UT Dallas
Comet Wind Team

Turbine Design Report

Submitted to
2022 Collegiate Wind Competition

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1. Executive Summary

The University of Texas at Dallas Wind Energy Club is grateful for the opportunity to participate in the 2022 Collegiate Wind Competition as a learn-along team. The following document describes the inspiration for, and construction of, the UT Dallas wind turbine for the competition.

For our first year in the competition, especially as a learn-along team, the turbine design team aimed to develop a baseline understanding on the design and assembly of a model wind turbine. Additionally, as a learn-along team, the final design of the turbine excludes any of the foundation design since that will not be tested on the official testing day. The final product is a three bladed turbine with fixed pitch and commercial generator.

The design process for the turbine blades centered around the GOE342 and NACA 6409 airfoils. In order to get the electric generator to run, NACA 6409 airfoils with the chords adjusted to be thicker will be 3D printed using PLA filament. To prevent power losses from inverter usage, the team selected the Walfront 12v3000 rpm Permanent Magnet DC motor for the design's generator.

The design for the hub prioritized simplicity, strength, and stiffness. A fixed-pitch hub was modeled then 3D printed using PLA filament. PLA's yield strength of 60 MPa makes this material an appropriate choice for the testing conditions of our wind turbine. The hub is designed so that the blades are interfaced using screws and nuts. The hole in the center of the hub has a keyway for the keyway to be firmly affixed. Notably, the hub's large size is intended to increase surface area, reducing stress and distributing force.

By 3D printing both the blades and the hub, manufacturing and testing was expedited. Utilizing an on-site 3D printer and inexpensive material saved the team time and money. Stress anaylses were run to ensure the durability of the PLA blades.

The nacelle needed to effectively house the turbine's power producing components. This requires the nacelle to be both stable and lightweight. Following the same line of reasoning stated in the previous paragraph, the nacelle plate was 3D printed. Additionally, 3D printing allowed us to easily add mounting holes to the plate for the components. This additive process was deemed more favorable compared to the subtractive processes other materials might have required. Additional housing was modeled for 3D printing for the nacelle's bearing and generator.

The electrical system consists of an Arduino Uno Rev 3 microcontroller a 9v battery, a MOSFET, and two AD8400 digital potentiometers. The Arduino is able to measure voltage and control the other electrical components. One potentiometer is to control load resistance to optimize power and the other one is used for shutdown. The latter helps safely slowdown the turbine by increasing resistance.

A button changes the state in our control system. This switches the state between "operational" and "shut down" modes.

2. Design Objective

The UT Dallas team is a first-year learn-along team, and thus our objective was to keep the design simple in order to obtain a working prototype as soon as possible.

Our team took inspiration from last year's design report winner – Kansas State University – to develop our wind turbine. Kansas State used 3D printing to develop many of their components, such as the rotor blades and hub, and we took note of this to fabricate our components as well. Furthermore, we saw that they had a fixed-pitch hub design and commercial off-the-shelf generator, which we also followed suit from to further simplify our design.

3. Mechanical Design and Analysis

Turbine design necessitates iteration: no matter how good the results of an analysis are, the real-life implementation and fabrication may yield different results. For this reason, our team sought to develop a test stand that would allow us to create a turbine prototype and iterate upon our design.

Before manufacturing or purchasing any components, our team designed a SolidWorks assembly of our desired turbine components. This model allowed our team to check part alignment and ensure that the components could be properly assembled.

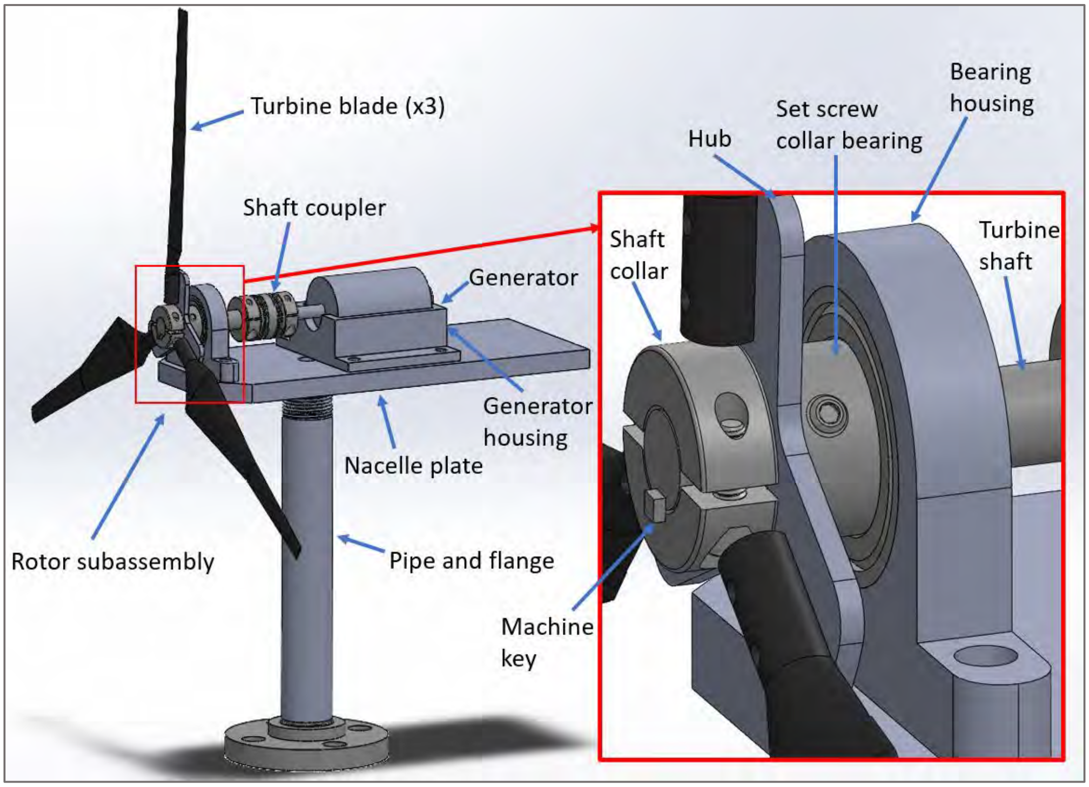


Fig. 1 SolidWorks assembly of wind turbine test stand and closeup of hub subassembly

3.1 Blade Design

The primary objective for the blade design was to maximize the ratio of lift coefficient (C_L)to the drag coefficient (C_D) for the Reynolds numbers between 50,000 and 100,000. Considering the size constraints and wind velocities during testing, the team knew we were to be operating at the lower end of this range.

Using an airfoil database, the QBlade analysis software, and the Betz optimum criterion, the team was able to design and test many combinations of blade designs. The two airfoils the team liked were the GOE342 and the NACA 6409. The GOE342 was the favorite because of the high-power coefficient (C_P) and low thrust coefficient (C_T) over serval different Tip-Speed Ratios (TSR). One issue with the GOE342 airfoil is its likelihood to deflect to beyond the allowed amount. This is when the team agreed that the NACA 6409 airfoil would be a good back-up. The increased thickness of the NACA 6409 will prevent undesired deflection.

Upon preliminary physical testing, the team discovered that the NACA 6409 airfoil doesn't produce enough torque, at the testing air speed, to turn the electric generator that will be used. Therefore, the next blade iteration will feature a thicker chord in order to increase the lift coefficient and, as a secondary effect, stiffen the blade. Physical testing of the GOE342 airfoil is still yet to be done but will commence soon.

The blades were manufactured using the lab's 3D printer, in PLA, so the team could perform rapid physical testing and iterative blade design.

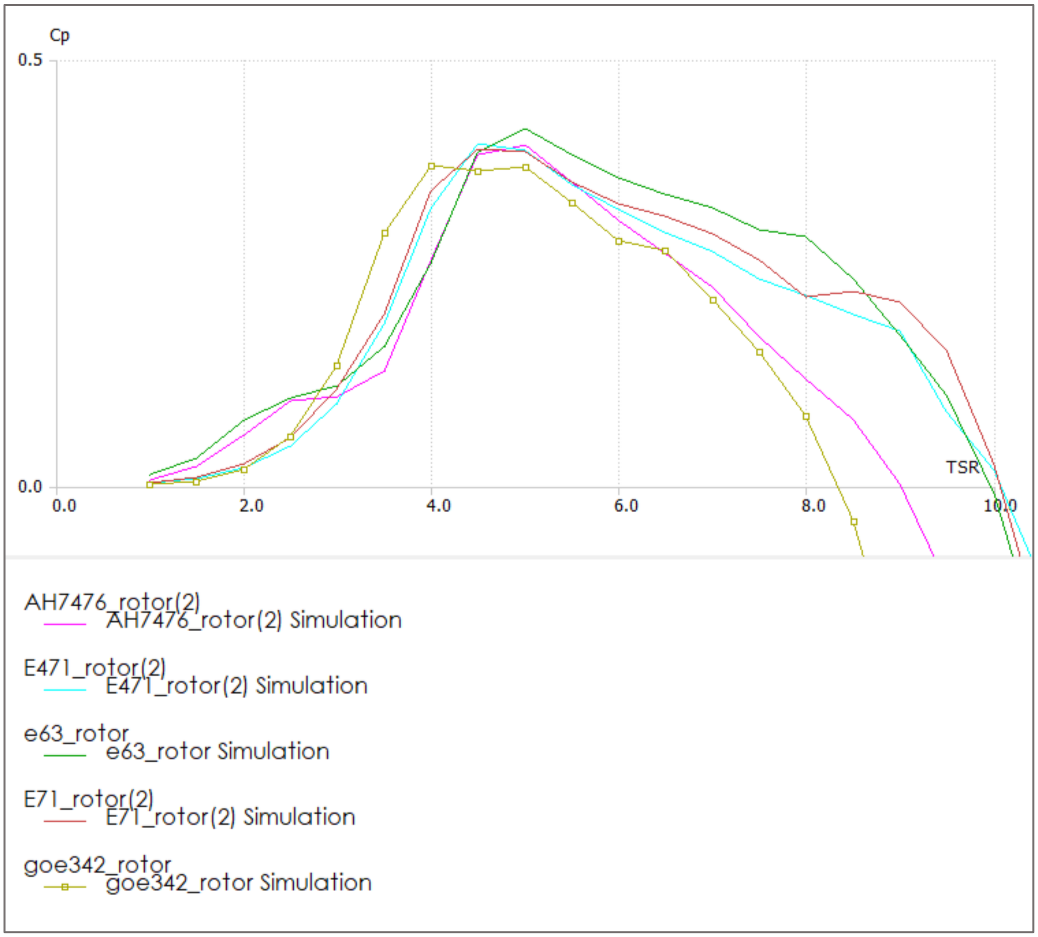


Fig. 2 C_P - λ curves for the different airfoils the team tested

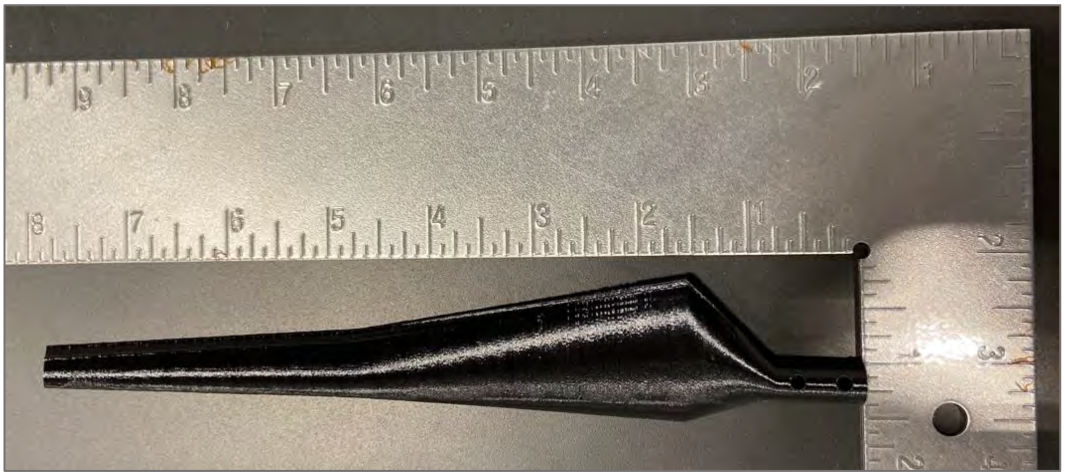


Fig. 3 Close-up image of a 3D-printed turbine blade

3.2 Hub Design

The hub is the main point of connection between the rotor blades and the rest of the turbine. Key considerations for the hub include simplicity, strength, and stiffness. Our team decided to keep the design simple both in fabrication and implementation by designing a fixed-pitch hub.

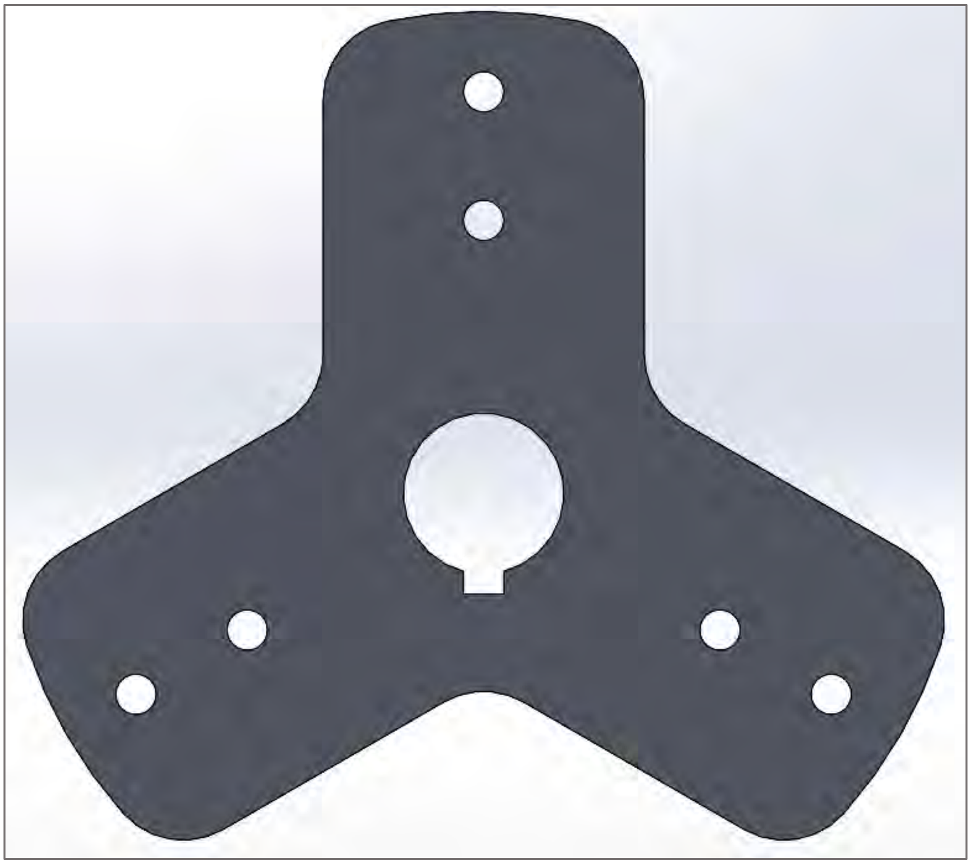


Fig. 4 Hub design with interfacing holes and keyway

Though the hub is 3D-printed with PLA, it is still extremely stiff and strong. PLA has a yield strength of 60 MPa [1], meaning our hub can withstand the relatively low loads experienced by our turbine. The hub is designed to be larger than the blades that screw onto it. This increased surface area allows for a better distribution of force and reduction of stress on the backside of the blades, and keeps the hub from deflecting when put under wind and thrust loading.

In addition, 3D printing allows for easy manufacturability and redesign: a part of this size (3 inches in diameter) is much cheaper to print with PLA as opposed to machining with aluminum or steel. If the hub needs to be redesigned to accommodate a different set of blades, it can be easily modified and reprinted according to the specifications.

The hub interfaces with the rotor blades via a set of #4-40 x 1/2-inch machine screws and their corresponding nuts. The holes on the hub are designed to align with the holes on the root of the turbine blades, and are designed with slightly larger hole tolerances to ensure that the screws can pass through both sets of holes. Furthermore, the keyway designed into the hub allows for interfacing with the turbine shaft and preventing any slipping between these components.

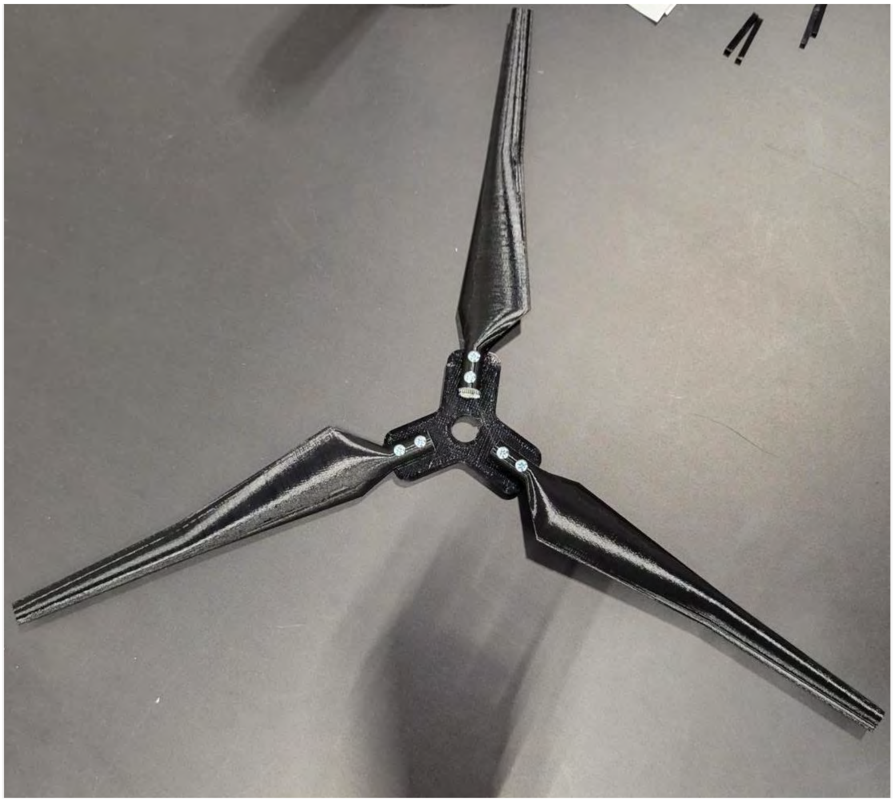


Fig. 5 Rotor blades and hub assembly

3.3 Nacelle Design

The nacelle is crucial for housing the power-producing components of a turbine, including the shaft, generator, and electronics. The focus of our nacelle design consisted mainly on the nacelle plate where these components would be housed. Our team considered two design alternatives for a nacelle plate: machining a metal plate or 3D printing a plastic plate. We opted for the 3D printed option for our test stand because of the greater accessibility, lower cost, and ease of manufacturability. By additively manufacturing the nacelle plate, mounting holes for the components can be easily created during the printing process and do not require additional processes to create. In contrast, machining an aluminum or steel plate would require a subtractive manufacturing process to create these mounting holes. Furthermore, 3D printing a nacelle plate is substantially more cost-effective than machining a metal plate.

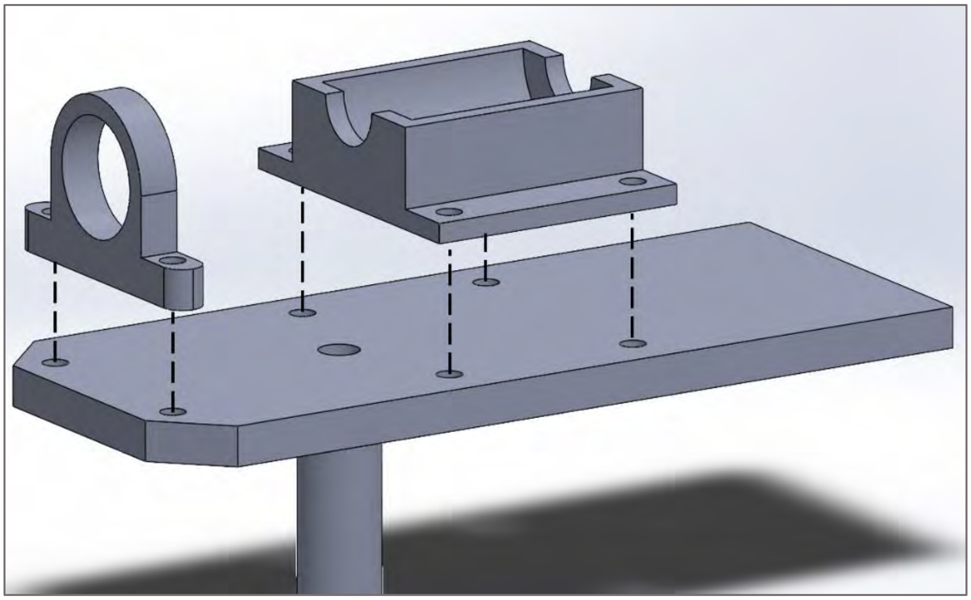
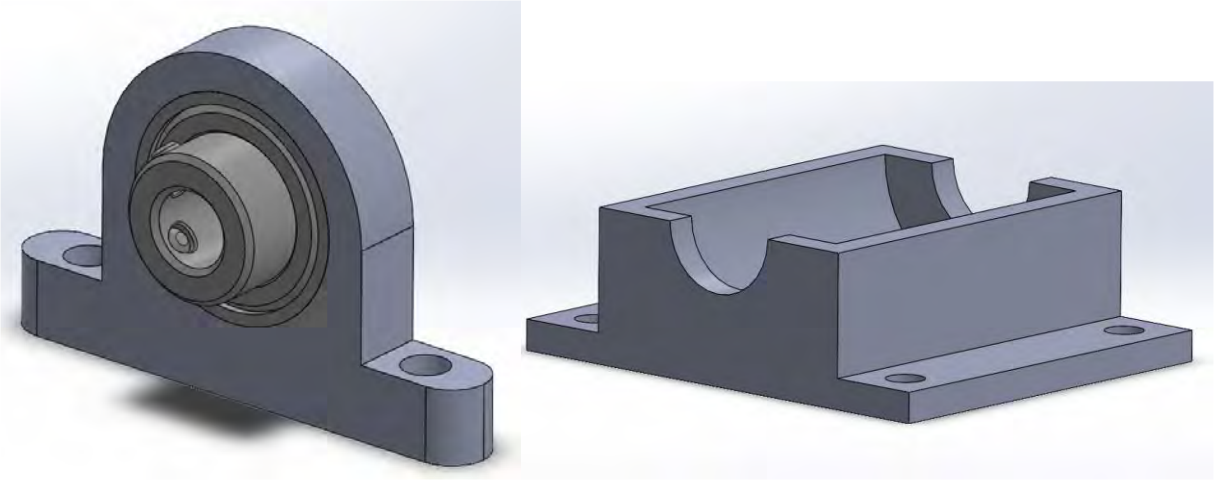


Fig. 6 Nacelle plate design with holes for mounting components

3.4 Structural Components

Several structural components need to be mounted to the nacelle for proper turbine operation. Our team designed a bearing housing and generator housing that would provide a stable mounting point for their respective components. These components are yet to be fabricated while other aspects of the turbine are being finalized, but will be 3D printed for ease of manufacturability and to ensure a light-weight nacelle design.



(a) (b)

Fig. 7 (a) Bearing housing and (b) generator housing designs

Furthermore, our design requires parts whose purpose is primarily to connect other components together. Some of these components include the shaft coupler, which couples the 1/2-inch turbine shaft to the 8mm generator shaft. These components are typically purchased as a commercial off-the-shelf item. In order to maintain a light structure weight while not compromising strength, we looked for aluminum components for bigger components like the shaft coupler.

3.5 Stress Analysis

The loading on the blade can be considered a thrust loading. It can be found using the equation

$$T = \frac{1}{2}\rho A V^2 C_T$$

The force the blades experience is 29.67 N, or 9.89 N per blade. It was found using the values below. The area was calculated as the blade swept area minus the hub area, and the wind velocity of 22 m/s was considered as it is the highest windspeed during the durability task.

ρ = 1.225 kg/m^3
A = 0.143 m^2
V = 22 m/s
C_T = 0.7

The moment of inertia for the blade was found by averaging the cross-sectional area moment of inertia from the SolidWorks model along different blade spans. This value was calculated as 155 mm^4, or 1.55×10^{-10} m^4.

The effective unclamped blade length is 0.18m, which gives a distributed load value of 54.94 N/m. With these values for moment of inertia and thrust loading, combined with the material's elastic modulus (PLA at E = 2.3 GPa), the stress and deflection calculation results can be seen below, assuming the load is applied along the length of the blade.

σ = 2.87 MPa

δ = 20.2 mm

The bending stress the blade experiences is well below the material yield stress of 60 MPa [1], therefore the blades will not yield. Of course, there may be stress concentrations at certain portions of the blade, but in general, the blade is designed with smooth transition regions in mind to minimize this effect.

4. Electrical Design and Analysis

4.1 Overall Design

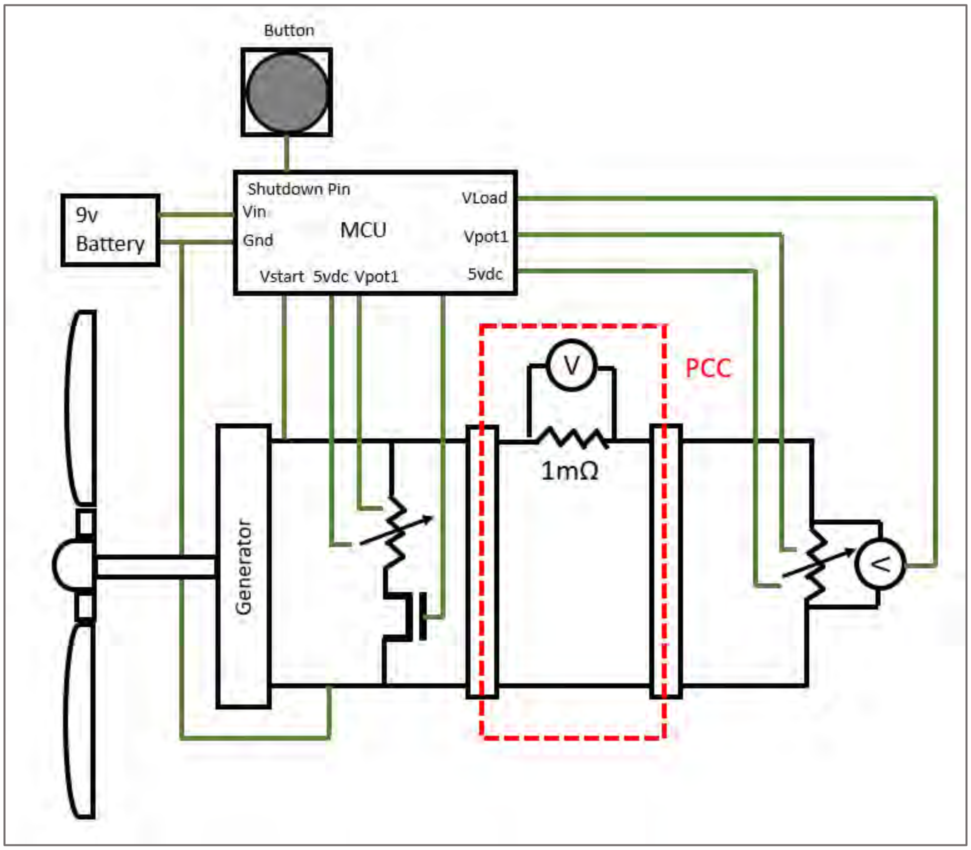


Fig. 8 High-Level View of the Electrical System

A high-level view of the electrical system is shown in figure 8. We used an Arduino Uno Rev 3 for our microcontroller. It is powered by a 9v battery. The Arduino measures the voltage across our load, controls the resistance of the digital potentiometers, and controls our MOSFET. The Arduino has a 5 vdc and 3.3 vdc output pin that powers our digital potentiometers. We are using AD8400 digital potentiometers. The one in the load section is used to control our load resistance to optimize power. The potentiometer on the generator side is used for shutdown. When the load is disconnected, the MOSFET turns on and the potentiometer is used to safely slowdown our turbine by increasing the resistance.

4.2 Generator Model

Fig. 9 Generator used for power generation

We are using the Walfront 12v 3000 rpm Permanent Magnet DC motor. We chose a DC motor because then we would not have any power losses from using an inverter. They are also easy to control and model because of their simplicity.

The steady state values for back EMF and generator torque are calculated with the respective equations.

$$e = R_{load} \cdot I_{load} \tag{1}$$

$$T_{gen} = k_t \cdot i_f \cdot i_a = B \cdot \omega + T_L \tag{2}$$

4.3 Electrical Load Model

The digital potentiometers can go up to 1kΩ, and they have 255 bit resolution, which means it can be incremented in steps of 3.92Ω.

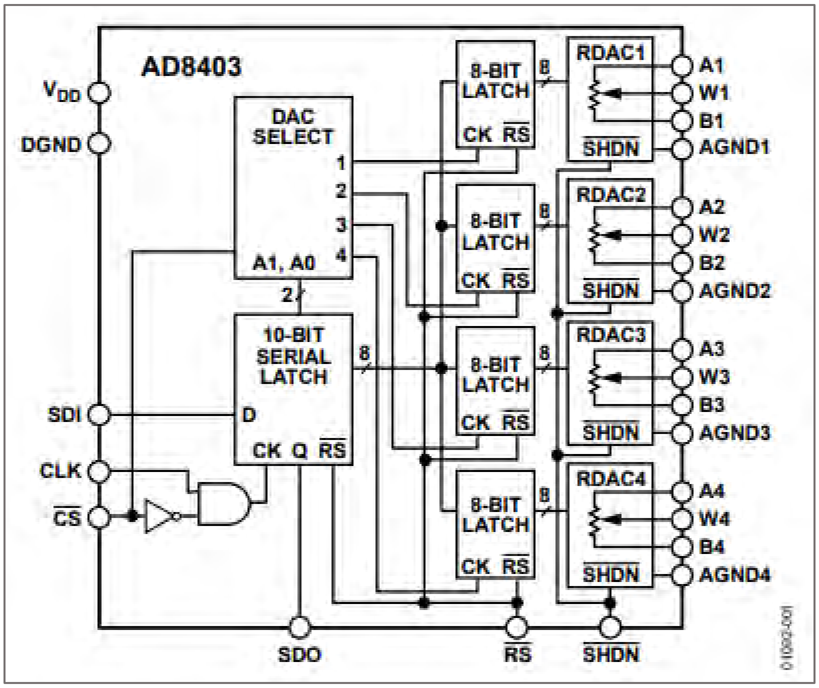


Fig. 10 High Level Overview of the AD8400 Digital Potentiometer's Design

4.4 Voltage and Current Regulation

The voltage and current are regulated using the two potentiometers. Load current can be regulated using equation 1. And by combining equations 1 and 2, the back EMF can be calculated using the following equation.

$$\omega = \frac{k_t \cdot i_f \cdot e}{B} \cdot \frac{1}{R_{load}} - \frac{T_L}{B}$$

(3)

The current limit for the PCC is 3A. We can stay below this limit using equation 1.

5. Controls Design and Analysis

A key factor in the operation of a wind turbine is managing the power produced by the generator as well as the rpm experienced by the turbine. Large fluctuations of power due to differences in wind speed can have a large effect on not only the performance efficiency and the life of the wind turbine's electronics, but potentially the electric grid to which the generator is connected to. Additionally uncontrolled rpm can lead to structural damage and severe shortening of the operational lifetime. Designing the controls of a wind turbine is a vital part in the creation and operation of wind farms, as many situations and conditions need to be considered and planned for. As such our turbine must meet the requirements of the safety task, the power curve task, and the durability task, where we will be testing the wind turbine against a variety of scenarios. The response of our wind turbine to each task is shown in the state-diagram below.

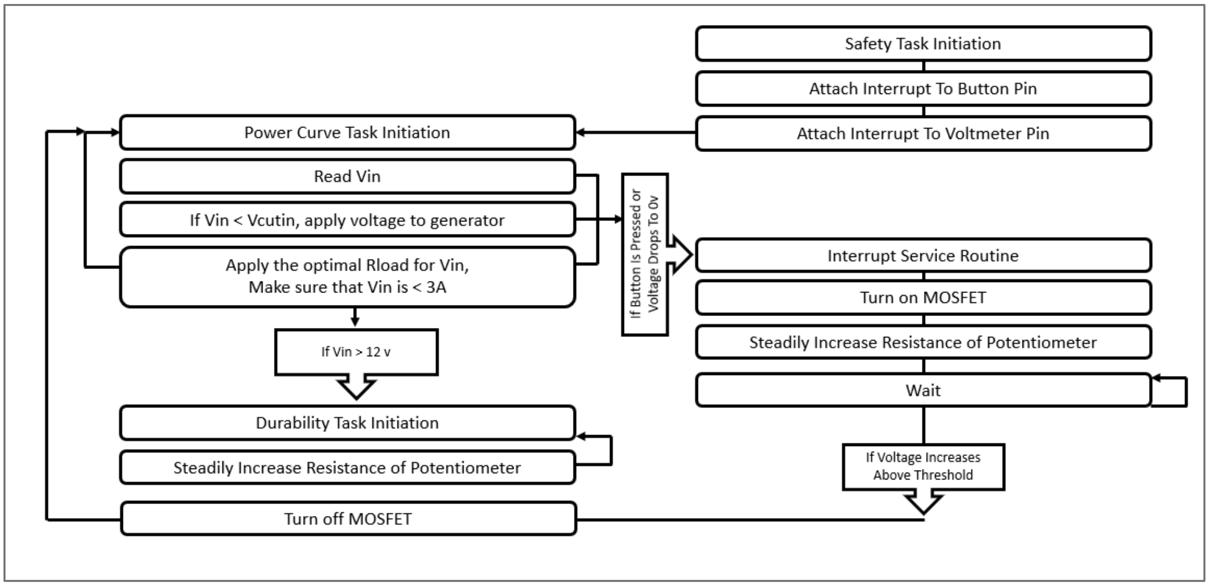


Fig. 11 State Diagram

5.1 Power Curve Task

In order to achieve optimal power output through different wind speeds, we will be adjusting the resistance of a digital potentiometers connected in parallel to the generator (which we named load potentiometer). By adjusting the resistance to its optimal value for each windspeed, an optimal power output will be produced throughout the power curve task.

Due to our universities wind tunnel being slightly smaller than our wind turbine, we had to improvise to test our finished construction at different windspeeds. Our wind tunnel consisted of a high-speed fan as well as several surfaces to help funnel the wind, which allowed us to test our wind turbine at three different wind speeds. Due to this, we cannot experimentally find the optimal resistances for our power production at the 7 different windspeeds at which we will be tested. As such we will be finding the optimal resistance for our three windspeeds and measure the windspeeds at those three settings, then using this data we will be plotting a curve of best fit to help find the optimal values at the windspeeds to be tested. As an example, below is an example chart of how we will be approximating the power curve, which will allow us to find the optimal resistances for each windspeed, where k is a constant.

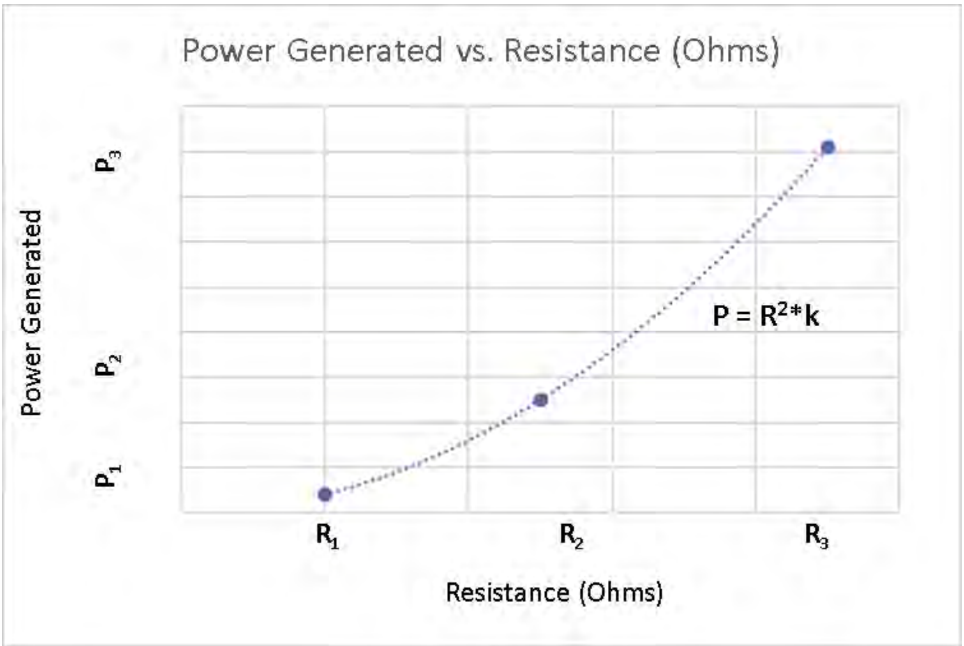


Fig. 12 Short description, k is a constant

5.2 Safety Task

For the safety task we will have a button that will change the state, from operational to shut down and vice versa. During the shutdown state we will be using a MOSFET connect a digital potentiometer (which we named the shut-down potentiometer) to ground which is controlled by the Arduino. Since a generators torque can be changed according to the resistance it is facing, one can control the speed of a wind turbine by adjusting the load. Using the Arduino as a PI controller we will adjust the torque generator experiences by adjusting the value of the shut-down potentiometer, which will in turn adjust the voltage, measured across the load potentiometer, to around 0-1V which should be around 10%

To tests whether the PCC has been disconnected, the voltage across its connection points can be measured using the Arduino. If the voltage falls to zero volts, this would indicate that the PCC has

been disconnected. This too would start the shutdown sequence, where the MOSFET would connect to ground, allowing the Arduino to act as a PI controller an adjust the shut-down potentiometer and the voltage to be within acceptable levels which will be around 0-1V

5.3 Durability

In order to control the rotations per minute the turbine undergoes through different windspeeds we will implement torque control. As the torque a generator experiences is related to the size of the load connected to it, the load potentiometer can be used to electronically control the torque the generator will experience, and as such help control the changes in the rpm the wind turbine will experience as the durability task is performed. In order to do this, we will be using the Arduino as a PI controller, and by reading the voltage across the load potentiometer we will be able to accurately adjust our load according to the changing windspeeds

6. Assembly and Testing

6.1 Turbine Commissioning Checklist

Checklist	
1	Secure blades onto the hub of the turbine using screws and nuts
2	Thread wires through the nacelle and turbine tower
3	Fasten the tower onto the wind tunnel mounting stub
4	Secure the rotor and nacelle assembly onto the tower
5	Connect the load to the PCC and the generator side to the PCC (see figure 8)
6	Connect the button at the testing site to our Arduino for shutting down the turbine
7	Verify that all necessary connections are made before beginning testing

6.2 Turbine Testing

Testing proved difficult as there were issues getting the turbine blades to produce enough torque to turn our larger generator. However, our team was able to get a smaller generator to turn using the current rotor setup. As we approach the competition deadline, the team will fine-tune our turbine design to ensure that both the mechanical/aerodynamic team and the electrical/controls team can interface their subsystems to work with each other.

7. Conclusion

Our goal next semester is to improve the aerodynamics, structure, and electronics. The maximum power we can produce in the wind tunnel according to Betz's limit is shown in equation 4, and the highest generator power with an efficiency of 95% is shown below in equation 5. In table 1 are the Paero and Pelec values for the different wind speeds in the power curve challenge.

$$P_{aero} = \frac{1}{2} \cdot p \cdot A \cdot v^3 C_{p,betz}$$

(4)

$$P_{elec} = P_{mech} \cdot eff$$

(5)

V	P_{wind}	P_{rotor}	P_{elec}
5	48.70696	28.86374	27.42056
6	84.16562	49.87655	47.38272
7	133.6519	79.20211	75.24201
8	199.5037	118.2259	112.3146
9	284.059	168.3334	159.9167
10	389.6557	230.9099	219.3644
11	518.6317	307.3411	291.9741

Table 1 Highest Wind Power, Rotor Power, and Electrical Power for Different Wind Speeds in the Power Curve Challenge

We can reach these values by designing with them in mind. The electrical team wants to build their own generator to ensure high efficiency for the correct size, and they want to increase the resolution of our resistor banks. Our mechanical team will continue to redesign and test different rotors to produce the maximum torque to turn the generator.

8. References

[1] Travieso-Rodriguez, J Antonio et al. "Mechanical Properties of 3D-Printing Polylactic Acid Parts subjected to Bending Stress and Fatigue Testing." Materials (Basel, Switzerland) vol. 12,23 3859. 22 Nov. 2019, doi:10.3390/ma12233859