cody Arvonen
Crewse Peterson
Bryce Richard

Power Team
Carson Townsend
Bryce Dickey
Jake Sweet

Contact Information
byuwindenergyclub@gmail.com

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This report details the design, construction, testing, and performance results of a small-scale wind turbine created by the Brigham Young University CWC team for the 2023 Collegiate Wind Competition. The objective of the design approach was to score the most points possible, which was achieved by organizing design teams based on the various scoring categories. These include the foundation team, the blades team, the controls team, and the power team.

The foundation team focused on the durability task, the foundation success task, and structure weight. Because last year's foundation design was successful, this year's foundation team focused their efforts on improving the 2021-2022 design. The design is a corkscrew that can be twisted into the sand without the need for excavation. After installation, a massage gun is used on the foundation to cause it to vibrate and compact the sand around it. In testing, the foundation can withstand any wind speed up to 22 m/s without any displacement. The total weight of the in-water support structure is 1 kg.

The blades team focused on the power curve performance task. Using Qblade, the team designed and simulated the performance of several different blades. After evaluating the simulated data, a final blade design was selected with a coefficient of performance of 0.38. The resulting design was then 3D printed on an FDM printer, an SLA printer, and a nylon resin printer. After testing each in a wind tunnel, a final manufacturing method was selected based on durability and measured power curve performance. The final manufacturing method selected was FDM with a power curve score of 19.03 points.

The power and controls team worked together to maximize the power curve performance task score, the control of the rated power and rotor speed task, and the safety task. For the power curve performance task, these teams designed a variable load controlled by an Arduino that switches between an array of resistors to maximize power output. For the control of the rated power and rotor speed task, the teams designed a pitch system that adjusts the pitch using a linear actuator to maintain rated power and rotor speed. For the safety task, the teams use the pitch system to completely feather the blades coupled with a servo motor to push a brake pad to bring the turbine to a stop. The system is then restarted by routing external power up to the nacelle to restart the turbine. During mock competitions, these teams score 0 (currently testing) on the control of rated power and rotor speed task and 0 (currently testing) on the safety task.

4.1 Design Objective:

From the beginning, the Collegiate Wind Competition team from Brigham Young University has had the objective to win the Collegiate Wind Competition. An analysis of the competition points revealed that the team's design decisions should focus on the power curve score, control system, and foundation in order to earn the most points. Each subsystem worked towards achieving the maximum number of points in its respective category.

Figure 1: Full turbine assembly. Note that the foundation has changed but the basic assembly is the same.

To optimize the turbine blades for the power curve score, the blades team designed blades to achieve a peak power output at wind speeds between 7-8 m/s. Simulations were first run in Qblade, then manufactured using 3D printing, and finally tested in a wind tunnel. After simulating several different airfoils, chord lengths, and twists, the team was able to achieve a simulated power coefficient of 0.38 using two different s-series airfoils along the blade profile. The simulated blade was then manufactured out of several different materials to determine which material would provide the highest power output and be able to withstand wind speeds greater than 11 m/s. After a series of tests, the team found that an FDM-manufactured PLA blade produced an optimal power output and could withstand wind speeds exceeding 11 m/s.

Maximizing power output depends on both the effect of the turbine blade profile and the electrical component configuration. To maximize the power output, variable resistors with relays and an appropriate generator were chosen. Resistors were chosen to achieve the maximum power at the integer wind speeds between 5-11 m/s. The generator efficiency was maximized by selecting a generator with a rated voltage and speed that matched the turbine's produced voltage and blade RPM.

The turbine controls were designed to maintain rated power and to stop and restart under prescribed circumstances. Through testing, a rated power for the turbine was chosen by averaging the turbine power output at 11 m/s. A voltage divider allows the Arduino to sense when rated power is achieved, at which point the turbine adjusts the pitch of the blades to maintain rated power and maximum rotor speed. The E-stop button and voltage divider trigger the Arduino to shut down the turbine during an emergency stop or a load disconnect respectively. The turbine then completely pitches the blades out of the wind and activates the servo brake to bring the turbine to a stop. External power is then routed up to the turbine to restart when ready.

The foundation was designed to keep the turbine completely stable for an indefinite amount of time up to wind speeds of 24 m/s. The corkscrew design employed allows the foundation to be screwed into the sand without the need for excavation. Massaging the foundation after installation helps to compact and settle the sand around the foundation. This design proved to effectively engage the sand and completely stabilize the turbine.

4.2 Similarities with Last Year's Design

This year's team has a new nacelle, new shaft support system, new cabling, an entirely new load box, new blades,

This year's team has kept a similar foundation and nacelle design while making incremental improvements to each. The generator, encoder, brake pad, pitch system, and nacelle stand are the same components used last year. Each of these designs and components is discussed below.

Last year's team spent much of their time designing a foundation that would reduce displacement at high wind speeds. They had great success at the competition with their corkscrew foundation that displaced less than 1 cm at wind speeds as high as 23 m/s. The installation process and the use of a massage gun to help the sand settle proved to be unique and effective. This year's team decided to adopt the same corkscrew design and focus on making minor improvements that would reduce the foundation's weight while still maintaining minimum displacement. The team accomplished this by using a thinner pipe gauge and thinner sheet metal while maintaining the same corkscrew design. The installation process also remained mostly the same with the addition of a guide rod to help keep the foundation vertically straight.

The turbine nacelle and its contents are another part of the design that this year's team decided to adopt and improve upon from last year's team. The shape of the nacelle proved to be very aerodynamic and aesthetically pleasing, therefore the overall design was kept the same. However, the team did decide to 3D print a new nacelle with screw holes that streamline the process of opening the nacelle to access interior components. The team also added their own personal touch by making the nacelle blue and inscribing "BYU" down the sides.

Many of the interior components of the nacelle have remained the same including the generator, the encoder, and the brake pad. The team decided to continue to use the Maxon 60W graphite brushed motor as the generator because of its exceptional performance during last year's competition. The team also kept the same integrated encoder that allows us to interface with it easily. The pitch system was also kept the same because of its great success at last year's competition and its ability to give us a wide range of motion. Finally, the nacelle stand was kept the same as last year's design to save us time from having to manufacture a new one.

4.3 Static Performance Analysis

The blade design team was responsible for the design and analysis of the turbine blades. After airfoil selection the operating Coefficient of Power not only increased from last year, but the curve shape is much more advantageous- at higher wind speeds, if the TSR increases the C_p does not decrease dramatically and will increase for a time. This effect is observed in Figure 2.

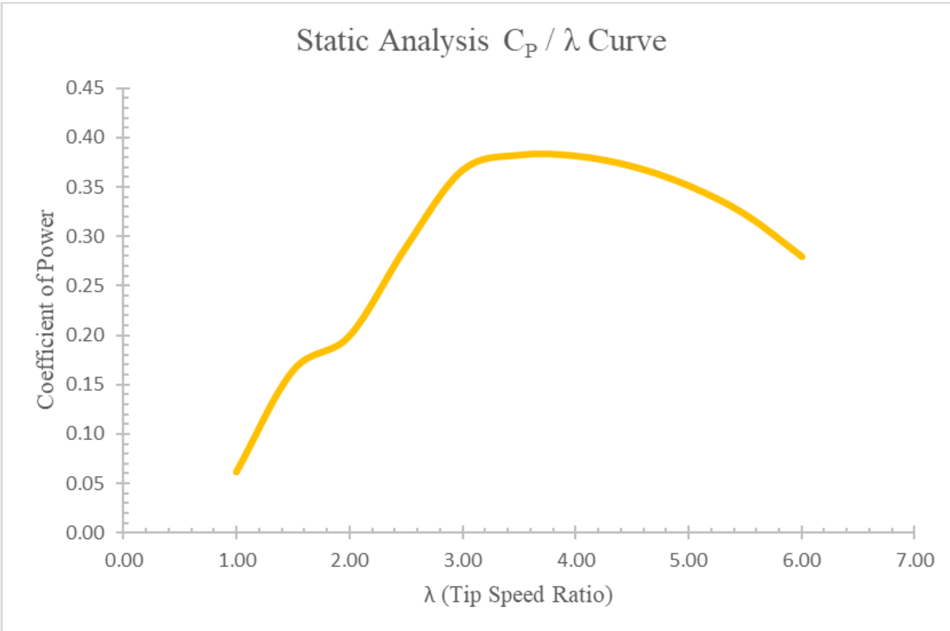

Figure 2: The Power Coefficient (C_p) plotted with changes to the Tip Speed Ratio (λ) at wind speeds of 6 m/s. The designed operating point was a TSR of 3 and a C_p of about 0.36.

The annual estimated power production of this turbine is estimated to be 40 kWh/year. This was found by importing the wind tunnel power data into the Furow wind farm analysis software, assuming a hub height of 125 m, and calculating the average power production of the turbine. The hub height was selected to be similar to modern wind turbines and be at the same height as chosen wind data. To make this calculation, 4 years' worth of 125 m ERA wind speed data at the offshore Louisiana location was used and averaged.

4.4 Engineering Diagram of Mechanical Systems and Analysis of Loads

Figure 3 shows all the mechanical systems inside the nacelle. The pitch system is comprised of a commercially purchased pitch assembly, a linear actuator, and a 3D-printed adapter to connect the pitch system to the linear actuator. The braking system has a servo motor, a brake, and a brake pad. A shaft collar is used to incorporate passive yaw and connect the nacelle to its stand. The generator connects to a shaft through a coupler which is stabilized by a mounted ball bearing before it gets to the blades. The nacelle itself is 3D printed PLA and the halves connect by using heat-set threaded inserts and screws.

Figure 3: Diagram of nacelle design and component layout.

An analysis of loads was only performed on the blades and the foundation. Because the forces on the nacelle were just due to drag forces from the wind, it was determined that any stresses were well within the capabilities of having a 3D printed nacelle to house the mechanical and electrical components. Testing in the wind tunnel confirmed that these stresses could be safely withstood by the 3D printed nacelle.

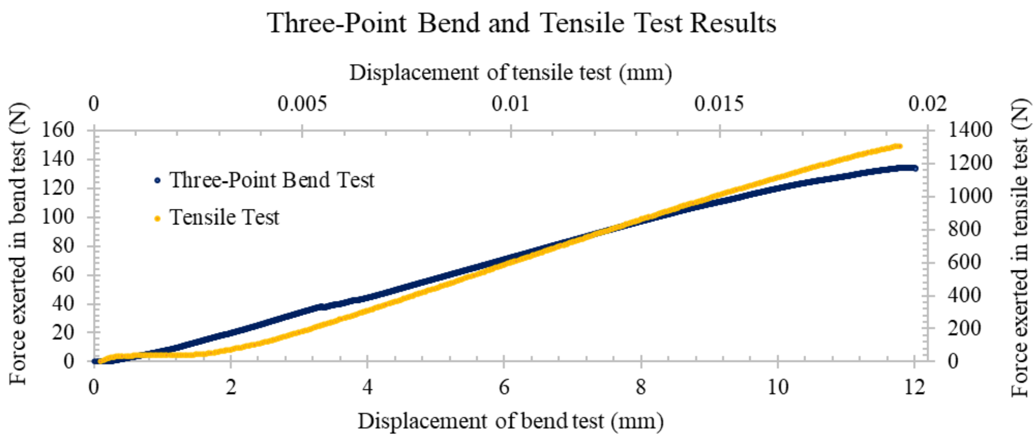

Figure 4: Results from both a three-point bend test and a tensile test on the same blade design. The blade bent about 12 mm before breaking under a 134 N load and endured a tensile load of 1305 N.

A three-point bend test was performed on a PLA blade to determine how well it would withstand the bending force due to the thrust that the turbine endures at high wind speeds. The thrust was estimated using a thrust coefficient pulled from Qblade simulations and assuming a solid disc area with a radius equal to the blade length. The maximum thrust is expected to occur at 14 m/s when the blades have not yet been pitched. This estimated force is 18 N, but as can be seen in Figure 4, the blade withstood 134 N of force before fracturing. Thus, the PLA blades have a safety factor greater than 7 for thrust. The testing process that collected these results is shown in Figure 5 below.

The other main force exerted on the blades while in the wind tunnel is the tensile load as the turbine spins. This force is of concern, particularly at the root of each blade. In previous runs, blades broke off at the connection point with the pitch system when the RPMs got too high for them to handle. The comparatively weak bond between the print layers of an FDM root accounted for these failures, so the roots were printed in a different orientation. A tensile test was then performed to assess the strength of the new root. This tensile load, based on the max RPM of 3054, is estimated to be 186.5 N. However, the root endured 1305 N without breaking, meaning the improved print orientation leads to a safety factor of at least 7. Figure 4 has the collected data and Figure 5 shows the test setup.

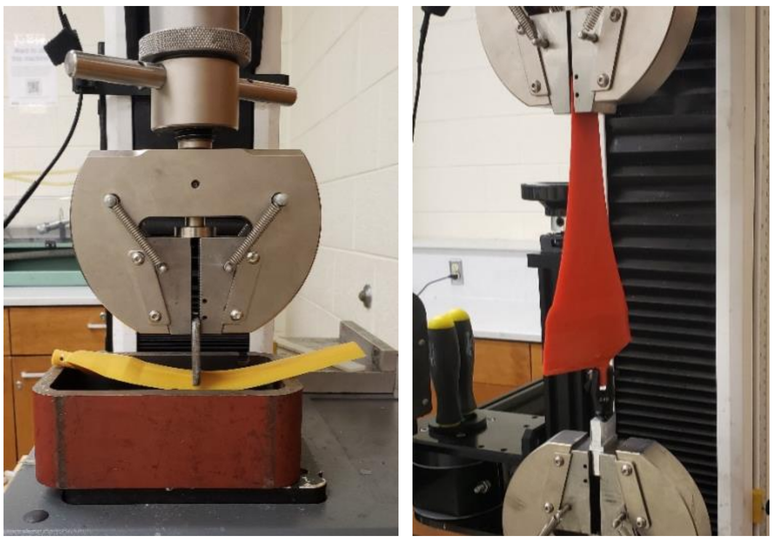

Figure 5: On the left, the blade is shown under pressure right before it breaks due to bending. The photo on the right is before the blade breaks due to tension.

4.5 Engineering Diagram of Foundation and Structural Analysis

As mentioned, the foundation is inspired by a helical pile and is lighter than last year's design. The rules changed this year and prohibited excavation, but this did not affect the reuse of the design. Other designs were considered but the helical pile was chosen because of last year's proof of concept and ease of manufacturing.

Analysis began with an examination of the predicted thrust loads and resultant moment on the foundation. The output from the QBlade software indicated a thrust load of 18 N at the axis of rotation of the blades. This was multiplied by the 83 cm distance from the axis of the blades to the top of the foundation to produce a moment of 15 N-m. After further research into helical piles, the axis of rotation of a foundation failure was moved down slightly, resulting in a moment of 18 N-m.

Initial testing was performed by installing the foundation and pulling on the top with a fish scale to create a moment. Some of the prototypes succeeded at resisting a static load from this test equal to or greater than the expected moment of 18 N-m. After testing these reduced diameter designs in the wind tunnel, however, there were unacceptable deflections in excess of four centimeters. Similar testing was done using smaller gauge materials. These tests showed no difference in the strength of the foundation; therefore, the smaller gauge was used to lower the weight of the structure.

Ultimately, a foundation with a helix diameter of 25 cm was selected. The team also produced a new design with a simplified manufacturing method, using two semicircular plates set at equal angles of about five degrees to the horizontal (Figure 6). This foundation was tested to loads much greater than the loads the turbine would experience during the competition with little to no displacement. During the testing, the wind tunnel speed reached up to 20 m/s with the blades not feathered to create as much thrust as possible and the turbine displaced a total of 1 mm. This means as far as wind speed is concerned, there is a factor of safety of at least 1.4 with a displacement factor of safety of 25.

Figure 6: Turbine foundation

To install the foundation, the intermediary cable that runs between the load box and the turbine is first fed through the foundation. The foundation then is screwed into the sand and vibrated using a massage gun so the sand around it settles. During the vibrating process, the foundation is adjusted to ensure it is level.

4.6 Electrical Analysis and Electrical One-Line Diagram of Overall System

The power team was responsible for designing, testing, and constructing all of the power electronics for the turbine. The team's design sought to accomplish the following three objectives: Maximize the turbine's output power to the Point of Common Coupling (PCC), filter out any unexpected power oscillations, and be able to switch between internal power (from the generator to the load) and external power (from the wall to the nacelle). The power electronics of the turbine are broken down into three main pieces: The load design (Figure 7), the nacelle design (Figure 8), and the motor specifications (Figure 10).

Load Electrical Analysis:

To improve upon last year's electrical design, the team implemented a variable load design to maximize the turbine's power output. The variable load consists of 5 resistors and 4 switches (Relays 1-4 in Figure 7). Relays were used for switches and 18-gauge wires were used to connect the components. 18-gauge wires were selected to ensure the load met current and voltage safety specifications. The team configured four resistors in parallel with four separate switches, which will all be placed in series with each other. This configuration allows the Arduino to switch between sixteen different resistor values with just 4 resistors. There is a fifth resistor that acts as a small voltage divider to read the turbine's output voltage and switch load values until the power output is optimized.

In addition to the various power resistors and corresponding switches, the load box also contains two relays (Relays 5 and 6 in Figure 7) that switch the direction of power between the load and the PCC. This function is important during the initial start-up of the generator and during the restart sequence after a stoppage. Only one of the two relays is closed at a time. When Relay 5 is closed and Relay 6 is open, power is flowing from the PCC to be dissipated in the variable load. When Relay 6 is closed and Relay 5 is open, rectified AC power from the wall is "bucked" down to 7 volts and travels to the nacelle through the PCC. The operating voltages at each node of the load are labeled in Figure 7. The Arduino receives a 7V signal regardless of how Relays 5 and 6 are configured. All power that travels between the load and nacelle interfaces with the PCC to be in accordance with the CWC requirements.

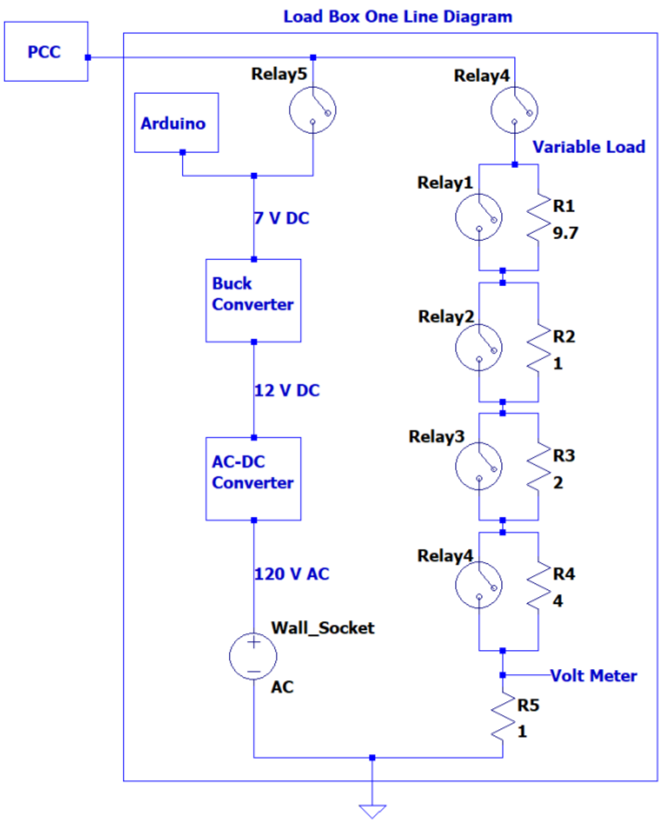

Figure 7: A one-line diagram of the power electronics in the load.

The transition from one static resistor to an array of variable resistance has proven to be very effective in maximizing power output from the turbine. In comparison to last year's results, there is an increase in the power curve score from 10 to 19 points. Through rigorous testing, optimal resistor values were determined for each wind speed to help the turbine produce a maximum stable power output during the competition. These resistor values were selected by measuring the voltage output of the turbine at a given wind speed and calculating the power using the following equation:

$$P = \frac{V^2}{R}$$

The resistor values can be found in Table 3 of section 4.11 of this report.

In addition, the added functionality of being able to switch between sending power from the generator to the load vs. sending power from the load to the nacelle has been crucial in the correct operation of the turbine during shutdown and startup states. During normal operation, all power will be sent from the generator in the nacelle, through the PCC, and finally to the variable load. However, when the turbine testing is beginning or when the turbine has been shut down and needs to restart, it is extremely helpful to be able to power the nacelle components such as the brake and linear actuator from the load via the 120 VAC wall plug. According to the datasheets for the linear actuator and contact brake, they each require at least 5V to operate. Through testing and analysis, the team observed that the generator does not begin outputting 5V until wind speeds reach 5 m/s and above. The ability to power nacelle components from the load allows the turbine controller to disengage the brake and pitch the blades to an optimal angle while wind speeds are low and the generator is not producing significant power. This is a tremendous improvement upon past designs since last year's team received 0 points for turbine functionality in the shutdown and startup conditions. The team is confident the turbine design and performance will receive more points at the competition thanks to this improved functionality.

Nacelle Electrical Analysis:

The electrical components of the nacelle were designed to accommodate three functional states. These states are not the control states, but rather design states for the electrical system:

A. Transfer power from the generator to the load (during normal operation),
B. Transfer power from the generator to both the load and components (when adjusting pitch or activating the brake).
C. Transfer power from the load to the nacelle components (during startup and restart),

These modes of operation maximize the power output to the load by ensuring components are not drawing unnecessary power, while permitting rapid power allocation to nacelle components when needed. Reference Figure 8 for a one-line diagram of the design. A compact PCB houses all of the components featured as shown in Figure 9.

In state A, a normally closed N-MOSFET switch labeled Relay 7 in Figure 8 opens the component circuit, preventing power losses when not required. All switches in the nacelle are controlled with signals from optically isolated cables from the load box. Power generated by the motor flows to the PCC through an optimized LC filter which drops the cutoff frequency to 21.2 kHz as required by the competition guidelines. The generator also powers the encoder which sends RPM information to the load via optically isolated wires.

When state B is activated by a low digital signal to Relay 7, the switch closes and power is bucked down to 7V, powering the actuators for pitch control and braking if necessary. Optically isolated digital signals are sent from the microcontroller in the load to these components to engage/disengage the brake and set the blades to an optimal pitch angle. During the brief moments in which the microcontroller is interacting with these components, the turbine's measurable power output at the PCC will decrease, however, this will have minimal impact on the overall power curve score at the competition.

During startup or restart, state C is enabled by closing two parallel relays (represented collectively by Relay 6 in Figure 8) which stops the generator from outputting power to the PCC. The relays are activated by a digital signal from the load. The relays are wired in parallel to ensure sufficient protection against current overload. In this mode, Relay 7 is closed allowing the components to receive power that is routed up to them externally from the load.

The improved nacelle electrical design includes a PCB with several features for troubleshooting and modification optionality. Power and signal wires connect via screw terminals, ensuring secure, removable connections and mechanical resilience. Heat sinks and spacing in the PCB were designed to prevent overheating of components.

As was stated above, states A, B, and C are not the control states. They are integral processes that are used for control of the turbine during nearly each control state that the turbine enters.

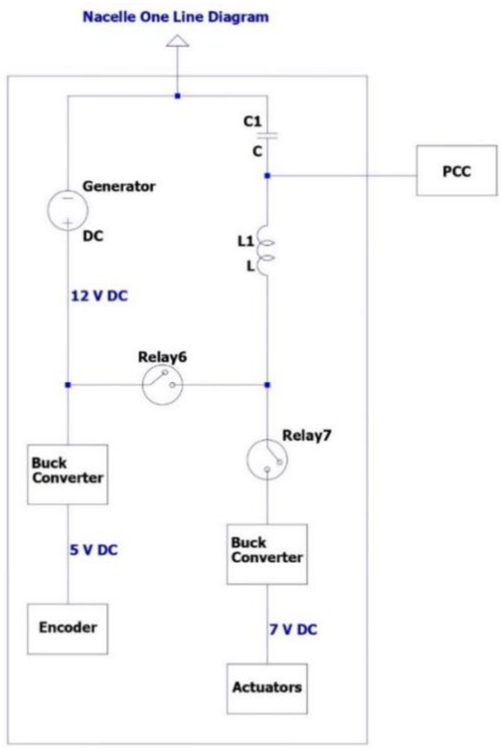

Figure 8: One-line diagram of the nacelle's electronic design showing the fundamental connections.

Figure 9: A picture of the designed PCB used in the nacelle for sturdier connections.

Generator Specs:

Considering the test results collected throughout this year, the data last year's team collected, and the CWC's 48V limit, the same generator was chosen that last year's team used: the 310009 Maxon graphite brushed, 60-watt DC motor. The 310009 Maxon motor has adequate voltage rating, torque constant and nominal current to meet the CWC requirements and be competitive during the turbine testing competition. Figure 10 details the specifications incorporated into the electrical design.

VALUES AT NOMINAL VOLTAGE	
Nominal voltage	48 V
No load speed	8490 rpm
No load current	78.6 mA
Nominal speed	7760 rpm
Nominal torque (max. continuous torque)	89.7 mNm
Nominal current (max. continuous current)	1.74 A
Stall torque	1050 mNm
Stall current	19.6 A
Max. efficiency	88 %

Figure 10: A table containing the nominal and maximum specifications of the motor.

4.7 Control Model Analysis of the Operational Modes

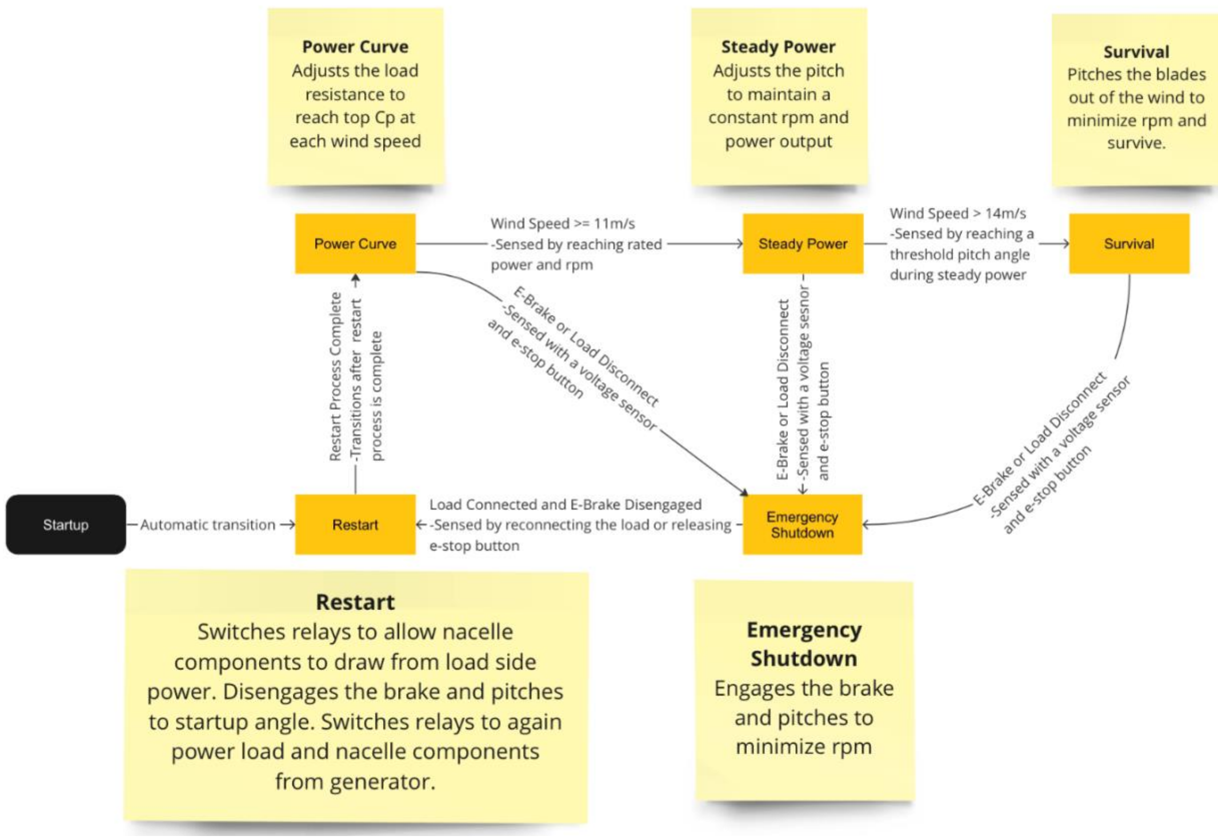

Figure 11: A Controls flow chart for the turbine

Primary Operational Modes:

Startup: This is the initial state of the turbine. In this state, a connection is established with all the control components. Once the connection is initialized, the system switches to the Restart state.

Restart: In this state, the load side relays are changed to allow power to flow up to the nacelle to set the pitch of the blades to the startup angle. The load resistor gets set to the ideal value identified for 5 m/s. Once the RPM of the blades reaches the value corresponding with 5 m/s found through testing, the power relay switches to draw power from the turbine and switch to the Power Curve state.

Power Curve: In this state, rotor RPMs are monitored as well as the power output of the turbine in order to determine what combination of resistors to use from the resistor relay to maximize the power output at each wind speed from 5 m/s to 11 m/s. Changes in wind speed are identified by significant changes in the measured RPMs. Once the system identifies the change in wind speed, it switches the load resistance value to the next optimal value that was found during testing. When the RPMs and power output have reached the rated rotor speed and rated power at 11 m/s, the system transitions to the Steady Power state.

Steady Power: In this state, rated power and rotor speed is maintained by pitching the blades. To do this, the turbine monitors the RPM and power output of the turbine and pitches the blades to adjust these values and keep them within the desired range. The system will transition to the survival state once the blades have pitched to a hardcoded value found during testing which corresponds to a pitch needed to maintain rated power at 15 m/s.

Survival: In this state, rpms and thrust loads are minimized by fully pitching the blades out of the wind. The system transitions out of this state only when the system is restarted or an emergency shutdown is detected.

Emergency Shutdown: This state is entered from the Power Curve, Steady Power, or Survival states in the case of an emergency stop button press or a load disconnect as recognized by a power output of 0W. In this state, the system decreases the RPM of the blades to below 10% rated rotor speed. This is achieved by first pitching the blades completely out of the wind. Then a friction brake is applied to the brake pad on the axle of the generator in the nacelle. For an emergency stop button press, external power is used to change the pitch and power the brake. For a load disconnect, internal power from the generator and power stored in a capacitor are used to change the pitch and power the brake. This state is left when the Emergency Stop button is disengaged or the load is connected.

4.8 Software Architecture and Development

The software system was designed to allow for the development and testing of each component as well as the system as a whole all on the same script. This was done by creating a state machine that allows for optional manual input from the Arduino IDE's serial monitor.

To tackle data acquisition, the team opted for a manual approach, given the changing circumstances envisioned as data was gathered for the competition. The wind tunnel used to test all year is not the same wind tunnel that will be used in competition, and because of this a "test" state was created that could be used to gather important values (RPM, most efficient resistor values, pitch values, etc.). This way, regardless of the environment, optimization can be performed effectively. This state allows us to manually set load and pitch values while reading RPM, so the most optimal resistor and pitch value can be found at each wind speed to preprogram the turbine.

The values acquired using the test state were manually collected in various spreadsheets. An example is below, where a test was done, acquiring data via the test state, to find the most efficient resistor at 6 m/s. An example of one of the data sets at 6 m/s can be shown below:

Table 1: Resistor testing results in BYU's wind tunnel

Resistence (Ohms)	Generator Speed (RPM)	Voltage (V)	Power (W)
1.7	1450	0.139	0.0114
2.6	1455	1.23	0.5819
3.3	1475	1.67	0.8451
4.7	1490	3.04	1.9663
5	1500	3.02	1.8241
6.7	1520	4.27	2.7213
7.5	1550	4.7	2.9453
8.4	1570	5.13	3.1330
9.7	1620	5.57	3.1984
10	1620	5.52	3.0470
11.7	1625	5.69	2.7672

13.5	1700	6.6	3.2267
14.5	**1710**	**6.85**	**3.2360**
16.7	1745	7.2	3.1042
17.8	1755	7.39	3.0681

These values acquired during testing were used as benchmark values for the turbine and values to use for state transitions, such as looking for an RPM spike when going from 6 m/s to 7m/s.

The safety system consists of sensing a load disconnect and a button push by a user. The button was simple, as the team set up the code to sense a signal from the button when it is pressed, which will be constantly looked for in a function in each state. The load disconnect will be sensed using a voltage divider. Since the Arduino can only handle up to 5 V as an input, the voltage from the turbine is scaled down using a voltage divider. The Arduino constantly reads the analog voltage from the divider, and if the Arduino ever reads 0 volts and the code is not in the restart or setup state (states where 0 volts is a reasonable outcome), the Arduino will trigger the shutdown state. In this case, a 0.33 F capacitor will be used to feather the blades and apply the brake. The capacitor, labeled C1 in Figure 8, will be charged as the turbine is in use to an estimated 8 J. This energy estimate is derived using the voltage in the attached voltage regulator of 7 V.

Below is an example code snippet of how a load disconnect is detected. The voltage across the load resistor is read in from the Arduino using an analog pin connected to a voltage divider. The analog value that is read is converted to the proper voltage and if it is zero, the function will return false.

```
bool is_load_connected() {
    float voltage = (analogRead(VOLTAGE_PIN) / 1023.0) * 5.0 * voltage_factor;
    return voltage != 0.0;
}
```

Figure 12: Load disconnect code.

A similar function is used to determine whether the emergency brake button has been triggered, allowing the state machine to be able to react to emergency stop situations.

The outputs to the turbine actuators are primarily controlled by an open-source library for Servo motors. More details about this library can be found on this GitHub page: https://github.com/arduino-libraries/Servo. This library takes care of the pulse width modulation for the actuators, allowing us to simply write digital values in the software to control them.

4.9 Description of Final Wind Turbine Assembly

Bi-weekly team meetings and constant communication between subsystem team leaders allowed the integration of subsystems and the final turbine assembly to go very smoothly. Each subsystem interface was also defined at the start of the design process. The foundation team interfaced with the rest of the team through the CWC-provided connector stub, the blades team integrated with the rest of the team through the connector screws on the pitch system, and the controls and power team worked together to design the rest of the physical and electrical components.

The final assembly of the subsystem is fully defined in Figure 13 and Figure 14. Engineering assembly drawings were used to define the assembly to make the process clear, concise, and repeatable.

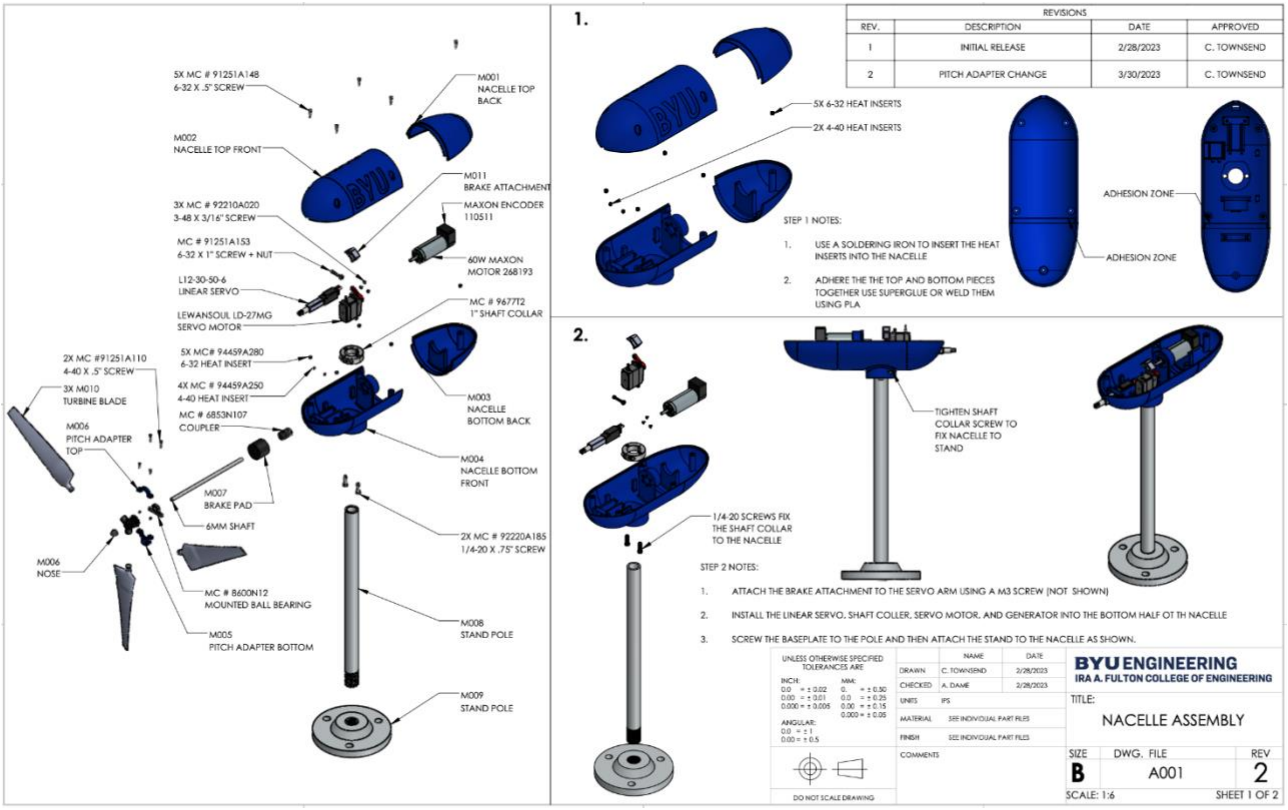

Figure 13: Final assembly sheet 1

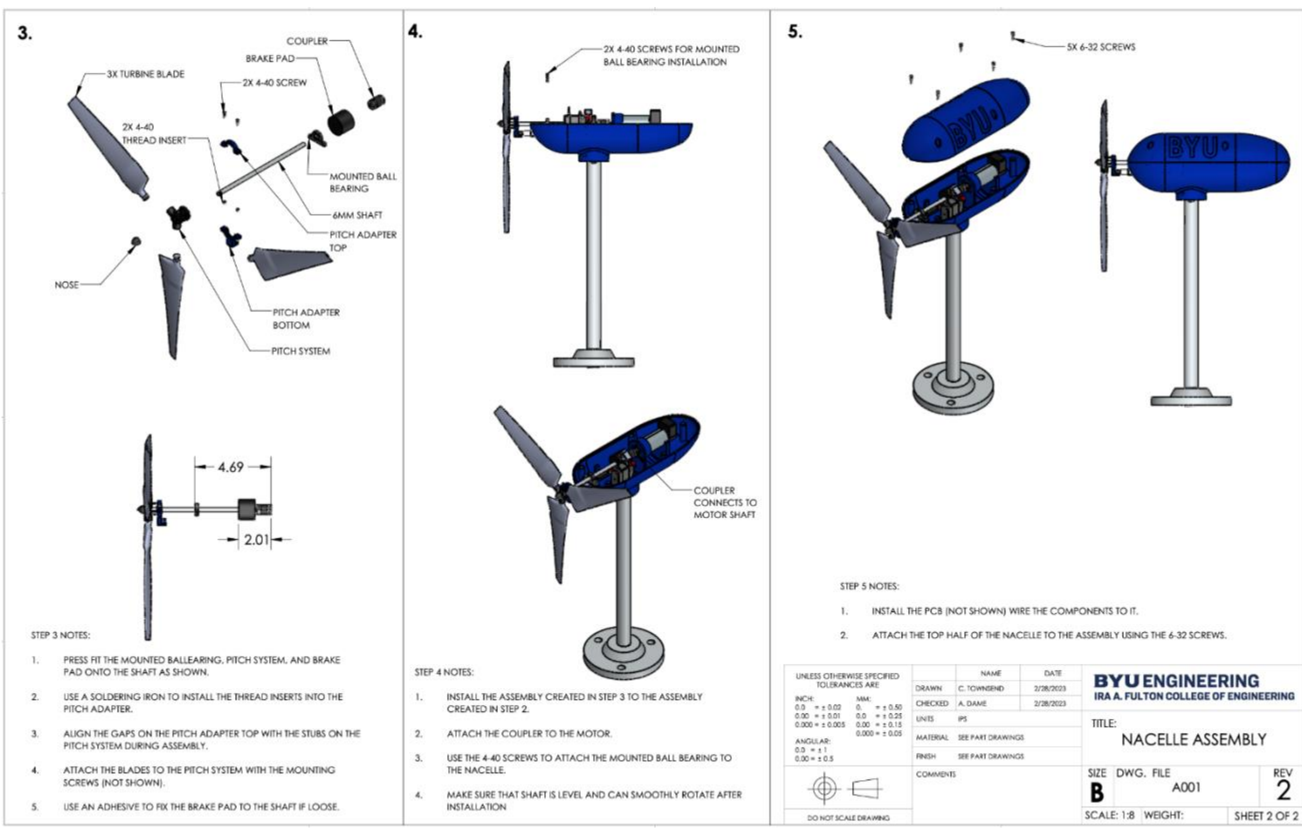

Figure 14: Final assembly sheet 2

4.10 Assembly and Commissioning Checklist

Within 25 minutes of the competition, the following installation procedure should be completed:

- First, feed the intermediate wire through the hole in the tubing of the foundation, and the spiral design is then placed on top of the sand.
- Screw the foundation clockwise via a handle that attaches at the top until 9 or 10 cm of tubing is sticking out above the water (doing so gets the base close to the 20 cm depth limit and maximizes the sand's potential to support the foundation).
- Apply the massage gun to the portion of the pipe that is still above the water to straighten it until a bubble level shows that the foundation is perpendicular to the floor. The foundation should sink another centimeter into the sand as it is vibrated.

Once the turbine is in the wind tunnel, within 5 minutes, the following commissioning checklist should be completed to ensure 20 minutes are available for testing:

- Connect the foundation to the competition-provided stub. The intermediate wire must be pulled from the top of the foundation to the top of the stub to connect with the turbine.
- Connect the wires between the stub and the bottom of the turbine shaft and screw the turbine base to the stub.
- Manually pitch the blades out to fully feathered and visually verify the pitch mechanism linkages are aligned properly.
- Manually spin the blades to ensure that the shaft can rotate freely and is free of all obstacles.
- Ensure that the bolts on the pitch system are fully tightened.
- Test the emergency brake by ensuring that power output has decreased to 10% of the maximum RPM within 10 seconds.

4.11 Results from Laboratory Testing

Starting early in the turbine development, mock competitions were performed to understand how the turbine would perform in a competition setting. The first mock competition set a baseline for future tests and has since guided the design and prototyping decisions. The results of the initial mock competition test are described in Table 2.

Table 2: Initial mock competition data

Wind Speed (m/s)	**Generator Speed (RPM)**	**Power (W)**	**Score (Points)**
5	954	1.20	0.84
6	1235	2.00	1.60
7	1505	3.25	2.60
8	1772	5.12	3.58
9	1807	5.45	2.18
10	1970	6.30	1.89
11	2138	7.60	0.76

Note that in the initial mock competition, a static load was used. The total initial power curve score was 13.45 points. Outside of mock competitions, subsystems were tested individually to make specific design decisions and to ensure a more robust system. While subsystem testing was integral to the development of the turbine, the depth of these tests will not be explained in this document as the results of the full turbine prototypes validate the function of each subsystem. After testing subsystems separately, all the systems were integrated to select appropriate resistors to maximize power output. The results of resistor testing are shown in Table 3. Power is generally expected to increase as resistance decreases, but the generator works more effectively at higher resistances. This complex interaction causes the optimal resistor values to fluctuate in order to obtain the highest power output at each wind speed.

Table 3: Optimal resistor testing

Wind Speed (m/s)	Optimal Resistor Value (Ohms)	Generator Speed (RPM)	Power (W)	Score (Points)
5	16.7	1365	1.88	1.32
6	14.5	1710	3.24	2.59
7	13.5	2005	4.62	3.70
8	16.7	2310	5.89	4.12
9	16.7	2578	7.65	3.06
10	9.7	2676	9.70	2.91
11	15.1	3054	13.26	1.33

The turbine design decisions were driven by whether design changes would improve the points scored on the power curve. Table 3 shows the loading that will score the highest on the power curve. The total power curve score obtained during the optimal resistor testing was 19.03 points.

All scored tasks in the turbine testing contest were tested and evaluated throughout the team’s work on the turbine. The most current scores for these tasks are shown in Table 4.

Table 4: Current competition scores

Task	Scored Points	Possible Points
Power Curve Performance Task	19.03	50
Control of Rated Power and Rotor Speed Task	50	50
Safety Task	35	50
Foundation Success Task	50	50
Durability Task	60	60
Structure Weight	36	40
Total	**250.03**	**300**

The current foundation only displaces 1 mm, which is much less than the 25 mm of allowable displacement. This is reflected in the Foundation Success Task score. The foundation was also able to successfully perform within the competition parameters at wind speeds up to 22 m/s, which is reflected in the Durability Task score. The foundation mass is 1.15 kg, which when compared to last year’s design reports, is lighter than many other teams. While this comparative score is impossible to know before the competition, the score assigned in Table 4 is assuming a 3rd place finish in foundation weight.

To ensure safety, shutdown capabilities must be built into the wind turbine. One shutdown method lets the operator press an emergency stop button at any wind speed and stop the spinning within 10 seconds. The turbine must then restart after an indefinite time. Both the shutdown and restart have been a success in testing scenarios, awarding 25 of the 50 Safety Task points. The second method is a load disconnect, in which the turbine shuts down when disconnected from the grid. As of the most recent test, the turbine successfully stops but cannot automatically restart. These results award only 10 of the remaining 25 points for the Safety Task, so the two portions total 35 points, as seen in Table 4.