# Technical Design Report

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## University of Colorado Boulder

Submitted to
Collegiate Wind Competition 2021

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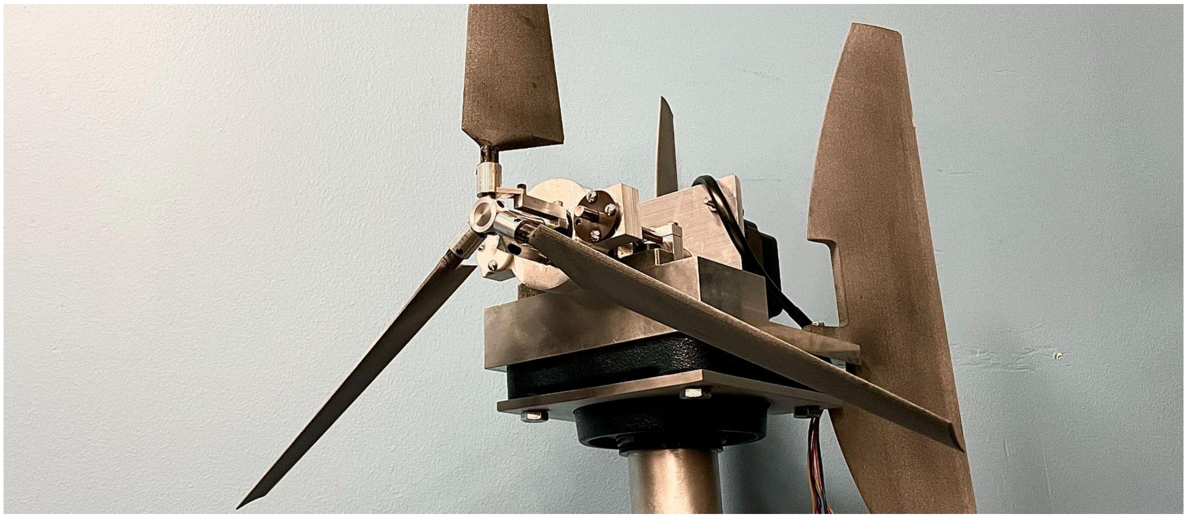


## Executive Summary

The Wind Turbine Prototype aimed to utilize the team's technical skills to design and fabricate a fully functional turbine. The team approached the learn-along status as an opportunity to pursue more ambitious designs without risking competition scores. By attempting all five turbine testing tasks, the team sought to build experience across the competition tasks to build a comprehensive baseline for future teams and define challenges and areas of focus for future competitive teams. This document discusses design decisions, system testing and characterization, and the attempts of the CWC Turbine Testing Tasks. All wind tunnel testing was conducted using the CU Boulder Aerospace department's wind tunnel. Although the test section was too small for testing, the outflow proved sufficient for basic performance testing. The team achieved a turbine design that reliably demonstrated a functioning passive yaw system, and an effective pitching system for turbine control and emergency stop capabilities. Future teams can improve the current design by building a generator that allows for a lower cut-in wind speed and have a more robust control system that allows the user to control each system remotely. Overall, the team is proud to have a functional prototype as University of Colorado Boulder's first wind team that will help future teams further develop and improve the turbine for future Collegiate Wind Competitions (CWC).

## Design Objective Description

The CWC specifies five turbine testing tasks that competing teams can attempt. As a first year learn-along team, CU decided to try all five tasks to learn as much as possible about the design process required to be successful in each piece of the contest. While CU hasn't had the opportunity to test the turbine prototype in the competition wind tunnel, the team is confident that at least two of the tasks were successfully accomplished. These two tasks are the Durability and Safety tasks, because the team's passive yaw system and emergency stop procedure worked very well during tunnel testing on CU's campus. The Power Curve Performance and Control of Rated Power and Speed tasks had promising test results, but the CU wind tunnel was not able to produce wind speeds above 10 m/s, and the team has some minor remaining issues to solve with the pitching control system. The Cut-In Wind Speed task was the only component the team was not able to come close to. The motor purchased to function as a generator does not have a small enough cut-in torque to produce sufficient RPMs for power production below wind speeds of 6 m/s. The issues with the generator and pitch control system will be explained to CU's 2022 learn along team, and the current team has a plan for how the successors should successfully iterate the turbine.

## Design Influence

The team was inspired to model the airfoils in QBlade used from Penn State and Virginia Tech in 2019 as a benchmark of possible blade designs. After selecting other airfoils to compare with the previous team designs the team found that a combination of newly selected airfoils and one from a previous team was the most optimal design for our turbine. We selected the same generator, in this case a DC brushless motor, from

## Mechanical Design & Analysis

### Blades Design and Analysis

The goal of the blade design is to maximize the amount of power coming from the wind. This translates to maximizing the amount of torque that the force of the wind produces on the blades, thus increasing the acceleration and rotational velocity. There were key metrics used to quantify the performance of the blades and this includes the Tip Speed Ratio (TSR) and the Cp ,or coefficient of power.  The theoretical maximum Cp that the blades can produce is 59% which is derived from the Betz limit and our team focused on maximizing the Cp of our turbine blades.

To design the blades, the range of reynolds numbers that the blades would experience was calculated using assumed overall airfoil dimensions. The team then selected various airfoils to use as the defining structure of the blade.  The team decided to have two airfoils for the blade, one for the root and one for the tip of the blade. This allowed us to choose a design for the root that would maximize torque at lower wind speeds and a design for the tip that would maximize speed at higher wind speeds. Additionally, the root of the blade was chosen to be thicker to provide stability. Using this knowledge the team ended up with two sets of airfoil designs to use for our blade design.

The airfoils were loaded into the open source software, QBlade, to perform blade optimization. This decision was made after seeing many previous CWC team members also utilizing the program. This software optimizes the blade geometry along with twist angles and chord lengths to run for a specifically chosen tip-speed ratio, Reynolds numbers, rotation speeds, and other tunable parameters.

The finalized selected airfoils were the GOE195 and the Eppler 67. While the power coefficient was slightly lower than other iterations by roughly 2% this selection was more consistent when testing at different ranges of Reynolds numbers and wind speeds.

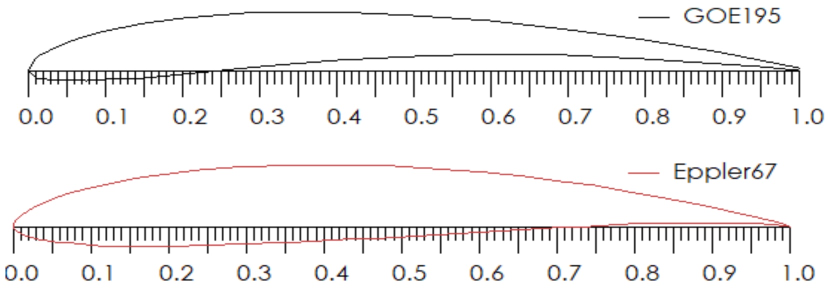


**Figure 1.** Iteration 7 using GOE 195 as tip and Eppler 67 as root. Iteration 2 replacing root with FX63-137

The final turbine blade design showed an average Cp of 37% with an optimized TSR value of 5.

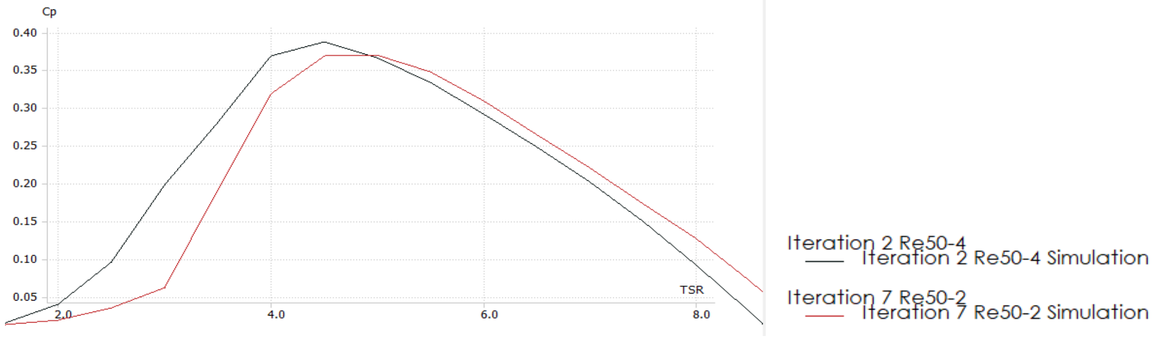


**Figure 2. Performance Coefficient vs Tip-Speed Ratio** A comparison of Iteration 7 using GOE 195 as tip and Eppler 67 as root and Iteration 2 replacing root with FX63-137 in assumed performance conditions.

### Tailfin Design and Analysis

The tailfin was designed with simplicity and stability in mind. The tailfin uses a single airfoil as the cross-section to efficiently direct air and to use the cross flows to realign the nacelle of the turbine for maximum energy capture. To reduce the amount of potential oscillation of the nacelle a second tailfin was implemented, one on either side, to increase the stability of the turbine.

In yawed flow, the resultant force on the tailfin nearest to the wind drives a moment aligning the nacelle with the airflow. When the nacelle is aligned, the positive angle of both tailfins results in equal, canceling moments from the airflow, maintaining stable alignment of the rotor with the flow. Furthermore, the nacelle with the generator was massive enough to mitigate the impact of moments from the rotation of the blades.

**Figure 3. Demonstration of Passive Yaw System** a) Turbine in yawed flow. b) Turbine after aligning with airflow and capturing energy. Note the stability of the passive yaw system when aligned with the airflow.

### Pitch System

The mechanical blade pitch system is inspired by a helicopter swashplate. The system is centered around a thrust bearing, a nonrotating plate secures the outer race of the thrust bearing, and a rotating driver secures the inner race of the thrust bearing. A stepper motor mounted in the nacelle pushes the plate in and out, which pushes the rotating driver up. Three blade mounts are connected to the system with three rods, as the driver is pushed up, the rods are pushed up, which pushes the side of the blade mounts, rotating the blades. Every component in the rotor is 6061 T6 Aluminum except for the driveshaft and driver, which are 303 Stainless Steel, the blades are 3D printed Nylon PA12.

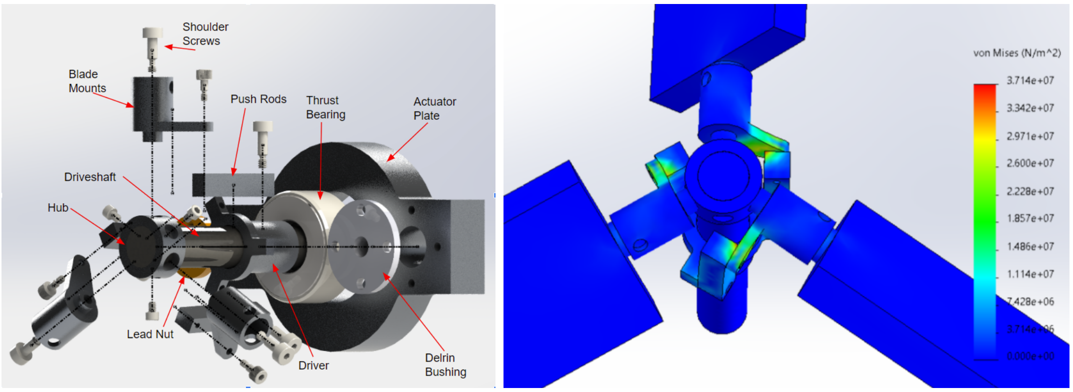


**Figure 4. Pitching System Design and Analysis** a) Exploded diagram of pitching system components. b)

FEA simulation of pitching system, Note the high loads at the blade mounts and rods.

An FEA simulation at max loading conditions was applied to the rotor, parts of concern were the blade mounts and the driver. The simulation in **Figure 4b.** shows that the blade mounts and rods have the highest stresses, however even under extreme loading conditions, the components maintain a factor of safety of 7.5 before plastic deformation.

### Yaw System

The turbine uses a passive yaw system with 2 tailfins described in the above section. The tailfins were 3D printed out of Nylon PA12. The entire nacelle is mounted on a large bearing, and contains the rest of the turbine components. The Nacelle Bracket provides a platform for the components, which are all machined out of 6061 T6 Aluminum.

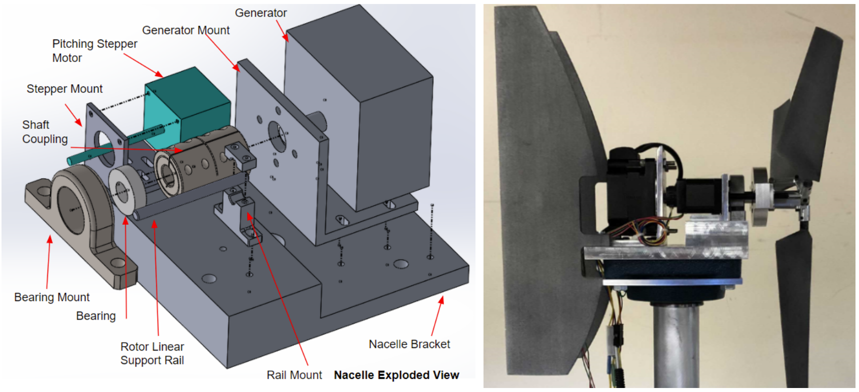


**Figure 5. Passive Yaw System Design and Analysis** a) Exploded diagram of nacelle components. b) Assembled nacelle including the 3D printed tailfins, generator, and pitching stepper motor.

### Structure

The entire turbine is supported by a 6061 T6 Aluminum hollow tube, which is mounted to the baseplate with 6 #10 screws. FEA analysis demonstrated minimal stresses in the tower at maximum operating conditions, so more thorough analysis was not required.

## Electrical Design & Analysis

### Generator selection

As CU's first learn-along team and with the limited resources at its disposal, a decision was made early on in the process to buy an off-the-shelf generator. Since CWC encourages each team to learn as much as it can from previous teams, the team inspected reports from previous competition years and came across a brushless DC motor used by California Maritime Academy. The generator is a critical component in the performance of the wind turbine and the team was mainly concerned with three aspects of it. First, the generator needed to produce at least 4V at the minimum expected RPM in order to achieve the cut-in wind speed task. The rectifier would have a voltage drop across it, so a portion of the output voltage of the generator would be lost to it. Hence, the idea with aiming for 4V was that it would have provided enough slack to account for this scenario. Second, generators are non ideal and have losses associated with their internal resistance. Therefore, the higher the armature resistance the less efficient a generator is. However, the selected generator only has an internal resistance of 0.18Ω and would therefore only dissipate a small amount of power. Third, it was really important that any selected generator had a low cogging torque. In order for the shaft to rotate and the generator to produce harvestable power, this cogging torque has to be overcome and at low wind speeds it is critical to have low cogging torque. As an added bonus, this particular generator has a built-in Hall Effect Sensor which provides RPM data in real time. That RPM data was used to inform the design of the dynamic control system used to optimize power production.

The team independently characterized the purchased motor as a generator because these specifications were not available. The team purchased two motors, allowing for one to be used as a motor to drive the other one in order to determine the power curve characteristics of the motor when used as a generator. This strategy also allowed for a spare generator in case the other one broke. For the test, the two motor drive shafts were connected using a shaft coupling as shown in **Figure 6a**. A power supply was connected to the three phase motor driver purchased for the power curve testing, and the team obtained data for the period at different currents from the generator hall sensor outputs. The team measured the voltage output of the generator at the output of our turbine PCB's rectifier circuit so that the three phase sinusoidal output of the generator could be read as a constant DC voltage as shown in **Figure 6b**. Using current and voltage data, a power curve could be found to help inform the control code of the blade pitching controls mechanism **Figure 6c**.

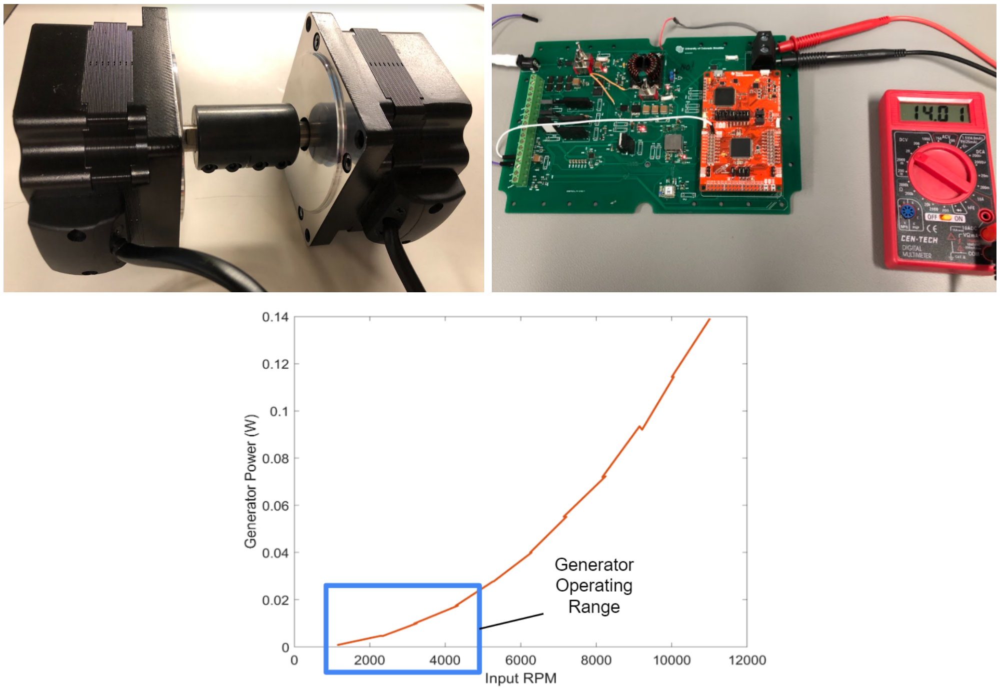


**Figure 6. Generator Characterization** a) Generator and motor clamped together for initial generator testing. b) DC voltage output of the turbine PCB when powered. c)Power curve of generator

### Rectifier Design

To transform the three-phase output of the generator into the DC voltage that is fed into the SEPIC, the team implemented a full-bridge rectifier. The rectifier uses six schottky diodes that are forward biased only when a positive voltage is applied to them. To filter the output voltage and reduce its ripples, three capacitors are added to provide an extra boost. The team tested the circuit shown in **Figure 8** by first connecting the generator three-phase wires to an oscilloscope to observe its sinusoidal behavior.

Thereafter, the generator was connected to the circuit and a DC voltage was observed with minimal ripples.

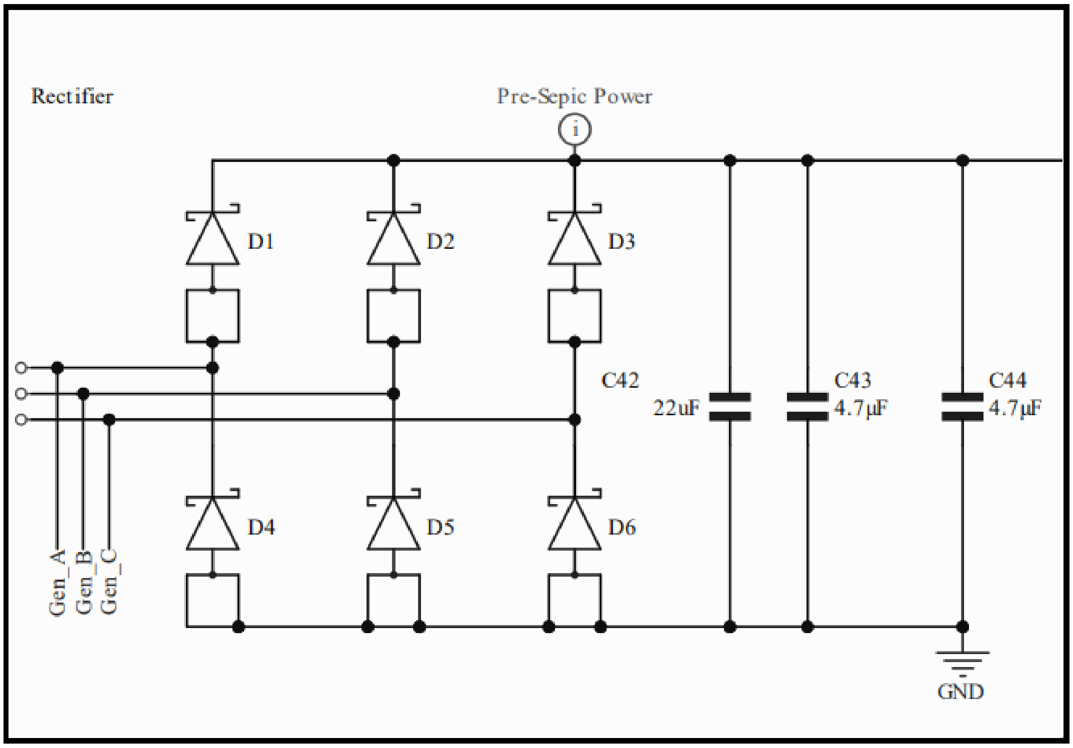


**Figure 7.** The rectifier circuit is shown above. It turns the three-phase AC output of the generator into a DC voltage.

### DC-DC Converters Design

The load would contain a 12V rechargeable battery and given that the generator output would depend on wind speed, a converter had to be designed in order to obtain a steady voltage. A desired voltage of 14V was chosen as it would be ideal to charge the battery and would meet the CWC's voltage limit of 48V, and initial calculations suggested that the generator would output anywhere from 4V to 20V. The ability to maintain a steady voltage would also meet the durability task requirements. Therefore, a Single-Ended Primary Inductor Converter (SEPIC) which has the ability to buck or boost input voltages was implemented. The converter would contain its own Texas Instruments regulator chip which would handle the fast switching of the MOSFET in order to set the duty cycle according to the input-output relationship and a compensation feedback loop to improve performance. Two other buck converters were also designed , a 3.3V and 5V to power some of our critical systems.

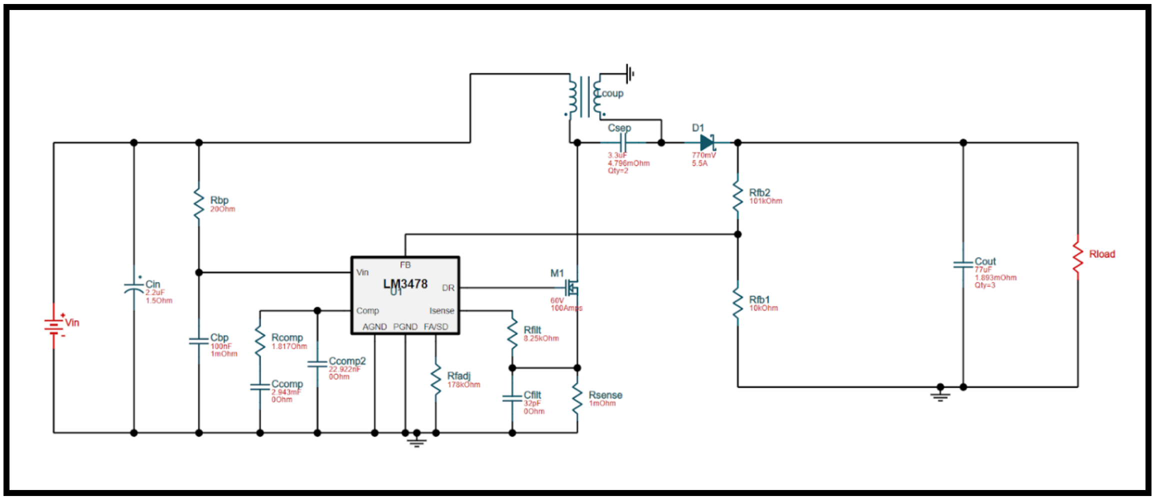


**Figure 8. SEPIC Circuit Schematic** The SEPIC circuit uses an LM3478 IC regulator from TI to set duty cycle.

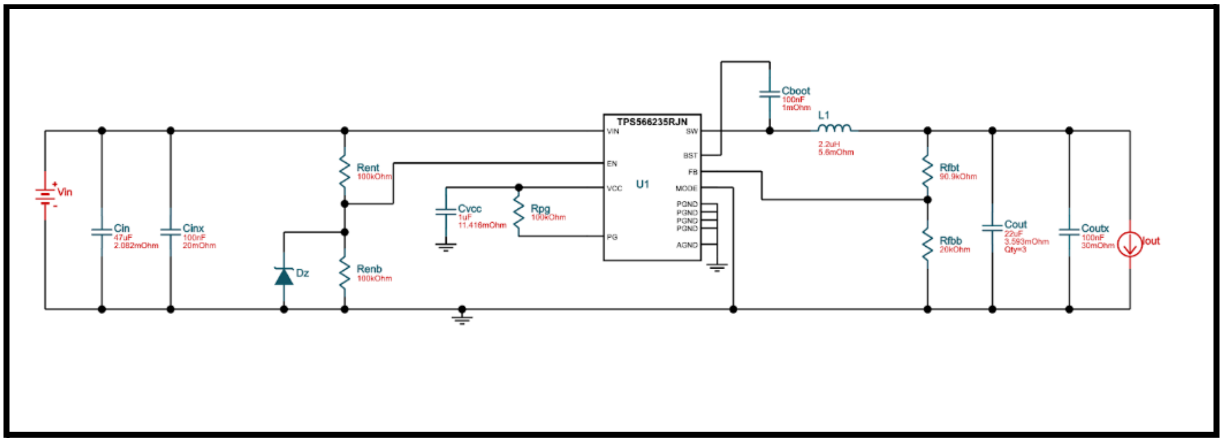


**Figure 9. 3V3 Buck Converter Schematic** This converter provides power to the MCU and other electronics.

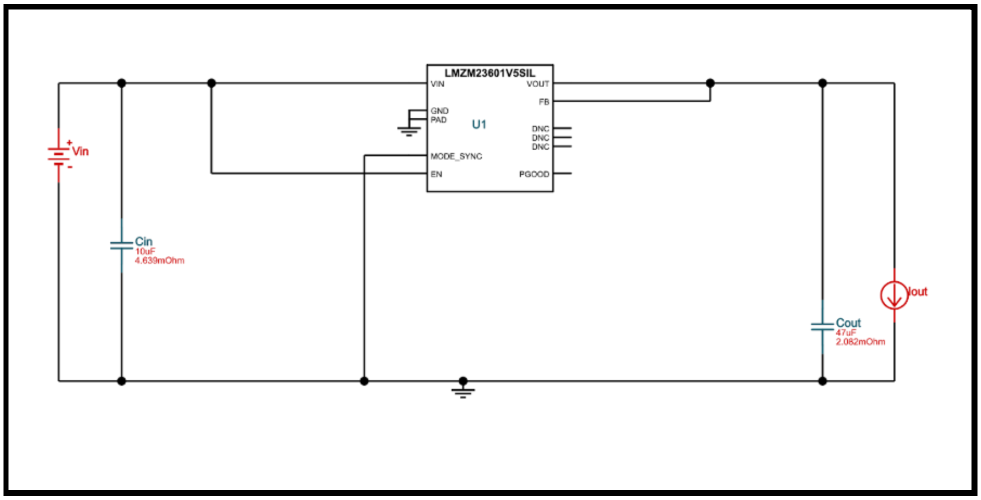


**Figure 10. 5V Buck Converter** This converter powers the stepper motor used in the pitch system.

### Load

The goal of the load circuit is to enable the charging of the 12V battery while also allowing the turbine to meet the safety task requirements. CWC requires that turbines have the ability to safely shut down rapidly when either disconnected from the grid or upon command through the push of a button. Both scenarios would cause an open-circuit in the load, so the team implemented a circuit to sense any fault in the path of the current through the use of a current sensor. The sensor feeds the information to the MCU which in the event of a shutdown sends an initiation signal to the stepper motor driver in order to pitch the blades to their feathered position causing zero lift and no net drag. Turbines are also required to restart at any wind speed above 5 m/s. In order to accomplish this, the battery must supply power to the electronics until the turbine gets up to speed and the generator begins to produce sufficient power again. Therefore, current has to flow from the load side to the turbine side to supply any necessary start up power. The load circuit was designed to do exactly that. The team tested this theory using an LTspice model and the simulation seemed to confirm that the design would work.

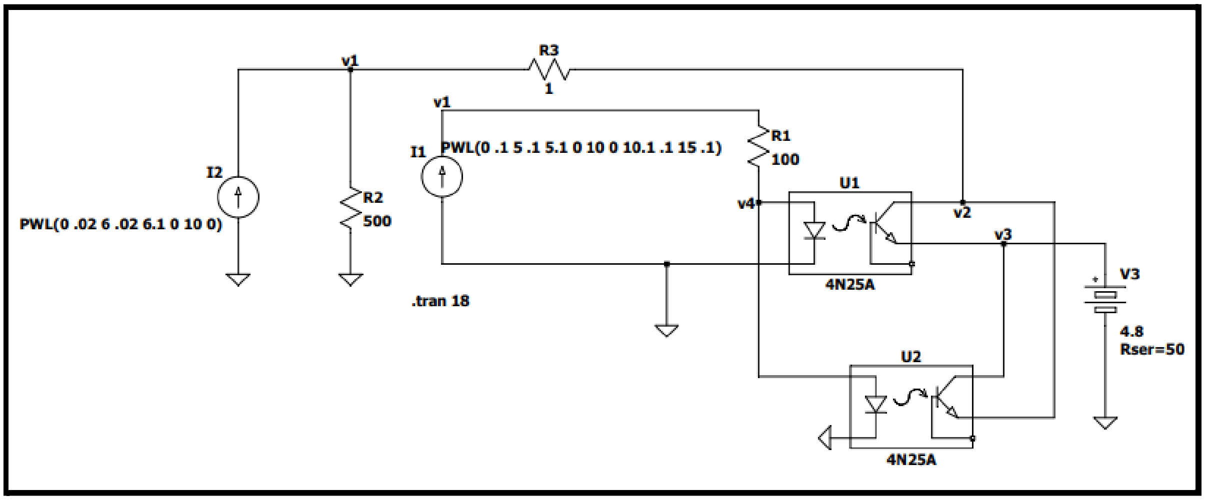


**Figure 11. Simulation LTspice model** The model uses two photorelays to mimic the behavior of the single AC photorelay used in the actual load.

**Electrical Assembly and Verification**

The first revision of the PCB was just a bare board, which meant that all components (~90 resistors, capacitors, integrated circuits, etc.) had to be placed by the team. A sheet metal stencil was laid over the PCB to apply solder paste on all the copper pads to eliminate the need to hand solder each piece and provide a more consistent layer of solder for each pad as shown in **Figure 12a**. After the solder paste was applied, the team used a microscope to verify sufficient coverage on each pad of the PCB as demonstrated in **Figure 12b**. A pick and place machine was used for the smallest components. The team did not want to connect the PCB to power for fear of damaging the ICs without first ensuring that a continuity test was conducted with all the necessary components, so a multimeter was used to test for any short circuits. The team had to reorder/replace around a dozen pieces that were not the correct size/specification for the board, however the board worked well enough to use for testing as the board's second revision was finalized. Critically, the team learned how tedious PCB assembly is and will likely order revision two pre-assembled to save time and prevent errors in the future.

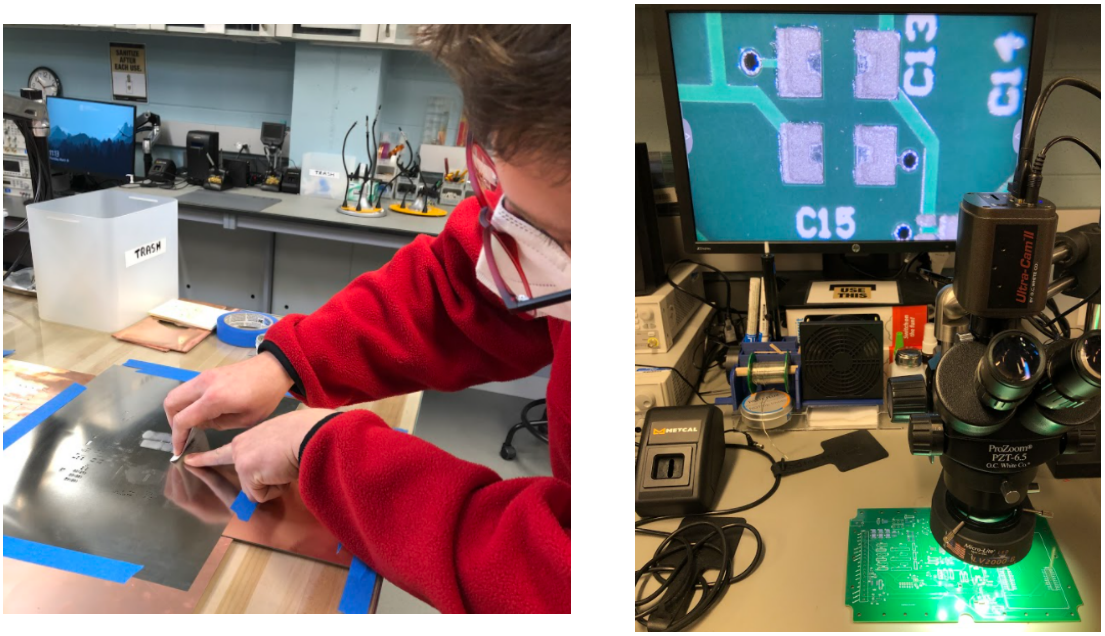


**Figure 12. Electrical Assembly** a) Solder paste application process. b) Microscope used to verify uniform coating of solder paste on metal pads during initial PCB assembly.

The team also did some simple multimeter continuity testing on the cables that connect the generator outputs in the nacelle to the turbine PCB screw terminals in the enclosure, and from the turbine PCB enclosure to the load PCB enclosure. As specified by the CWC rules, the team is utilizing quick connectors so the turbine, turbine PCB enclosure, and load PCB enclosure can be disconnected and moved separately. The PCC between the turbine and load PCBs will be attached using Anderson Powerpole connectors as specified by the rules.

## Controls Design & Analysis

### Wind Turbine Control Theory

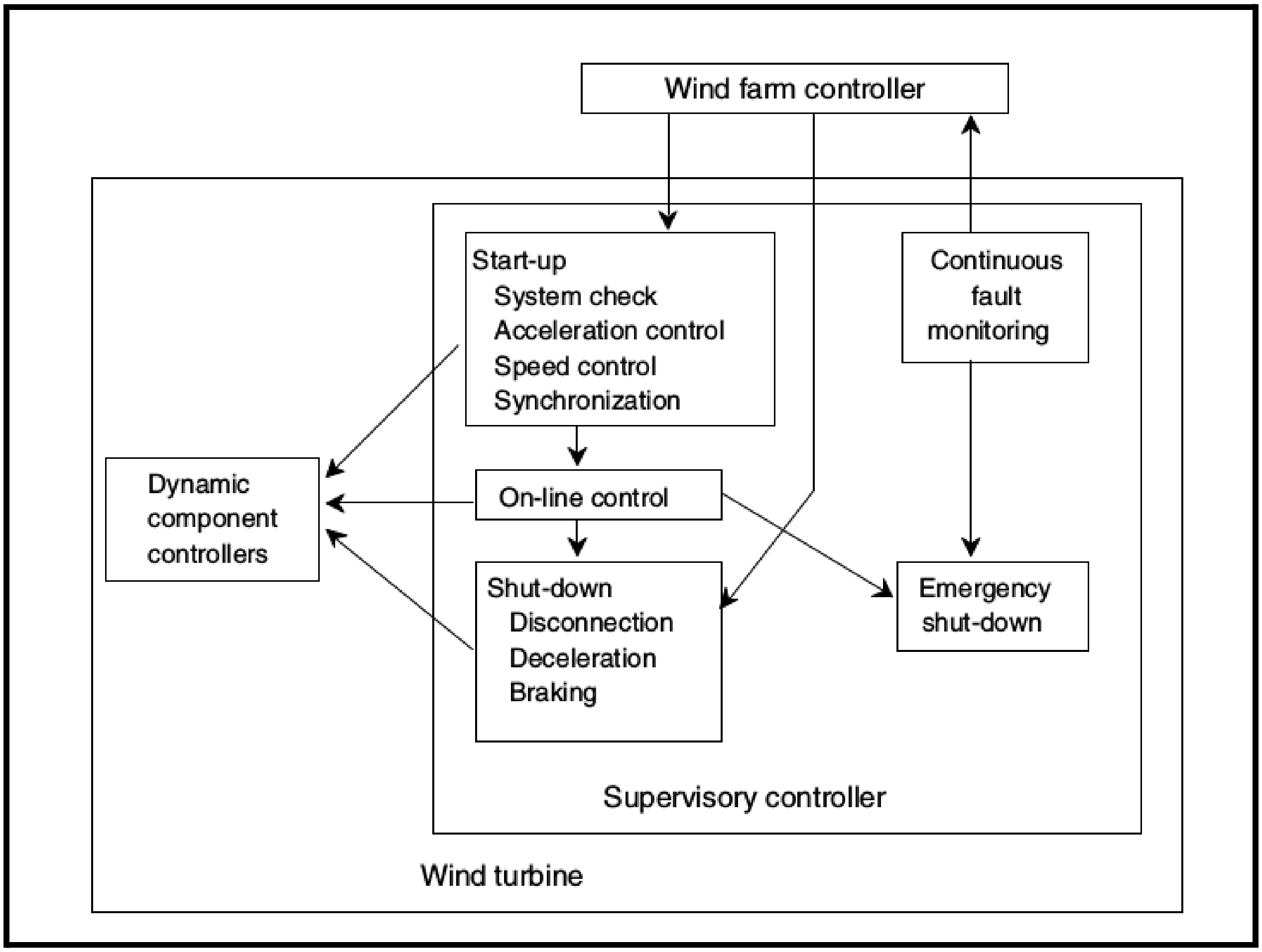


**Figure 13.** An overview of wind turbine control systems, as seen in *Wind Energy Explained: Theory, Design and Application, Second Edition James Manwell, Jon McGowan, and Anthony Rogers*.

As seen in the above figure, wind turbine control is divided into several components. For this project, the wind farm controller is irrelevant, as we're only working on a single wind turbine. The Emergency shutdown and Shut-down control systems are included elsewhere in this report. We will focus on the dynamic component controllers. The dynamic component controllers that are a part of our wind turbine are the yaw control and pitch control. Since the yaw control for our system was completely passive, using mechanical components only, this system focuses on the more active pitch control, which is an active, electrically driven system.

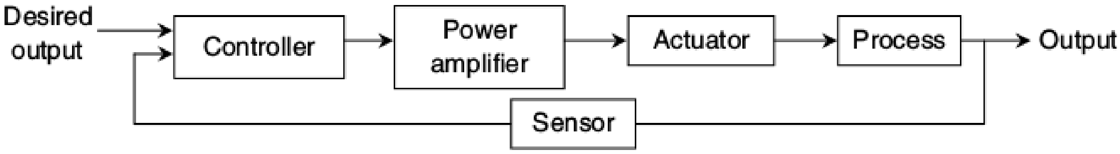


**Figure 14.** A typical control system for a single wind turbine, as seen as *Wind Energy Explained: Theory, Design and Application, Second Edition James Manwell, Jon McGowan, and Anthony Rogers***.**

A generalized control system that applies to almost all wind turbines can be seen in the above figure. Though similar, in the below figure, you can see a control system diagram specific to our wind turbine.

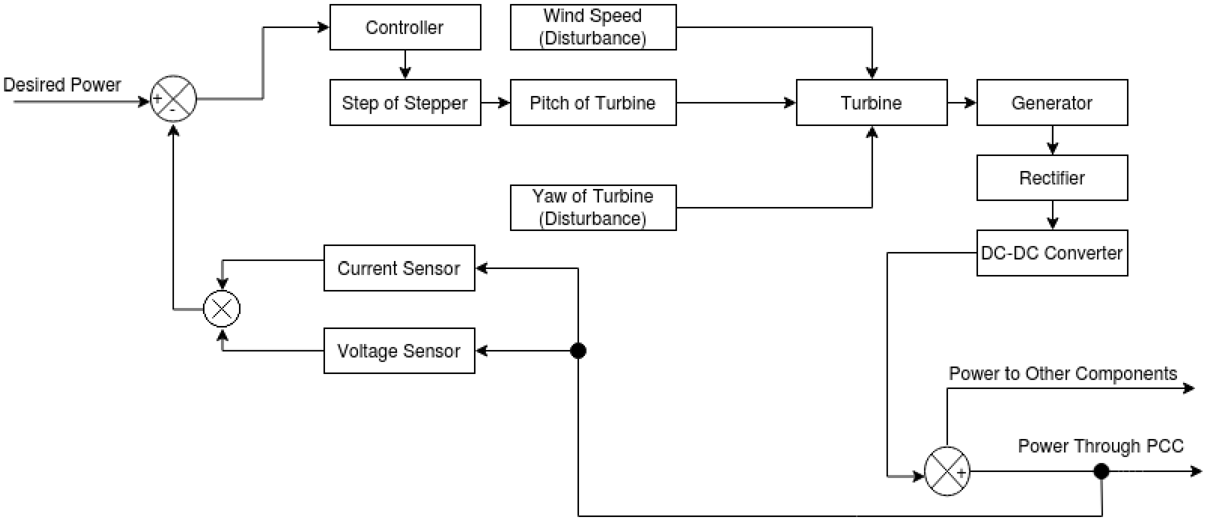


**Figure 15. A block diagram** specific to our wind turbine.

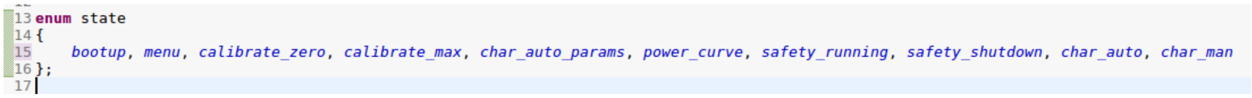
Note that the yaw of the turbine is considered a disturbance here. In the context of the whole wind turbine, the yaw of the turbine is a parameter to be controlled. However, this block diagram is from the standpoint of the pitch control only. Yaw is passively controlled, so it is a disturbance relative to the pitch control. Also note that the control system design only changes the Controller block, which lives on the microcontroller. Everything else in the diagram is a part of the physical system.

As described in *Wind Energy Explained: Theory, Design and Application,* "Below rated wind speed, control systems might attempt to maximize aerodynamic torque (or power); above rated wind speed, a control system would attempt to limit aerodynamic torque." The CWC's Power Curve Performance Task and Control of Rated Power and Rotor Speed Task are respectively analogous to these two general wind turbine specifications. However, one key difference in the Power Curve Performance Task is that the CWC specifies a constant power generation over varying wind speeds, which is different from the general turbine goal of maximizing power below its rated speed.

Description of design requirements, relevant theory and literature review, Simulink Models/Simulations,

### User Interface State Machine

Although Laplace-based dynamical systems modelled with feedback loops are what we usually consider control systems -- which is what we use for pitch control -- another important control system in our turbine was selecting between operating modes with the turbine. We were able to accomplish this with a state machine programmed into the microcontroller, which prompts and takes input from the user via a Bluetooth chip included in our PCB send over UART. Seen below are the various states of the state machine, which the user can switch between when prompted in the Bluetooth menu with his/her cell phone.



```
enum state
{
    bootup, menu, calibrate_zero, calibrate_max, char_auto_params, power_curve, safety_running, safety_shutdown, char_auto, char_man
};

```

Note that not all states are selected by the user. For example, bootup is the default state of the system, which the turbine enters upon startup. Different states correspond to different functions. They are described below:

- **bootup** -- not selected by the user. This is the default state of the wind turbine. It is entered by the turbine microcontroller when it first receives power. It is solely for the code to keep track of when to first display the menu.
- **menu** -- entered after bootup or when the user exits another state. In this state, a menu dialog is displayed on the user's Serial Bluetooth Monitor on his/her phone.
- **calibrate** -- In these two states, the user selects the minimum and maximum position of the turbine pitch, with the maximum position ideally being the stall angle. These tell the microcontroller's Laplacian dynamical control system how many steps it can feed to the stepper motor, which in turn pitches the blades.
    - calibrate_zero -- selected by the user from the menu. User enters step commands to pitch stepper motor's minimum step, and advances to the next state when satisfied.
    - calibrate_max -- selected by the user after exiting calibrate_zero. User enters step commands to pitch stepper motor's maximum step, and advances back to the menu when satisfied.
- **char_auto_params** -- selected by the user from the menu (not included in state machine diagram). While characterizing the system automatically, the system must step through various pitch configurations. The time for each step is set here.
- **power_curve** -- selected by the user from the menu. The user enters this when testing the power curve performance task, and instructs the wind turbine to control the pitch accordingly.
- **safety** -- selected by the user from the menu. The user enters this when testing the emergency shutdown task, and instructs the wind turbine to expect the shutdown cue.
- **char_auto** -- selected by the user from the menu. The user enters this when s/he wants to characterize the system automatically, and design a control law around what s/he gets.

- **char_man** -- selected by the user from the menu. The user enters this when s/he wants to characterize the system manually.

Below is a state machine diagram to visualize the above information.

**Integrator Controller Design**

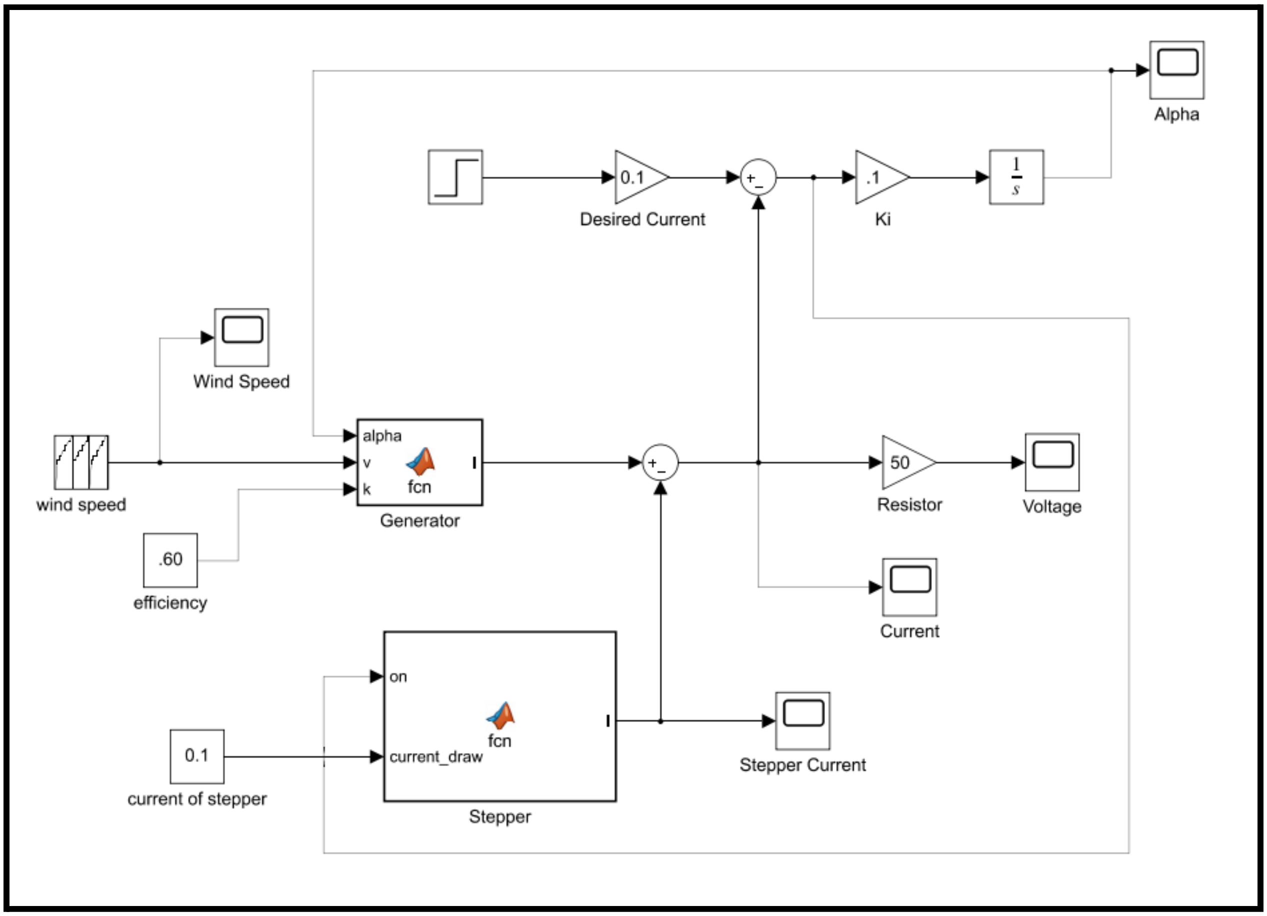


**Figure 16. Simulink Model** to simulate the wind turbine

Before designing a control law, we decided to simulate the system to be controlled in Simulink. In order to design a control law, we had to first obtain measurements from the system to determine its characteristics. We swept a range of wind speeds to determine the stall angle (see section Results from Laboratory Testing, Power Curve Performance Task). In order to have a controller that performed consistently, we needed to keep the angle below the stall angle at all times. These measurements were crucial in the control system design.

## Results from Laboratory Testing

The team conducted preliminary turbine tests against the turbine testing contest to demonstrate the capabilities of the turbine to succeed at more rigorous tests and identify areas for future improvement. Through the aerospace department at the University of Colorado, Boulder the team was able to get access to an eiffel configuration wind tunnel (Figure) for the turbine testing tasks. Unfortunately, the test chamber of the tunnel is too small to accommodate the full turbine so testing was conducted at the airflow exit of the tunnel. Although the outflow is more turbulent and spatially variant than in the test chamber, it was adequate for our tests and the best we could do with facility limitations due to COVID. The team used a handheld anemometer to determine the range of wind speeds as well as the controllability of the outflow wind speed. The outflow is more turbulent and inconsistent than in the test section due to the positioning of the fan, but wind speeds of 6-10 m/s were achievable for tests. Lower wind speeds were too inconsistent for reliable testing.

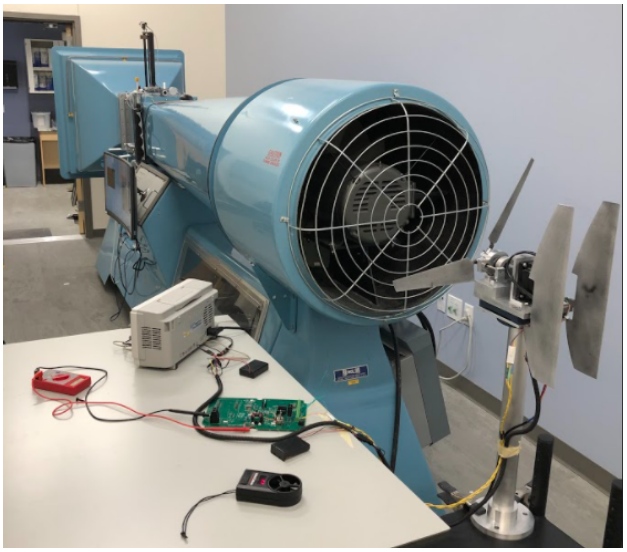


**Figure 17. Turbine Prototype Testing Setup** including the wind tunnel, fixed turbine, electronics, and oscilloscope for recording signals.

**Cut-In Wind Speed Task**

The team was unable to properly complete this test due to limitations in the testing setup. However, based on other tests, with the blades pitched to an angle of attack of 45 degrees, the maximum power producing angle through testing, the team expects a cut-in wind speed below the 6m/s at which testing was possible and positive power was achieved. Because autonomous pitching and control was not achieved

**Power Curve Performance Task**

The team came close to having functioning electronics and a controller that could maintain a stable power reading, but due to time, facility, and resource constraints, all the elements needed for the test weren't able to be implemented and integrated simultaneously for testing. The mechanics of the turbine were tested across wind speeds to characterize the pitching system, generator, and electronics to inform the controller design and demonstrate the mechanical functionality of the design.

Data was collected on the RPM produced by the driveshaft and the voltage after the SEPIC at different blade pitch settings and angle of attack at wind speeds of 6, 8, and 10 m/s. The final position being the blades at 90 degrees in full-stop position, which do not produce RPM at any wind speed. This data is shown in **Figure 18.** The data acquired from all the pitch settings and wind speeds revealed a region on the graph showing the transition from a fairly proportional relationship between RPM and angle of attack up to the stall angle of the rotor. This characterization was essential for the programming of the pitch control system. To program the pitch controls, the angle was maintained below the stall angle to enable a simpler linear control system. Ultimately, an integrator controller was designed, as the expected characteristics of the system were a first order system, and the dynamics of the system were slow to respond for which an integrator controller is sufficient. Because there was not a wind speed sensor in the system, wind speed was treated as a disturbance to the system, making the integrator term necessary for disturbance rejection. The team is hopeful that with further work on the controller and electronics, this testing task will be feasible in the near future.

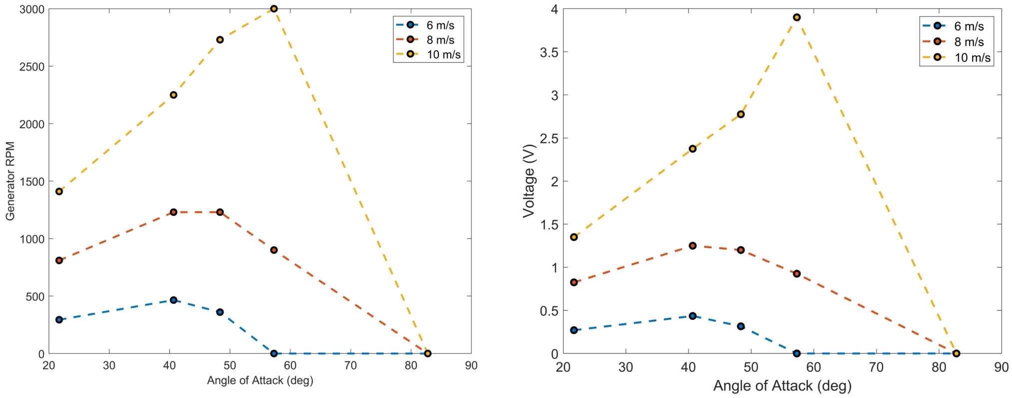


**Figure 18. Pitching System Characterization** a) Generator RPM as a function of the blade pitch angle of attack for 3 representative wind speeds determined by turbine testing requirements. b) Voltage at PCC vs blade pitch angle of attack.

### Control of Rated Power and Rotor Speed Task

Although the wind tunnel was incapable of achieving speeds above 10 m/s as required for this test, the team's turbine has the pitching and mechanical reliability to perform well at this task with an appropriate pitch controller. Figure x demonstrates the capability of the pitching system to alter rpm and output power at all wind speeds. Furthermore the blades and rotor successfully withstood the high loading of flattening the airfoils against the wind flow at 10 m/s without plastic deformation.

### Safety Task

The electrical and controls system was designed for both emergency stop scenarios required for the Safety Task, manual stop and disconnection of the load for the PCC. Between the flattening of the blades against the airflow and shorting the generator, 0 rpms is consistently achieved in shutdown at all wind speeds. The procedure executes and stops generator RPM within 10 seconds. The load circuit integrates an emergency stop button, which, via a relay, stops current flow to or from the load to the turbine. The turbine circuit's current sensor detects this lack of current flow and initiates the shutdown sequence, in which the blades are oriented in a position such that no lift occurs and hence shuts down the turbine. To reinitiate the sequence, the relay restores current flow, at which point the MCU turns back on, and pitches the blades back to a moveable position using the power supplied by the battery.

**Durability Task**

To demonstrate the capability of the team's turbine to perform in a wind variety of weather conditions, the team tested the yawing capabilities of the turbine in a variety of wind speeds over an extended period of time. In this task, the team's turbine was subjected to a wide variety of wind conditions from 6-10m/s. Yawed flow was achieved by manually misaligning the nacelle with the direction of wind flow from the tunnel.

The tunnel demonstrated that the passive yaw system consisting of a bearing and tail fins worked as intended. The bearing and tail fins maintained stable and smooth directional changes in every test scenario with yawed flow between 0-180 degrees across wind speeds. In each of these cases, positive power was consistently achieved. Furthermore, the passive yaw system did not experience unstable oscillations during operation thanks to the dual tailfin design and sufficient weight of the nacelle. Testing on this could be improved in the future with the addition of a turntable, like the one used in the CWC's in-person durability turbine task, however this test was sufficient to know that the yaw system is robust and capable of completing the task.

# Goals for Future Teams

The University of Colorado Boulder Wind Team aims to be more interdisciplinary in future competitions allowing better resource allocation and execution of project ideas. A major deliverable that the team was unable to achieve is providing a power curve that determines the performance of the turbine prototype. Recruiting more electrical engineers for the team allows the team to have more expertise in building a more effective generator and reduce the risk of overloading any electrical parts. This would allow the team to achieve the cut-in wind speed and power curve tasks that was not accomplished this year. As a learn along team, we were able to find the strengths and weaknesses of the current design, so future designs will have a better start in the design process. The documents and experience gathered from the current team will be a great resource for future teams which was the main goal of this project. As the first team in the CWC, we are proud of the progress we have made without any previous experience, and we are excited to see what future CU Wind Teams will be able to accomplish.

*The University of Colorado Boulder Wind Team thanks the Collegiate Wind Competition for the opportunity to gain insight in wind turbine design and acquire better practices for future teams. We thank you for your time, guidance, and resources.*