2020 COLLEGIATE WIND COMPETITION

Prepared by: University of New Haven Collegiate Wind Competition Team

Submitted to:

May 15, 2020

Team Members			
Mechanical Team	**Electrical Team**	**Systems Team**	**Structural Team**
Justin Beardsley Wayne Catucci CJ Conner	Byron Alvarado Jonathan Stanford Hangtao Xu	Zhou Shen Ximin Yue	Luke Amiot Matt Torri

Faculty Advisors:

Dr. Maria-Isabel Carnasciali, Dr. Byungik Chang, Dr. Junhui Zhao, & Dr. Ravi Gorthala

TABLE OF CONTENTS

EXECUTIVE SUMMARY

Over the past year, the team at the University of New Haven has worked together to design and develop a wind turbine according to the rules provided by National Renewable Energy Laboratory and the Department of Energy. Upon completing this task, the team has successfully designed a 3-bladed, horizontal axis wind turbine capable of producing up to 3.8W of power at 3000 RPM. This was done by designing the blades with a twist angle of 8-degrees while maintaining a fixed pitch when attached to the rotor; both of which were manufactured with chopped carbon fiber. This material was used because it is both lightweight and has a relatively high tensile strength of 6800 PSI. The generator was designed using neodymium magnets and 26 AWG wire to configure a 3-phase axial flux generator as it would allow for a constant power output while the turbine was under operation. Using these two components in tandem with a dump load system was crucial, as the dump load would allow the team to effectively control the speed at which the blades would spin being that the RPM needed to be held constant upon surpassing wind speeds of 11 m/s. With all these components, the nacelle would need to fit within a 45x45x45cm cube according to NREL's requirements.

INTRODUCTION

According to Environment America, power plants emitted released about 2.56 billion tons of pollutants in 2007; three times as much pollution from cars. Most of these were from coal plants built before 1980 (Power Team Arcadia). As a society we have become too reliant on non-renewable resources to produce power to the detriment of the environment. The Department of Energy (DOE) has begun looking into renewable resources such as wind farming to decrease the reliance on non-renewable resources. According to the *Wind Vision* report from the Office of Energy Efficiency & Renewable Energy, ten years from now wind farms could be responsible for 20% of our nation's electricity. To increase the number of wind farms in the nation, qualified engineers are needed to design and maintain these facilities.

PROJECT OBJECTIVES

To get engineering students interested in this field, the DOE and National Renewable Energy Laboratory (NREL) proposed the Collegiate Wind Competition. The Competition challenges students by testing their knowledge of civil, electrical, mechanical, and systems engineering to see which college can produce the best model turbine. The objective of this project was to design a turbine that will produce an output voltage no greater than 48 volts, maintain a constant output voltage in wind speeds between 11 m/s and 18 m/s, and have the ability to autonomously shut off safely once windspeeds of 25 m/s or higher is detected.

EVALUATION OF ALTERNATIVES

In the early design phase of the project the team needed to decide how many blades would optimize the performance of the wind turbine. This question has many implications for the overall design and performance of the turbine. Some designs are better for high wind speed applications as opposed to low speed applications. The power produced by the turbine is defined by Equation 1:

$$P = Cp\frac{1}{2}\,\rho\,V^2\,A \qquad (1)$$

where P is the power produced, C_p is the coefficient of power, ρ is the air density, V is the wind speed, and A is the surface area of the blade. The equation indicates that the produced power can be increased by enlarging the surface area of the blades. Although this is valid, extensive research shows that blade solidity influences the power produced by the wind turbine. As solidity increases pressure differentials are created that can reduce the power output of the turbine (Qing'an Li, 2016). The overall effect of high solidity is that the wind sees the spinning blades as a solid surface which causes the wind to bypass the blades entirely.

During this project two options were possible for the turbine generator: purchasing or DIY. Initially, the plan was to purchase a specially made generator that would fit the specifications provided by the project outline, but this option could have been time-consuming and costly.

As for the DIY option, the idea came from a trip the team took to a wind turbine manufacturing facility in Vermont. This would involve winding coils, creating a stator which would be used to hold the coils, and finding strong magnets small enough for use in our design. This option would require more testing to see the most optimal configuration and find the best materials to use. Despite these concerns, having the ability to custom-build a generator to our size and power requirements was deemed the best option.

The purpose of a pitch control and dump load system is to control the rotational speed of the turbine driveshaft and to ensure power output is constant. Although a pitch control was not a priority in our design, it would have done this by having the blade angle change when different wind speeds were measured. This would have been done using a feedback control system that would have two cutoff speeds, and if the specific conditions were met, then the blade angle would change to maintain a constant voltage output. A future iteration of this design would include a variable pitch system controlled through a feedback loop.

The dump load design maintains a constant voltage at the output by having a series of resistors connected in parallel with switch at each resistor controlled by a feedback system. The system would determine the number of resistors to have in the circuit to maintain a constant voltage by simply flipping the switch on or off. The biggest benefit of using the dump load rather than the pitch control was the fact that it was smaller in size and did not have to inside the turbine to function. This proved to be the simplest and most effective means of maintaining the voltage output constant.

DESIGN APPROACH

Due to unforeseen circumstances, major elements of the project were unable to be completed to have a final working product. Because of this, subsystems within the wind turbine are at different phases in the design process. Table 1 outlines the design process phase of each subsystem. The Theoretical Design phase applies to subsystems that have theoretical design work completed only with no prototyping or physical testing. The Prototype phase applies to subsystems that have at least one prototype created and tested with no finalized design. The Constructed & Finalized phase applies to subsystems that have been completed, tested, and finalized with the intent of utilizing them in their entirety in the final turbine design.

Table 1: Design status summary for the turbine subsystems.

System	Subsystem	Theoretical Design	Prototype	Constructed & Finalized
Electrical	Generator		**X**	
	Rectifier			**X**
	Voltage Regulation			**X**
	Dump Load		**X**	
	Speed Regulation	**X**		
	Braking System	**X**		
Mechanical	Base	**X**		
	Tower	**X**		
	Nacelle		**X**	
	Rotor		**X**	
	Blades		**X**	
	Speed Sensor			**X**
	Driveshaft		**X**	
Systems	Model			**X**
	Simulation			**X**

TECHNICAL DESIGN

MECHANICAL

Dynamometer

For the first milestone, the team was tasked with designing and constructing a rotary shaft dynamometer which would be used to drive the wind turbine drivetrain. A dynamometer is a device that is used to determine the power output of a mechanical drivetrain. In our case, the team would use the dynamometer to determine the power output of the generator coupled to the drivetrain and the torque experienced by the rotary shaft. Knowing the torque in the drive shaft is crucial for this design because if the max torque is exceeded, the drive shaft could break and the wind turbine will not operate as needed.

In order to construct the dynamometer, the apparatus included a DC motor to simulate the blades of a wind turbine, a torque sensor to measure the torque experienced by the driveshaft, and a generator to support resistor loads (see Figure 1).

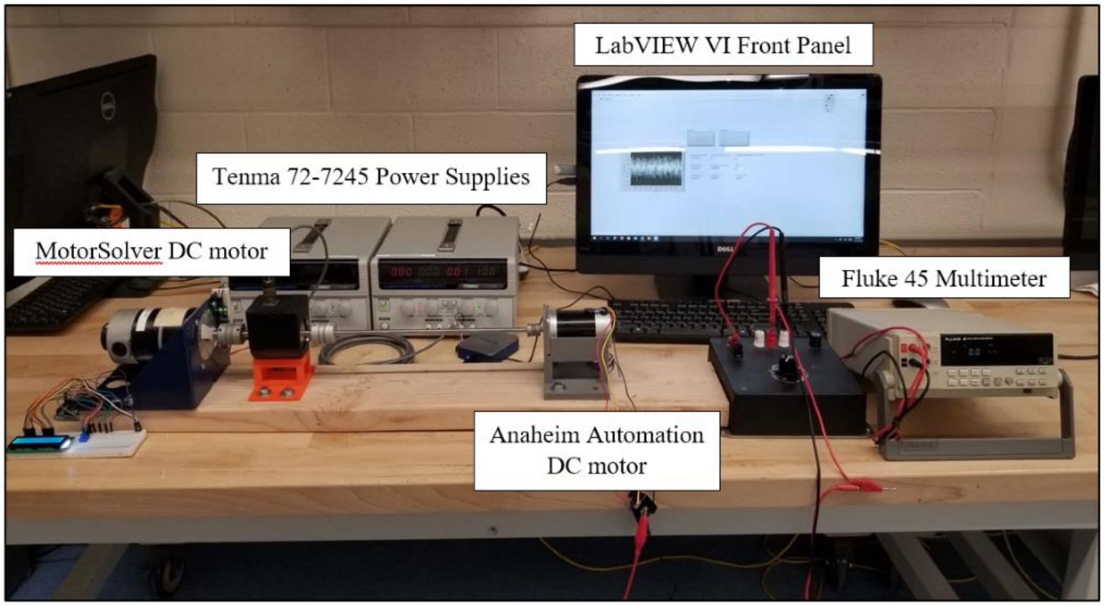


Figure 1: Dynamometer setup with labels

For data acquisition measurements, the dynamometer is designed to obtain a series of outputs (torque, RPM, and power output) while in operation. This allows the team to test some of the major components (i.e., generator, drive shaft, etc.) of the turbine without having to completely assemble it and place it in a wind tunnel. It provided a much more efficient and feasible method of testing the equipment. The team used in-house components that was compatible with the LabVIEW program to measure, calculate, and display the torque through the drive shaft while under operation. Taking that value and the projected RPM from the speed sensor, the team would be able to calculate the theoretical power output from the generator using Equation 2,

$$P = T\omega \qquad (2)$$

where P is the power, T is torque, and ω is rotational speed. A preliminary test was conducted before applying a load to the dynamometer which was to confirm that there was a linear correlation between the input voltage and drive shaft RPM **(**Appendix A)**.** With this, the team could then get the measured power output of the generator and compare the values to determine the efficiency of the generator. Additional images for the dynamometer setup can be found in Appendices B and C**.**

While other devices could have been used to design the team's dynamometer, the team chose to select each component considering feasibility, cost, and user-friendliness. A vast majority of the equipment was readily available to us in the labs on campus such as the DC motor, power supplies, multimeters, etc. When choosing a torque sensor, the Omega TQ513-062 model fit our budget more appropriately given the budget we received. We received a quote from other companies, however, although the equipment may provide better accuracy results, the cost for the sensor and other required equipment to be used with the sensor exceeded our limit. Other than the sensor, the generator and other hardware (couplings, drive shaft, etc.) were purchased through online vendors – such as McMaster-Carr – as needed throughout the iterative process.

The next step for the dynamometer would have been to replace the DC motor with the manufactured blades and the prebuilt generator with the newly manufactured generator. By doing so, the team would have assembled the dynamometer and placed it in a wind tunnel to receive live feedback of the machine under operation. This would have provided the team with much better results and understanding of where the design needed to be improved to obtain the best cut in wind speed and best power production. Unfortunately, due to the sudden shutdown, the team was not able to complete this step due to the inability to access the supplies on campus.

Blades/Rotor Preliminary Information

The blades of the wind turbine translate the energy from the wind into mechanical energy by rotating the driveshaft. There are many factors that relate to the performance of the blades within a wind turbine. Some major design components are maximum lift over drag, tip speed ratio, structural integrity, solidity, and coefficient of performance. All these attributes are determined by the geometric shape of the airfoil blades.

Maximum lift over drag is a major design characteristic because the lift that the blade produces is the driving force of the blades spinning. When designing a wind turbine, the lift and drag of the blade change proportional to wind speed and the angle of attack of that wind. Graphical analysis like Figure 2 can be compiled for any specific airfoil blade.

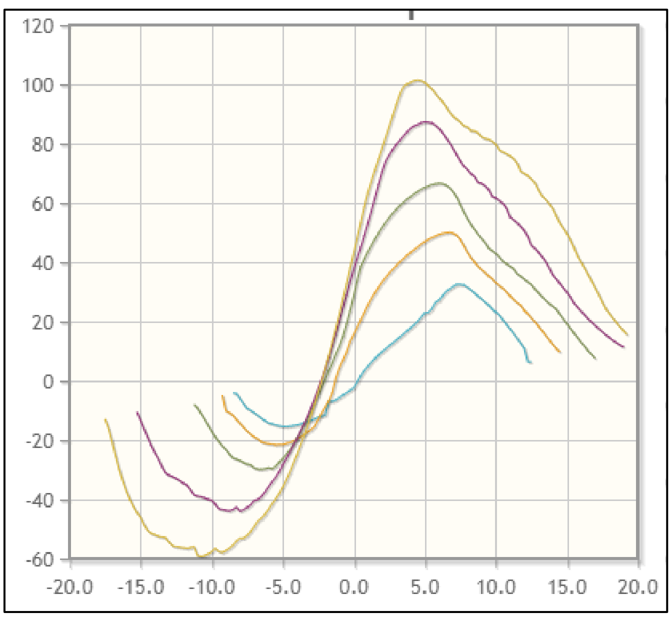


Figure 2: Coefficients of lift over drag graphed against the angle of attack.

Figure 2 illustrates how coefficients of lift and drag change with the angle of attack of the wind. As shown, the optimum lift over drag for this airfoil would around 8 degrees (Airfoil Tools, 2019).

In addition to the lift and drag coefficients, another major design characteristic is the tip speed ratio. This ratio, which is abbreviated λ, is defined as the linear speed of the tip of the blade divided by the prevailing wind speed (Carriveau, 2012). Tip speed ratio can also be defined by Equation 3,

$$\lambda = \frac{\Omega R}{V} \qquad (3)$$

where Ω is the rotational speed measured in radians per second, R is the wind-swept radius, and V is the velocity of the wind. This equation clearly shows that if the design wishes to have success with low cut-in speeds, a high tip speed ratio would be optimal. As the wind velocity decreases, the design will maintain relatively high RPMs therefore the higher tip speed ratio is optimal.

The number of blades on typical wind turbines varies from two up to as many as six. The solidity of a wind turbine is the ratio of the blade area to the turbine swept area. As more blades are added, the surface area that is exposed to the wind is increased, as shown in Equation 4,

$$P = \frac{1}{2}\,\rho\,A\,V^3 \qquad (4)$$

where P is the power produced by the wind turbine, ρ is the density of the air, A is the surface area of the blades and V is the velocity of the wind. This equation indicates that as the surface area of the blades increases so does the power produced. Research indicates that as solidity increases, the pressure differentials created cause the power of the wind turbine to decrease (Qing'an Li, 2016). This effect is contradictory to what the equation indicates, therefore the design needs to maintain as many blades as possible without effecting the solidity of the wind-swept area. The team settled on 3 blades as this would give enough surface area to produce power at low wind speeds while maintaining enough free area to not hurt the performance in high wind scenarios.

The coefficient of performance for a wind turbine is defined by Equation 5.

$$C_p = \frac{P}{\frac{1}{2}\,\rho\,A\,V^3} \qquad (5)$$

This equation displays an efficiency rating as it compares the power harvested from the wind and the amount of energy that the wind contains. Through studies of German physicist Albert Betz, he states that any real wind turbine cannot produce a C_p greater than 0.59, or roughly no wind turbine could attain more than 59% efficiency (University of Calgary, 2018). Without a completed model of a wind turbine, this design parameter can only be calculated using Blade Element Momentum Theory. This theory approximates blade design characteristics that could otherwise only be found through actual testing. Knowing this is the case, the outcome of the theory will likely impose error in comparison to a full test module. With the risk of error, the optimal wind turbine design may not reach the highest C_p possible.

The last and most important design parameter for the blades is its structural integrity. Since the blades are the first components of the wind turbine to experience the forces and pressure due to the attacking wind, they were required to be put through a series of stress analyses to ensure the stability of the blades. Due to complications in the shape of the airfoil blades, the best way to analyze them for the design is using numerical modeling. In our case, the team used ANSYS to simulate the effects witnessed by the blades while operating at max speed (3800 RPM); tangential, normal, and centrifugal forces as well as material properties were simulated within the software using FEA modeling. The team can then compare the results from the Finite Element Modeling to the properties of the wind from variable scenarios using Equation 6 to confirm that the parts will not fail.

$$F_{wind} = \frac{1}{2}\, \rho\, V^2\, A \qquad (6)$$

In Equation 6, F_{wind} is the force of the wind, ρ is the air density, V is the wind speed, and A is the surface area of the blade.

To address the aerodynamic design challenges such as maximizing C_p, developing Cl/Cd graphs, and solving for projected rotational speeds, the design team utilized another software, QBlade. QBlade is a free software that allows for dynamic outputting of all the design parameters for custom shaped airfoil blades. The coding from the program was analyzed through hand calculations to double check the credibility of the graphical outputs. QBlade can create splines of airfoils meeting any shape. This allowed the team to create blades and change shape dynamically to adapt to all the wind conditions in the competition. Additionally, the program can output CAD files for use by the design team. The program is also able to utilize Blade Element Momentum theory to assist the design team with the development of C_p -λ graphs that will easily show which blades will perform best under low speed conditions.

Blade and Rotor Material Testing

To determine the overall shape of the blade, testing and analysis was performed on various materials. The design team considered both cost and constructability as major factors when looking at materials to use and decided that 3-D printing our blades and rotor would be the most efficient option. Polylactic Acid (PLA) and Chopped Carbon Fiber were tested to obtain their material strength properties. Both materials were tested using ASTM D638 testing standards for polymers with Instron 5982 tensile testing machine. Various infill percentages were tested for each material and the chopped carbon fiber had a much higher tensile strength than the PLA material. With an infill percentage of only 25% the chopped carbon fiber had a tensile strength of 6800 psi while the PLA at the same infill percentage had a tensile strength of 3900 psi. Considering that both materials had relatively the same weight, the chopped carbon fiber was chosen to be used for the rotor and the blades.

Blade and Rotor Structural Design

Designing the blade and rotor interface was one of the most crucial aspects of the blade design to assure safety and efficiency when the turbine is rotating at high speeds. Since the blade was designed with a fixed angle of 8 degrees the angle had to be built into the rotor design as calculations and analysis were performed. With a maximum calculated rotational velocity of 3800 RPM, the interface was designed considering lift, drag, and centrifugal forces. A partial safety factor of 1.485 was applied to all forces on the blades and rotor to account for uncertainties.

After analysis of the material and the forces acting on the blades, each blade would be held in place with two ¼” diameter bolts to resist centrifugal forces. The chopped carbon fiber around the bolts was also analyzed to confirm sufficient cross section to resist block shearing at the bolt locations. The design loads were applied to the blades and rotor using ANSYS FEA software to confirm its safety by comparing the maximum stresses each blade would take to the geometry and material strength of the blade. Figure 3 demonstrates the structural analysis performed on the blades and the stresses at each location along its length of the blade.

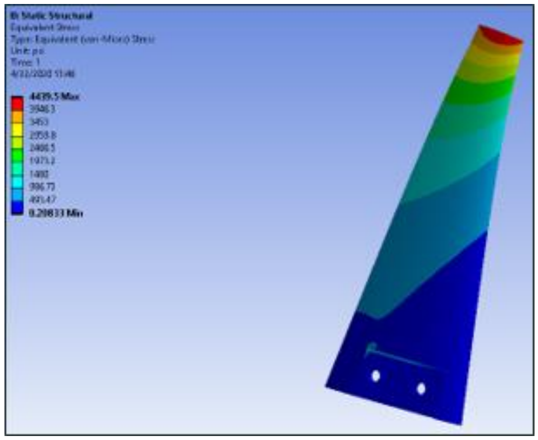


Figure 3: Numerical modeling of the blade

Rotor Strength Test

A rotor strength test was conducted in a controlled environment to confirm that the blade and rotor was structurally sound and could withstand the maximum rotational velocity it would experience during the competition. The test was performed using a DC motor to simulate the effects of the wind and was increased gradually (500 RPM increments) until it reached 3800 RPM. A test stand was built so that the blades and the drive shaft was positioned perfectly straight using a dual bearing system to reduce the vibration during operation. The testing stand was set up inside a 36” diameter steel duct covered with multiple moving blankets to ensure the safety of all participants. To measure the RPM of the blades during the test, a stroboscope was used so that when the blades appeared to be stationary, the user would know the rotational speed of the blades. This process was filmed with a GoPro Hero 7 to capture the blades and rotor operating at the max speed.

After the test was conducted, the blade’s design was reevaluated for changes to develop a more efficient system without compromising its structural integrity. Along with the weight of the blades, the original steel bolts were replaced with fiberglass reinforced polymer (FRP) bolts. FRP is a great alternative to metal bolts as it provides similar material strength with substantially less weight. Also, decreasing the width and thickness of the blade at its base was considered to decrease the weight and the centrifugal forces on the system.

Tower and Base

The tower and base of the turbine are important to the stability of the entire structure. The tower was designed to be stable enough to resist all wind forces and weight of the turbine while also acting as a conduit for all electrical wiring to the base. The maximum wind force on the turbine was calculated using the total swept area of the blades stem along with the maximum wind speed it would experience. After mathematical analysis it was determined that a 1 ½" Schedule 40 6061 Aluminum pipe would be sufficient to resist these forces and fit the wiring into the base.

ELECTRICAL

The electrical system encapsulates all the subsystems necessary to produce a regulated electrical power output in a safe and reliable manner using electromagnetic generation, power quality and speed regulation electronics and emergency braking. The electrical system overview diagram shown in Figure 4 describes the components of the system.

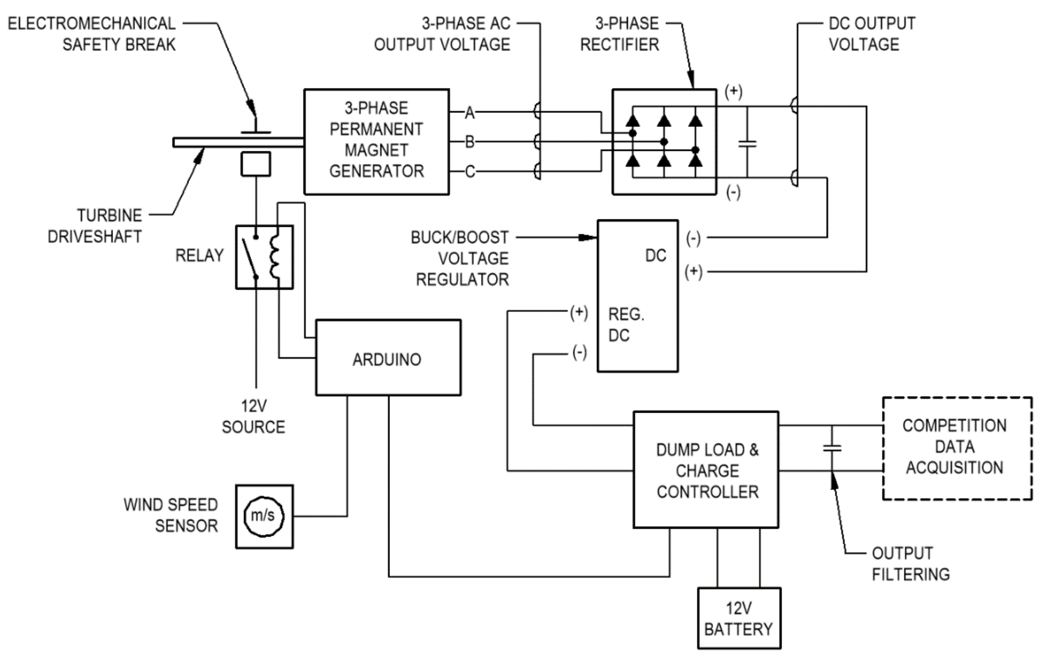


Figure 4: Electrical System Overview

Generator

The generator design is based on a 3-phase AC, permanent magnet, axial flux generator. The stator consists of two coils per phase. This type of generator was selected because the width of the stator and rotor with respect to the driveshaft length is relatively small allowing for additional stators and rotors to be added to increase power output. Three design iterations were constructed and tested. The designs are as follows:

1. Design Iteration 1
   a. 6 x triangular coil stator 0.25" thick
   b. 22 AWG wire, 70 turns
   c. Single N52 5/8" x 1/4" Disc magnet for each rotor magnet position

2. Design Iteration 2
   a. 6 x triangular coil stator 0.375" thick
   b. 26 AWG wire, 250 turns
   c. Single N52 5/8" x 1/4" Disc magnet for each rotor magnet position

3. Design Iteration 3
   a. 6 x triangular coil stator 0.375" thick
   b. 26 AWG wire, 250 turns
   c. Double N52 5/8" x 1/4" Disc magnets for each rotor magnet position

The stator design shown in Figure 5 is hand wound around three equally spaced nails arranged in a wooden block – this took considerable time. The coils in the second stator design shown in Figure 6 were wound using the triangular spool-like tool. The tool was rotated by an electric drill to evenly wind the coils as the number of windings was counted.

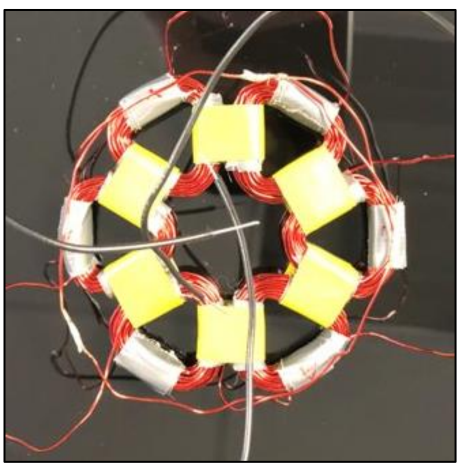


Figure 5: First stator design

Figure 6: Second & current stator design

The rotor shown in Figure 7 is constructed using 3D printed PLA. It has a 0.25" hole to connect to the turbine driveshaft and eight recessed cavities to house the eight 5/8" x 1/4" round N52 neodymium magnets. These magnets were chosen because they are the strongest magnet for their size. Because the generator utilizes two coils per phase, to maintain proper phase angles and optimal efficiency eight magnets were required with a diameter roughly equal to twice the thickness of one side of the coil. The magnets were set in place using epoxy resin to maintain structural integrity and rotor surface uniformity.

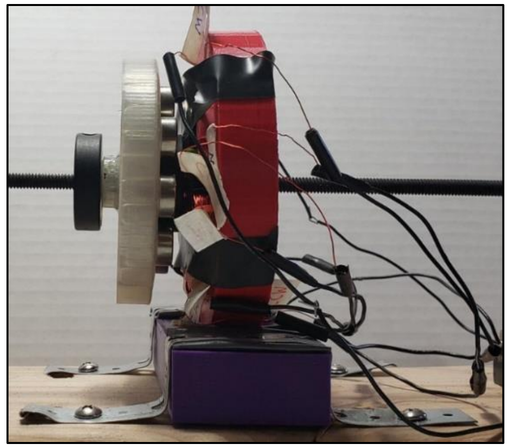



Figure 7 & 8: Generator prototype

For testing, all generator designs and revisions were tested on the dynamometer testing rig as shown in Figure 8 that was constructed to meet the requirements of the dynamometer competition milestone.

Rectifier

The competition requirements dictate that the output voltage of the turbine must be direct current. To achieve this, a 3-phase bridge rectifier is used to convert the alternating current of the output of the generator to direct current. The rectifier was purchased with a voltage rating of 100V and a current rating of 25A.

Voltage regulator

Because power efficiency was of great concern in this project, a standard voltage regulator IC was not an appropriate choice. Instead, a buck-boost voltage converter module was purchased and used because of its high efficiency and output stability. Preliminary testing confirmed that the converter's efficiency was greater when stepping down the voltage than stepping up the voltage with a minimum efficiency of 72% and a maximum efficiency of 96%. It was assumed that the voltage would be close to or above 12VDC output at rated speed so a decision was made to set the regulator to 12VDC output so that the efficiency would always be above 85%. This would also allow for easy interface with a 12V charge controller for an external battery. One limitation of the converter is that in order for the voltage to be stable at the set value, the power supplied by the generator needs to exceed the power requirement of the load.

Dump Load

The purpose of the dump load system is to slow down the rotational speed of the turbine and to absorb excess power, so the output power is constant. It is comprised of an Arduino microcontroller, an RPM sensor, four 10Ω resistors and four MOSFETs. As shown in Figure 9, the dump load accomplishes this by switching on and off multiple resistors in parallel. The Arduino uses feedback from the RPM sensor and comparative logic to determine the speed of the turbine. Then it outputs logic signals to switch MOSFETs that connect the resistors to the circuit to dissipate power. The charge controller and battery storage are intended to store unused energy before the dump load is required. The Dump Load System is shown in Figure 9.

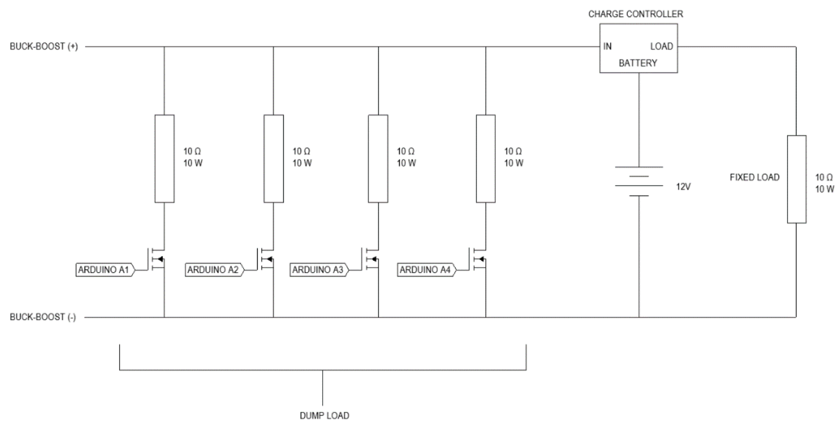


Figure 9: Dump Load System

Braking system

The braking system (Figure 10) is activated via a control signal from the Arduino microcontroller. An anemometer feeds real-time windspeed data to the Arduino which compares it to the maximum cutout speed of 22 m/s. When this speed is exceeded, the Arduino sends a 5V control signal to a 12V supplied relay which closes the contacts and engages a solenoid which causes contact with a disc connected to the driveshaft. The 12V switched by the relay will be supplied by the external 12V battery source which is charged by the turbine. Additionally, a normally open mushroom-type twist-reset emergency off switch will also be wired to the relay and will be supplied by a constant 5V supply from the Arduino.

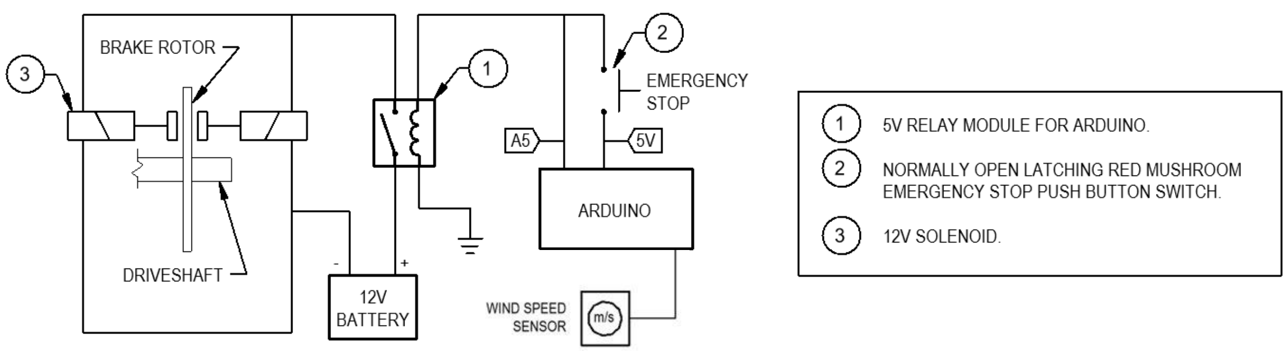


Figure 10: Braking System

Generator Test

Open circuit tests were performed for the first, second and third generator prototypes. The generator rotor was driven by the dynamometer motor at speeds from 0-3000 RPM and voltage measurements were taken after the bridge rectifier. Figure 11 compares the open circuit voltages of all three generator designs. Refer to Appendix D for the full testing procedure. Peak power measurements were taken for both the first and third prototypes by connecting a 5Ω resistor across the generator output and measuring the voltage. The first prototype produced 0.8W at 3000 RPM and the third prototype produced 3.8W at 3000 RPM.

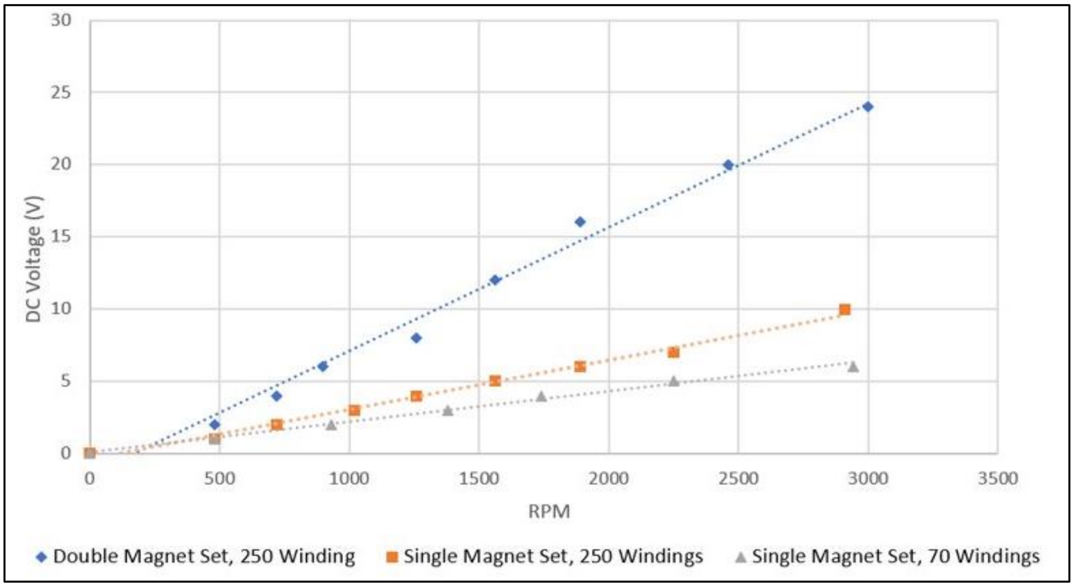


Figure 11: Generator Open Circuit Testing Data

SYSTEMS

Modeling

Due to the complexity of the integrated wind turbine system, the team used Vitech CORE™ software to model and simulate the operation of the wind turbine. The CORE™ model helped the team identify the components and their functions within the system. The CORE™ model also demonstrates the relationships between the components and the logic behind the wind turbine. Figure 12 shows the four-level hierarchy diagram of the wind turbine system's components. In the diagram, the upper-level components are built from the lower-level components.

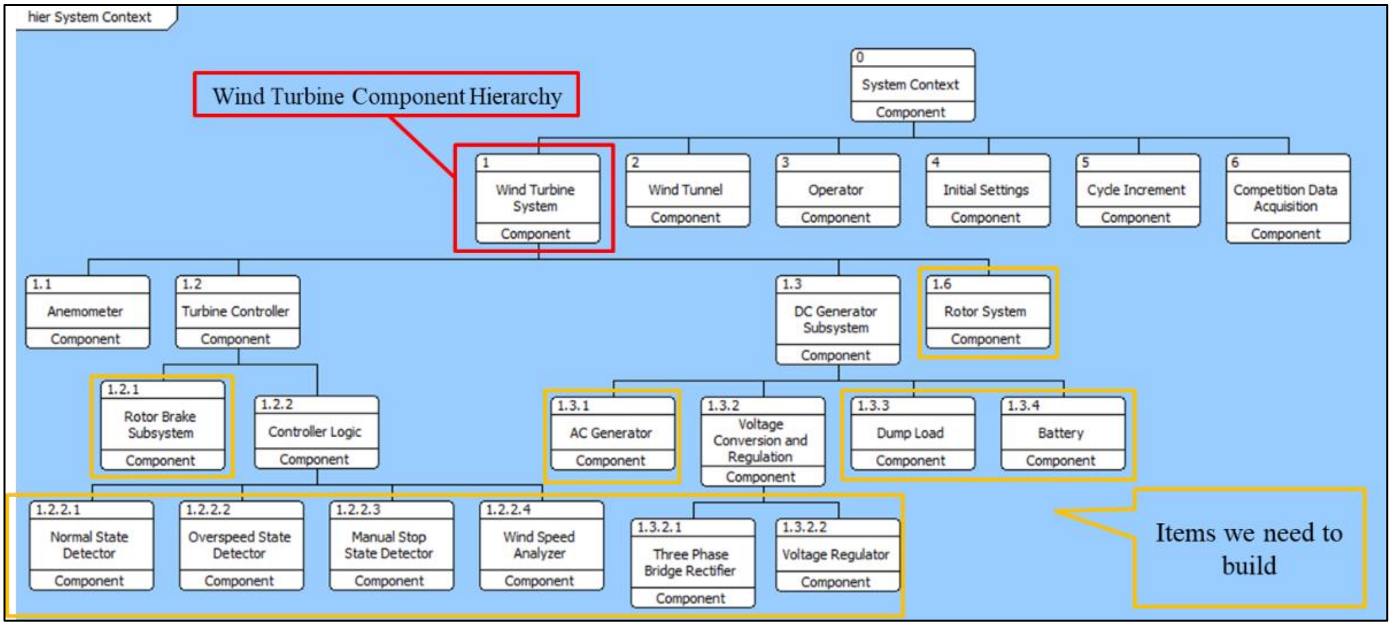


Figure 12: Components Hierarchy of the Turbine System; generated with CORE™

Simulation

The control of the turbine in Figure 13 represents scenarios under different situations. The wind speed is modeled to rise past the 22 m/s threshold to demonstrate the system's ability to apply braking, and then fall below the 18 m/s restart threshold to demonstrate brake release. A manual stop interrupt is included to randomly command a user-initiated stop.

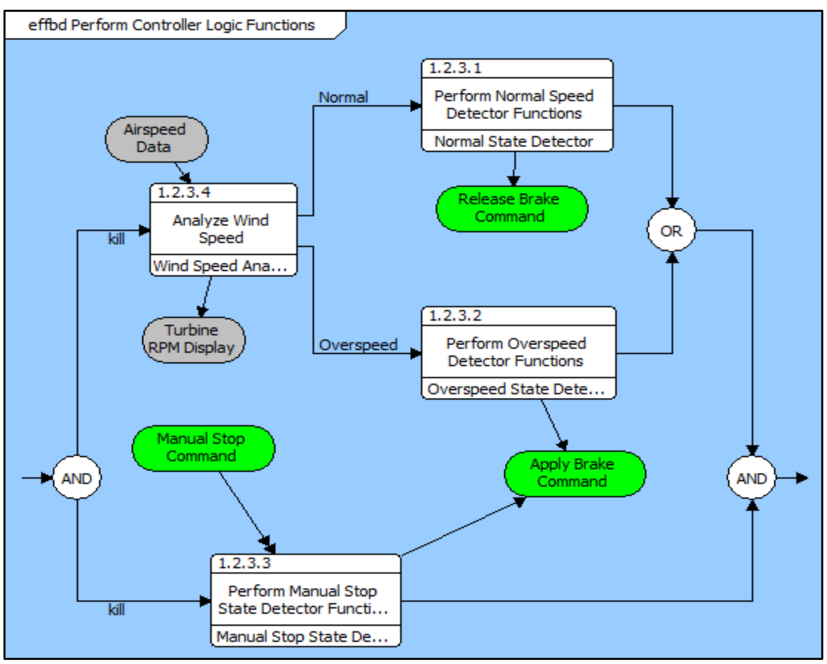


Figure 13: Control Logic of the Turbine; generated with CORE™

The over-speed scenario simulation in Figure 14 represents what will happen when the system detects over-speed. The over-speed detector will send a signal that releases the brake to slow down the turbine. Also, the AC generator will stop.

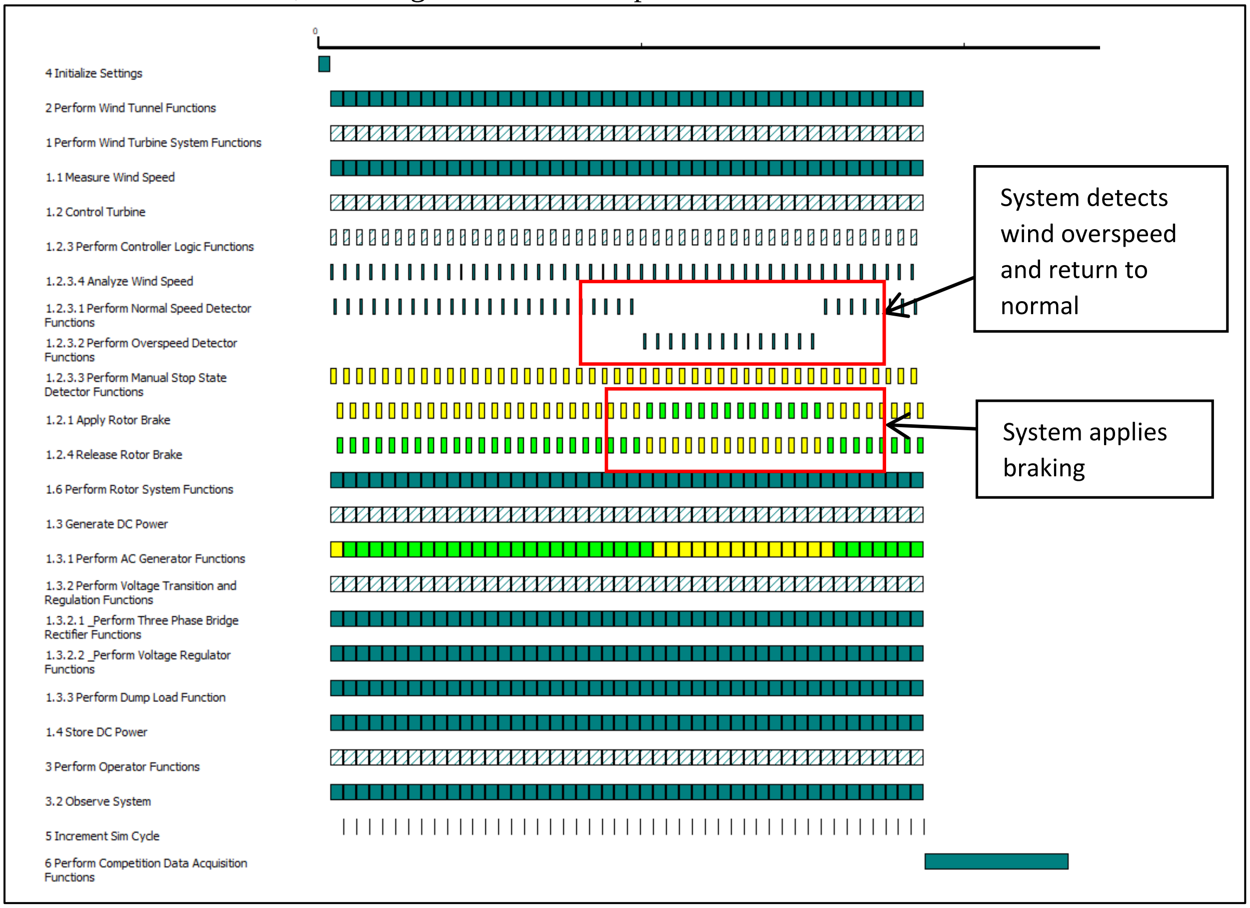


Figure 14: Overspeed simulation scenario

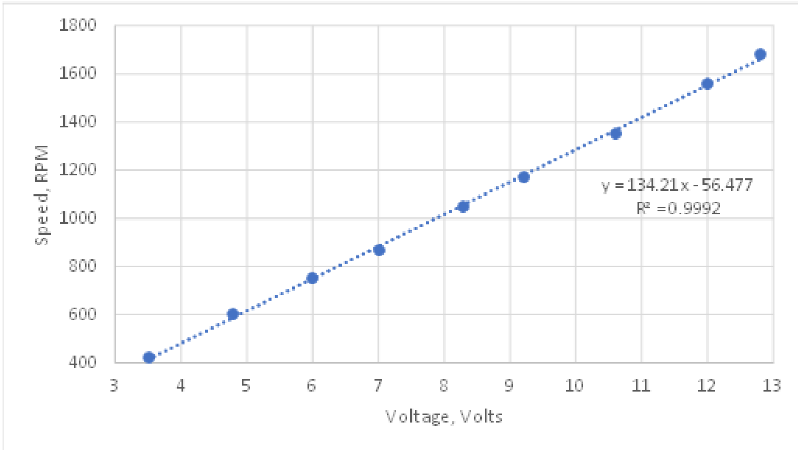
CONCLUSIONS AND RECOMMENDATIONS

The primary objective of this project was to explore the main design concepts behind a functional wind turbine while adhering to strict design criteria established by NREL and the DOE. The team at the University of New Haven successfully designed, manufactured, and tested critical components of a wind turbine that would have been able to operate safely and effectively. Although a tangible model was unable to be completed, as a result of the COVID-19 situation, the team would recommend that further testing be done on the final generator iteration, as well as optimizing the design of both the blade and rotor assembly. These components would then be coupled together and placed in a wind tunnel to measure the turbine's potential power output under competition testing parameters.

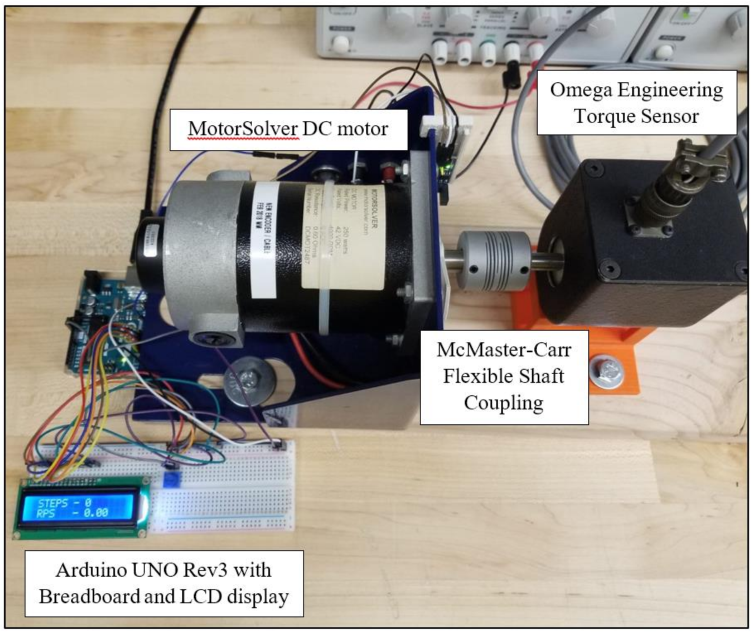
APPENDICES

A. Voltage and RPM Measurement Through the Sensor

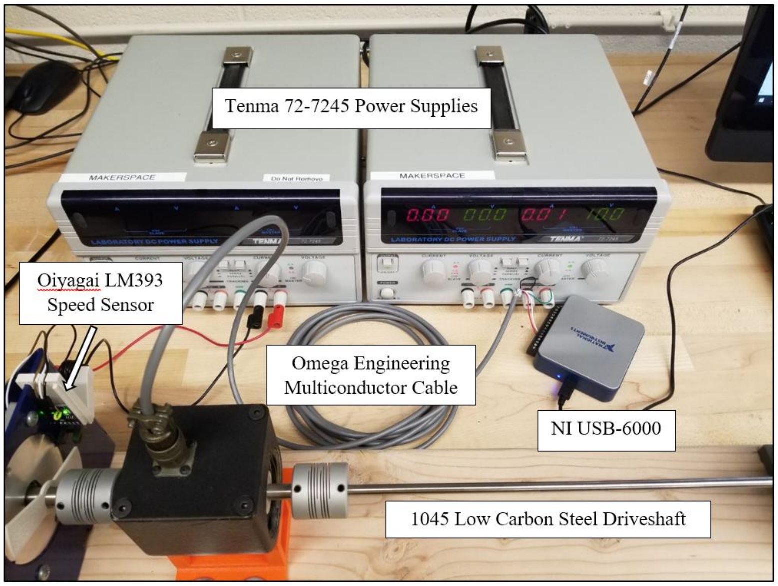
Volts	Current	RPS	RPM
3.5	0.72	7	420
4.8	0.72	10	600
6	0.75	12.5	750
7	0.77	14.5	870
8.3	0.78	17.5	1050
9.2	0.78	19.5	1170
10.6	0.79	22.5	1350
12	0.79	26	1560
12.8	0.79	28	1680



B. Drive System and RPM Measurement Components



C. *Dynamometer Components*



D. *Generator Testing Procedure*

Test #1 Procedure

1. Assemble each component of the test, including the motor (used to simulate the blades), the power supply, the multimeter, the rotor, the stator, and the speed sensor.
2. Turn on the power supply to power the motor, slowly increase the power supply, start record the reading of the speed sensor and the multimeter until get enough data.
3. Turn off the power supply, add the load to the circuit, and repeat steps 2.

Test #2 Procedure

1. The setting of the second test is the same as that of the first test. Due to the problems in the connection between the rotor and the shaft in the first test, a new connection method was adopted in the second test (used 1/4" Clamping shaft collars).
2. Turn on the power supply to power the motor, slowly increase the power supply, start record the reading of the speed sensor and the multimeter until get enough data.
3. Turn off the power supply, Double the magnet on the original rotor.
4. Turn on the power supply to power the motor, slowly increase the power supply, start record the reading of the speed sensor and the multimeter until get enough data.
5. Turn off the power supply, add the load to the circuit, and repeat step 4.

REFERENCES

Aw, Y.Y.; Yeoh, C.K.; Idris, M.A.; Teh, P.L.; Hamzah, K.A.; Sazali, S.A. Effect of Printing Parameters on Tensile, Dynamic Mechanical, and Thermoelectric Properties of FDM 3D Printed CABS/ZnO Composites. *Materials* **2018**, *11*, 466

Bannon, N., Davis, J., & Clement, E. (2013). Axial Flux Permanent Magnet Generator. Retrieved November 11, 2019, from http://depts.washington.edu/pmec/docs/Generator Final Report ME 495 Autumn 2013.pdf

Musial, W. D., & Butterfield, C. (1997, September). Using Partial Safety Factors in Wind Turbine Design and Testing. Retrieved May 12, 2020, from https://www.nrel.gov/docs/legosti/old/23257.pdf

Martinez-Marques, C. I. (2019, June 26). Small Wind Turbine Emulator Based on Lambda-CpCurves Obtained under Real Operating Conditions. Retrieved May 12, 2020, from https://www.mdpi.com/journal/energies

Wind Vision. (n.d.). Retrieved from https://www.energy.gov/eere/wind/maps/wind-vision

University of Calgary. (2018, July 21). *Energy Education*. Retrieved from energy education.ca/encyclopedia: https://energyeducation.ca/encyclopedia/Betz_limit