Conceptual Design Report

Turbine Prototype
NREL Collegiate Wind Competition (CWC)

University of Colorado Boulder
Department of Mechanical Engineering
November 1st, 2021

Roark Lanning - Director
Claire Isenhart - Project Manager
Simon Grzebien - Finance Manager
Alec Kostovny - Logistics Manager
Aaron Schwan - Systems Engineer
Anika Levy - Manufacturing Engineer
Charles Candon - Test Engineer
Graham Blanco - CAD Engineer
Kirollos Gerges - Electromechanical Engineer
Erik Feiereisen - Electromechanical Engineer
Luke Walker - Electromechanical Engineer
Mariam Gopalani - Civil Engineer

Introduction

The purpose of the turbine prototype is to develop fundamental design skills in the field of renewable energy, specifically wind. This prototype must balance standard industry practices with optimizing various small-scale components, while also attempting novel solutions. This document outlines the main subsystems and initial design considerations of the University of Colorado Collegiate Wind Competition Team.

Foundation

The foundation of the turbine needs to support the turbine under axial (vertical) loads, horizontal loads, and torsional loads (see Figure 1 in appendix). The foundation must also provide leveling capabilities and height adjustability. To determine the loads the foundation will experience, we must calculate the loads on the turbine exerted by the wind with Equation A1 (see appendix). See figure 1 in the appendix for a free-body diagram of the forces on the turbine. This force exerted by the wind will have a direct impact on our foundation as it will create a moment arm due to the forces on the turbine. We are currently designing a suction bucket made out of sheet metal (ferrous) as it will allow us to achieve the most lightweight design without sacrificing the stability of the structure. The top of the bucket will contain a sealed hole through which we will run a tube to suck out any water inside the bucket when placing the foundation in the offshore simulation tank. The suction effect will create a pressure difference between the inside and outside of the bucket that will hold the entire wind turbine steady during tests. Additionally, the top of the bucket will be designed to fit the Transition Piece (stub) provided by the CWC. This interface must be designed with height adjustability in mind to account for the foundation connection being within 3 cm of the top of the offshore simulation tank. Furthermore, it requires rotational adjustability to account for any imperfections in the sand that may cause the foundation to tilt. We plan to use a locking ball joint so we can easily adjust the foundation.

Tower

The tower is designed to support the nacelle structure and interface between the Transition Piece (stub) and the yaw mechanism. The tower design must incorporate a hollow center for electrical connections while ensuring structural stability under the weight of the nacelle, and loading under the wind.

Yaw System

The yaw system must be designed such that the axis of the drive shaft is anti-parallel to the wind at all times. This will be accomplished with a turntable bearing set at the base of the nacelle and the top of the tower. Furthermore, one fin with a large surface area will be set at the back of the nacelle so that as the wind contacts the surface, the force will push the fins and turn the nacelle at the top of the bearing (See Appendix, Equation A1 for force value). This passive yaw system will orient the blades to be aligned in the direction of the incoming wind. Another option is to combine subsystems and design the tower to be light weight and incorporate an airfoil such that it acts as the fin for the passive yaw system. This alternative is in an initial design phase and will be considered alongside the traditional turbine design described above.

Nacelle

To reduce the complexity of the turbine a passive yaw mechanism can be utilized. The design of which will be driven to minimize the rotational inertia about the central axis of the tower, balance the center of mass on the central axis, and allow for ease of maintenance. By reducing the rotational inertia as much as possible, the yaw mechanism will be more responsive, allowing for a larger resultant rotation due to the wind. By centering the mass about the central axis we can minimize the applied torque the foundation has to account for to maintain a vertical position. Finally, it must also allow for ease of maintenance to all associated components (Generator, E-Stop, Drive Shaft, and Pitching Servo). Based on initial research, a 4 in x 7 in rectangular shape will accomplish this task and provide adequate space for all subsystems.

Blades

The design of the blades will have a direct impact on the efficiency of the turbine as the blades turn the energy held in the wind into mechanical energy that will then be converted to electrical energy in the generator. The power that we extract from the wind can be approximated theoretically (See Appendix Equation A3). From this equation, it can be seen that the blade design affects two variables that we want to maximize to generate the most power. The power coefficient, C_p , will be affected by the airfoil or airfoils used in the cross-section, blade length, and any twist within the blade. The swept area S will primarily be affected by the blade and chord lengths. Altering these parameters to optimize S and C_p will be the main challenge of blade design and understanding what they do and how they affect blade performance as the blade is pitched is crucial. The airfoil used will affect the lift force of the blade and the main aspects we want to focus on for choosing an airfoil are the lift coefficient and the drag coefficient. A theoretically perfect blade would have a maximum lift and minimal drag. The chord and blade length act to change the surface area of the blade allowing for more wind to be caught but also increasing the rotational inertia of the blade making it more difficult to rotate. A twist within the blade allows for possible optimization of the aerofoils where the optimal angle of attack may be different at the same wind speed and rotational speed. By carefully manipulating these aspects we can optimize our blades and create the most efficient power generation process possible.

Pitching

To maximize power output at a given wind speed, the blades must be capable of pitching to maximize tip speed ratio, shown by Equation A2 in the appendix. The optimal λwill be determined based on the airfoil design that we choose, but it will likely be close to 7(N.S. Cetin et al.). To optimize λ, the lift generated by the blades will be adjusted by altering the pitch angle of the blades. The pitch of the blades may also be adjusted at high wind speeds to slow the rotation to a safe speed. Additionally, the pitching can be adjusted to minimize the lift and maximize the drag generated by the wind during an emergency stop.

Electrical Components

The electronics are an essential part in the overall function of our turbine. This includes turbine controls, power generation, emergency stop and the turbine load. Servos and a microcontroller will be utilized to control the pitching system. Pitching will occur in response to input data of shaft rotational speed and turbine output power. The RPM of the shaft can be directly utilized to monitor the tip speed ratio and power output can be derived from current and voltage measurements. Blade pitching will result in an optimal power output. In order to convert the mechanical energy of the blades into electrical energy, we will use a three-phase generator. We have opted for a direct drive generator input to minimize cogging torque. The output of the generator will be converted to a steady DC voltage through the use of a full-wave three-phase rectifier and a SEPIC converter. The power regulation must be robust due to the fluctuations in wind as well as efficient to minimize power loss. The emergency stop system must require minimal to no power when engaged. For this reason, we have decided our emergency stop will be two fold: the blades will be pitched so that little to no lift force is generated and the generator motor terminals will be shorted to produce a counter torque on the rotor. This will ensure a safe shutdown even when the load is disconnected. The turbine load will consist of a battery with a low terminal voltage and large energy storage capacity.

Appendix

Equations

[A1] $F = \frac{1}{2}C_d * \rho * S * V^2$ (Middleman, S.)

[A2] $\lambda = \frac{\omega R}{v}$(N.S. Cetin et al.)

[A3] $P = C_p * \frac{1}{2}\rho S V^3$ (Simon P. Neill, et al)

Table 1: Variable Definitions

Term	**Units**	**Definition**
ρ	$\frac{kg}{m^3}$	Density of air
S	m^2	Swept area of the blades
C_d	NA	Coefficient of drag
C_p	NA	Coefficient of power
V	$\frac{m}{s}$	Velocity of wind
ω	$\frac{rad}{s}$	Rotational frequency of the rotor
R	m	Radius of blades

Figures

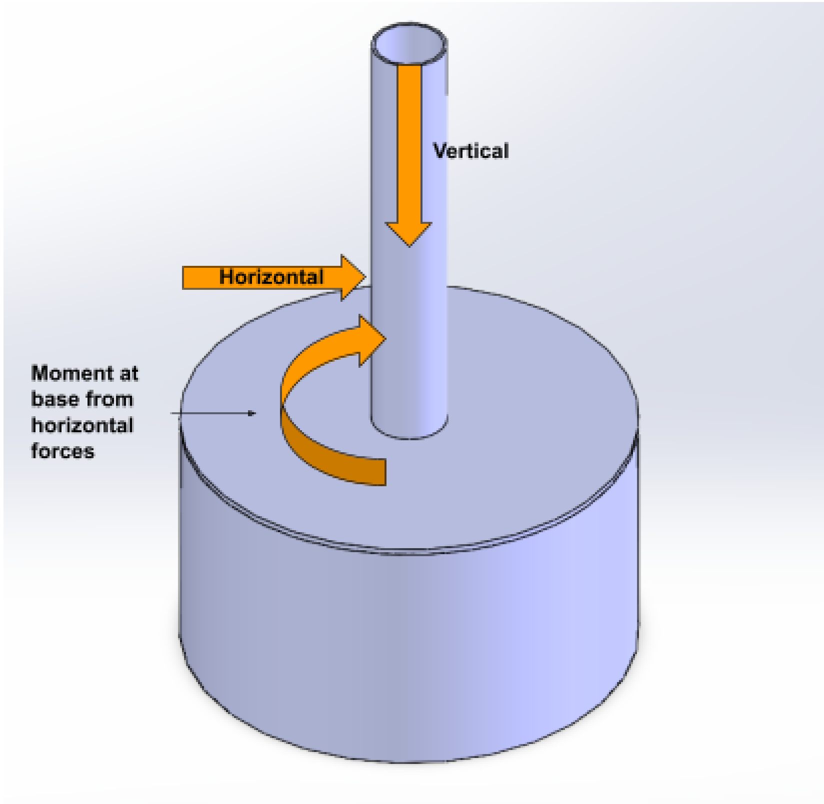

Figure 1: Free body diagram of the forces acting on the foundation

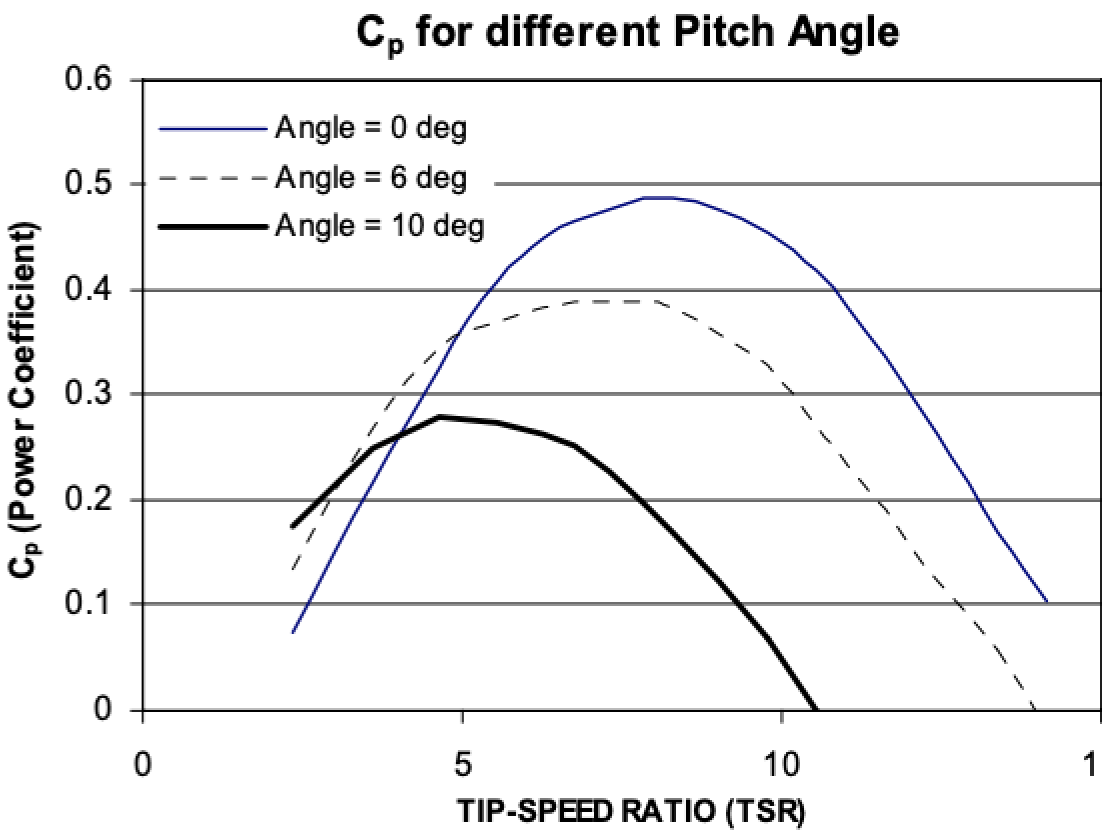

Figure 2: Tip-speed ratio and corresponding power coefficient for an example turbine[5]

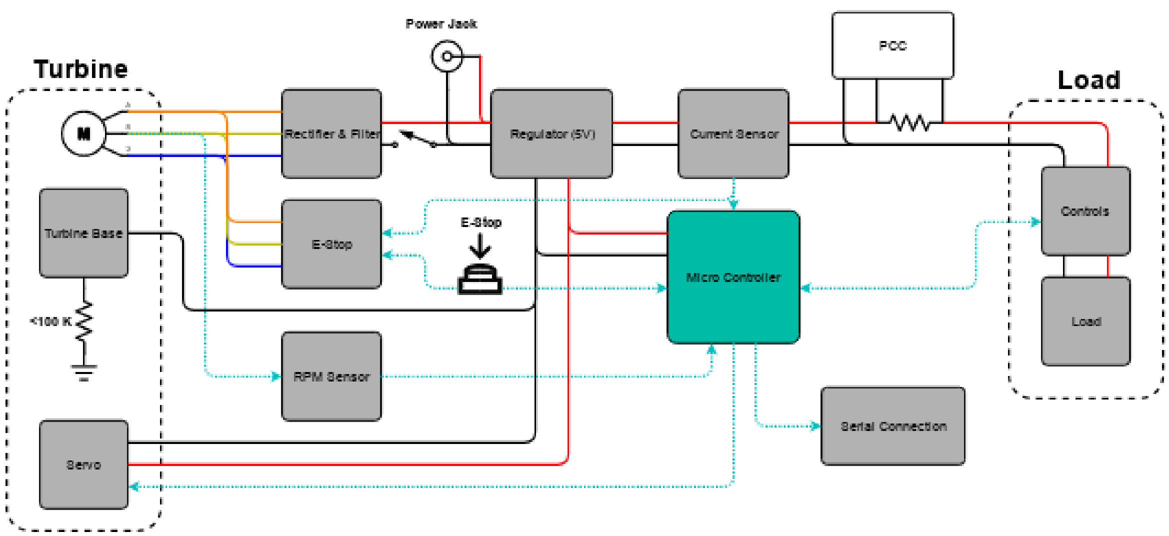

Figure 3: Functional Block Diagram of the turbine electrical/control system. All elements in the "Turbine" group are physically on the turbine. All elements in the "Load" group are in a separate enclosure from the controls. Power transfer is shown with red and black wires and signals are shown in dotted blue lines.

References

[1] Simon P. Neill, et al. Chapter 4 - Offshore Wind. Academic Press, 2018.
[2] Giguère, Philippe and Michael S. Selig. “Design of a Tapered and Twisted Blade for the NREL Combined Experiment Rotor.” 1999
[3] Woodhall, Jessica. *Wind Turbine Power Calculations*. The Royal Academy of Engineering, 2010, https://www.raeng.org.uk/publications/other/23-wind-turbine.
[4] N.S. Cetin, M. A Yurdusev, R Ata and A. Ozdemir, “Assessment of Optimum Tip Speed Ratio of With Turbines,” Mathematical and Conceptual Applications, Vol. 10, No. 1, pp.147-154, 2005
[5] Middleman, S. (1998). *An introduction to fluid dynamics: Principles of analysis and Design*. John Wiley & Sons.
[6] Muljadi, E., & Butterfield, C. P. (n.d.). *Pitch-controlled variable-speed wind turbine generation - NREL*. Retrieved November 2, 2021, from https://www.nrel.gov/docs/fy00osti/27143.pdf.