Technical Analysis of a Lab Scale Wind Turbine

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Abstract

Wind energy is emerging as a main source of power due to its renewable and clean nature. A lab-scale wind turbine was designed in order to be tested to meet the requirements of using a DC motor, having weatherproof materials, being free-standing, and passing the final test of lighting the green LED. Four different prototypes were developed and tested in order to select the best parts and characteristics of the final design, in the end, only one of the designs was able to light the LED, and thus the primary rotary system which was 3D printed blades and mount, and 12V DC motor was provided by that design. The tower structure of the turbine also needed to be weatherproof, so the materials were chosen from a different design because they met the requirements. The design that managed to power on the LED didn't have any special mechanism in place for it to generate electricity, the blades were directly connected to the motor and that was also implemented in the final design. These decisions were made after discussions with the group members and the most optimal parts from each of the prototypes were then chosen to be included in the final design. The final design was then tested for its performance in a lab-scale scenario using digital tools to measure the blade speed in rpm, voltage, and current. The lab testing was conducted using a box fan placed on a desk and at its max speed, there were three trials; in each one, the turbine was moved closer to the fan and the results improved significantly. The results of the design were measured using a digital anemometer for the wind speed and the RPM of the blades. The voltage and current were then measured using a digital multimeter by use of the cables from the dc motor on the design. The results for the design were able to meet the final requirement of lighting the green LED and had an efficiency average of 0.0006% and a final voltage of 2.95.

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1 Introduction

The following research is about the design, functionality, and history of wind turbines. Generally, there are two types of wind turbines: the Vertical Axis Wind Turbine(VAWT) and the Horizontal Axis Wind Turbine(HAWT), the latter being more commonly used. Wind turbines serve an important role in producing electricity with a clean source of renewable energy, Power companies can benefit from turbines and as well as regions with low power grids. These turbines generate energy while leaving little to no carbon footprint on the environment compared to alternative ways to generate electricity such as coal and other fossil fuels. Since most electricity is produced from environmentally harmful sources of energy, it is important to expand the public's knowledge of the safer options of renewable energy.

1.1 Problem statement

A wind turbine was designed and built to sustain enough energy to power an LED light with a specific voltage. Weather resistance was also taken into account when choosing the material that the turbine was built from. The turbine was built to fully capture and withstand the oncoming wind to generate electricity using a DC motor. The blades requirements were to generate a minimum of 2 volts for the first stage of testing which is for the red LED, and be able to generate a minimum of 3 volts for the final stage of testing which is for the green LED. The DC motor in turn stores the wind-powered energy after the rotor spins and converts it to electricity which will power the lights.

Along with functional blades and the motor, a sturdy base was assembled to withstand the weight of the turbine. Four turbines were built with differing characteristics and methodologies and tested for their ability to generate energy to power the aforementioned LED lights. The most efficient of the prototypes was selected to be improved on further. It was then tested and improved over time in order to optimize it for powering the green LED which was the final test. Along with powering the light, the final goal for the turbine was to be an adequate, reliable source of clean and efficient energy.

1.2 Background Research

Historically the VAWT and the HAWT were created to produce energy in two different ways based on the circumstances of the environment. According to [1], the HAWT has been used in more recent years because of its adjustability to capture the full speed of the wind by changing the turbine direction. While the designs change, so do the generators and grid codes, for example, most of the big wind parks in North America run off the bulk transmission system because modern wind parks require extra high voltage levels [2]. In 2017 however, the first floating wind farm was created. As mentioned in [3], they talk about the drivetrains on these offshore turbines and how they have been changing the mass to make them more compact and more cost-efficient. With wind power becoming more popular in North America, the United States exported nearly $200 million in wind turbine blades, nacelles, and other related materials to Canada between 2007-2011 [4]. As researched between 1974-2014 in [5], they studied the comparison of wind turbine markets between America and Denmark. The research concluded that Americans were more susceptible to making changes and abandoned designs while the Danish took a slower approach to better their turbines by using already established resources.

Wind turbines are beginning to overtake fossil fuels in popularity in terms of energy production, reliability, and nonexistent air pollution. Although wind turbines might have many advantages over other renewable energy sources, they also have their disadvantages, which is the noise pollution they produce. ~~The more wind turbines are used, the closer they get to human habitation which tends to make the noise pollution worse and have an impact on people's health~~ [6]. ~~Wind power might be one of the most reliable sources of renewable energy and it's becoming more accessible globally.~~ Another issue that comes with the use of wind power is that some regions of the world don't have wind speeds fast enough in order to keep sustainable energy generation [7]. The drivetrain is the part of the wind turbine that connects each piece together; a turbine drivetrain contains the generator, gearbox, rotor blade, and many other components. This is where most of the functionality and energy generation happens in the turbine. Locations of wind turbines are an important factor to consider when trying to produce electricity from wind power, high elevations and offshore in an ocean seem to be the most common locations for efficient energy generation [9]. The blades of the wind Turbine are one of the most important parts of the wind turbine because the blades are the parts that catch the kinetic energy of the wind and convert it into electrical energy [8]. Wind turbines create energy by using the blades to catch the wind's kinetic energy and spinning in the process, the rotary of the blades connects to the drivetrain's parts which then turn the generator. After the generator turns, it creates electricity and channels it through a power grid to a transformer in order to balance the voltage for safer use.[10]

Vertical Axis Wind Turbines or VAWTs, are being studied to see in what situations they could not only be a good source of renewable energy, but also a more efficient source than the traditional horizontal axis wind turbine. VAWT is much more useful in urban areas since the wind direction does not matter for a VAWT to convert it to power[11]. Since wind is not always blowing, ramp rates need to be understood to know the shortage or overage of power produced over time so stored power can be used to compensate[12]. VAWT placement is still important even though wind direction does not matter. When planning where to position a cluster of VAWT it is useful to use equations to predict the power output of the wind flow field[13]. Another way to predict the good positioning of turbines placed close together is using wake redirection to find the proper yaw angle between two turbines for maximum efficiency of power output[14]. One of the biggest problems with VAWT is unpredictable wind patterns. Therefore it must be observed how much wind is being converted to power by the VAWT. Predicting the amount and comparing it to the observed amount of power created by the wind allows for the error of the prediction to be calculated [15]. This is important in understanding how efficiently the VAWT is working.

“A wind turbine is a device, which extracts kinetic energy from the wind and converts it to torque at the shaft”[16]. To do this a wind turbine has to have proper aerodynamics to extract wind energy. There are mathematical equations to model optimal wind turbines as in this source [17]. Although there are physical limits to wind turbines which are known as the Betz limit and are discussed more in-depth in the source [18] which will not be reached with this experiment's model. Damage to wind turbine blades can be statically found and modeled to see the effects of aerodynamics as in this source [19]. Ice accumulation can also cause a decrease in aerodynamics and can be properly countered by deicing technologies as this source [20] states. The following are equations found from the sources.

Betz limit is found in equation [1] which should equal zero for maximum power output.

$$0 = dc_p/d(\frac{v_2}{v_1})$$

dcp=drag coefficient
d=distance
v1=velocity 1
v2=velocity 2

The tip speed ratio is important for calculation of efficiency and is found with equation [2]. Ω = rotational speed, R =Radius, v = Wind speed, ⋏ = tip speed ratio.

$$\curlywedge = \frac{\Omega R}{v_1}$$

$$\lambda = tip\ speed\ ratio$$

R=radius

$$\Omega = angular\ momentum$$

$$v_1 = velocity$$

A wind turbine harnesses power from a difference in kinetic energy in the wind which is calculated via equation [3].

$$P = \frac{1}{2} pv_1 A_1 (V_1^2 - V_2^2)$$

P=power
pv= potential velocity
A=acceleration
V= velocity

Maximum power output is calculated with equation [4].

Pturbine = I * v
I = current
v = voltage

Turbine efficiency is found with equation [5].

$$\% = \frac{P_t}{P_w}$$

%=efficiency
Pt=power turbine
Pw=power wind

2 Methods and Materials

To build the final turbine the team members came together to use their ideas from their individual designs to build the best turbine between them. The final turbine's design was the combination of Alex's base, shaft, and tower with Mustafa's DC motor and blades. From the results of individual testing it was decided based on the free standing ability that Alex's PVC base, shaft, and tower design were the best for the final turbine. His design was very stable and was ideal for the base/tower pair of our final turbine compared to the other team members designs. Mustafa's DC motor and 3D printed resin blade design produced the highest voltage at the highest efficiency during the individual testing which made them the ideal parts to be used for the final design. To incorporate these into one final product the team came together and discussed how the final turbine should be constructed out of the parts we deemed ideal from the individual testing. The base and shaft were from the largest scaled turbine in our group while the motor and blades were part of the smallest turbine. To make the parts compatible the tower and shaft were made from shorter PVC pipe, 0.368m tower and 0.178m shaft, and larger 0.1397m resin blades were 3D printed. The new parts were then constructed into the final turbine for testing the ability to light the 3-volt green LED. The new tower was connected to the weight at the bottom with a T shaped pipe perpendicularly connecting the shorter shaft with the tower at the top. The new 3-D printed mount and blades were assembled with the DC motor from Mustafa's Design and connected to were directly connected to the shorter side of the upper pipe shaft. Then the design was tested at the lab to see if it could light the 3 volt green LED light.

After measurements were taken about the dimensions of the turbine it was tested in front of a box fan. It was determined to be free standing and the wind speed was measured by a digital anemometer. The RPM of the turbine was then measured with a motion sensor from the aforementioned digital anemometer but that value was divided by the number of blades before bieng used for any calculations. The blade tip speed was calculated by finding the product of the RPM, blade diameter, and 0.262. The blade tip speed ratio was the blade tip speed divided by the wind speed. The power of wind was then calculated by the product of 0.5, airflow area (pi multiplied by radius squared), density of air, the wind speed cubed, and time. The current and voltage were then measured while the box fan was blowing on the turbine using a multimeter. The power of the turbine was then calculated by multiplying the current by the voltage produced by the turbine. Finally the efficiency of the turbine was calculated with the equation (power of turbine/power of wind)*0.593*100, this gave a percent efficiency of the turbine. After one testing more improvements were made to accomplish the goal. The motor was switched because it was burnt out during the initial testing. The original blades from Mustafa's individual design were used because of their high efficiency. The final turbine was finished after these changes and retested using the box fan to light the 3-volt green LED. All of the tests were run again and three trials were completed with the final turbine design which all succeeded in lighting the green LED light.

3 Results

Table 1 Below are the general dimensions and qualities of the Turbine design, the design had 6 blades made out of 3D print resin which also had a radius of 2.75 inches/0.06985 meters. The tower of the design was about 14.5 inches/0.368 meters, and the materials of the tower were mostly PVC pipes. The materials for this design were in fact waterproof, out of scratch, and the design was free-standing. The air density in the testing room was about 1.23 kg/m3.

Table 1-Wind Turbine Dimensions

Blade Material	3D Printing Resin
Number of Blades	6
Tower Material	PVC Pipe
blade’s Radius (In)	2.75
Tower Height(In)	14.5
Is the Waterproof?	Y/N
Is the model free-standing?	Y/N
Built from Scratch?	Y/N
Air density(kg/m^3)	1.23

The second table below contains the wind turbine results that were recorded in testing, in trial 1, the turbine was 35 cm away from the fan, The rotational speed of the turbine was 660.0 rev/min, and 11 in rev/s, the wind speed was about 3.7 m/s. The second testing trial had the turbine 20 cm away from the fan and had a rotational speed of 668.3 rev/min which is 11.139 in rev/s, the wind speed was 3.8 m/s. The third testing trial had the turbine 11 cm away from the fan and a rotation speed of 679.33 rev/min which is 11.322 rev/s, and the wind speed was 3.5 m/s.

Table 2-Wind Turbine Results

Trial Number	Distance from the fan(cm)	Rotational speed (rev/min)	Rotational Speed (rev/sec)	Wind Speed (m/s)
1	35	660.0	11.0	3.7
2	20	668.3	11.14	3.8
3	11	679.3	11.32	3.5

This is the second part of the results with the rest of the required calculations. The status of the LED light was also tested in each trial. The closer the turbine got to the fan, the more the results differentiated.

For the first trial, the blade tip speed was about 951.06 m/s with a tip ratio of 4.284, due to this the LED was powered on. The wind power calculation resulted in 7401.1 Watts, the current was about 0.03 Amps and also resulted in 1.98 volts. The turbine power was about 0.0594 Watts and had an efficiency of 0.0004%.

The second testing trial resulted in a blade speed of 963.07 m/s with a blade tip speed ratio of 4.224 which managed to power on the green light in this trial as well. The wind power result was about 8017.5 Watts, the current was also 0.03 with a voltage of 2.46. The turbine power calculation was about 0.0738 Watts and had an efficiency of 0.0005%.

In the third trial, the blade tip speed was about 978.92 m/s with a blade tip speed ratio of 4.662 and the LED was powered on again. The wind power calculation resulted in about 6264 Watts, a current of 0.03 Amps and a voltage of 2.95 was also recorded. The turbine power resulted in 0.0885 with an efficiency of 0.0008%.

<u>Table 3-Wind Turbine Results Continued…</u>

Blade tip Speed (m/s)	Blade tip Speed ratio	Led Status	Pwind (W)	Current (A)	Voltage (V)	Pturbine (W)	Efficiency
951.1	4.28	Yes	7401	0.03	1.98	0.0594	0.0004
963.1	4.22	Yes	8017	0.03	2.46	0.0738	0.0005
978.9	4.66	Yes	6264	0.03	2.95	0.0855	0.0008

Figure 3 Below is a plot of the wind power and the turbine power results from the 3 trials as a function of wind speed, linear trendlines are used with their equation displayed on the graph. The X-axis is the wind speed in m/s and the Y-axis is the wind power and the turbine power in

Watts. All three points of each calculation on the scatter plot are the results for each of the 3 trials. The turbine power plot is very low on the plot because the results were less than 1. The distance of the turbine would get close to the fan and the results would improve and differentiate in the location on the graph.

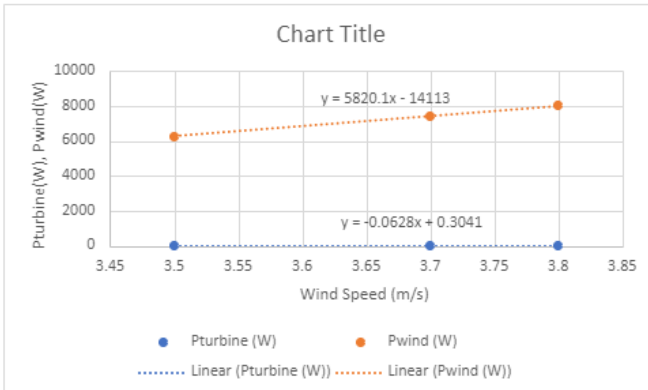

Figure 1. Wind Power and Turbine Power Plot

Below is a plot of the efficiency results as a function of wind speed, a linear trendline is used with its equation displayed. The *y*-axis represents the efficiency and the values are less than 1, The *x*-axis is also the wind speed in this plot as well. The three points on the scatter plot represent the results of each trial and would differ drastically as seen below.

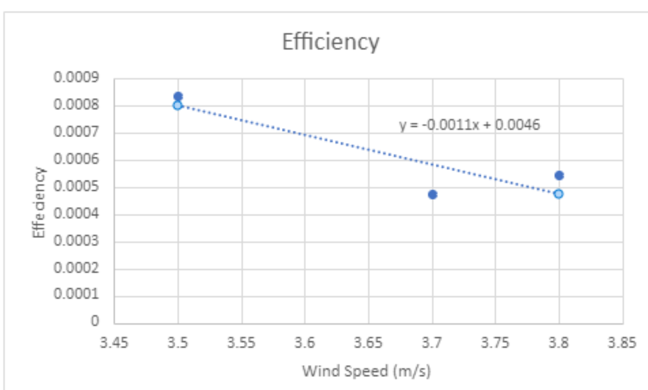

Figure 2. Efficiency Plot

Below is a plot of the power of the turbine as a function of the blade tip speed ratio. A linear trendline is used for the three points of the results, The Y-axis represents the power of the wind in watts and the X-axis is the blade tip speed ratio.

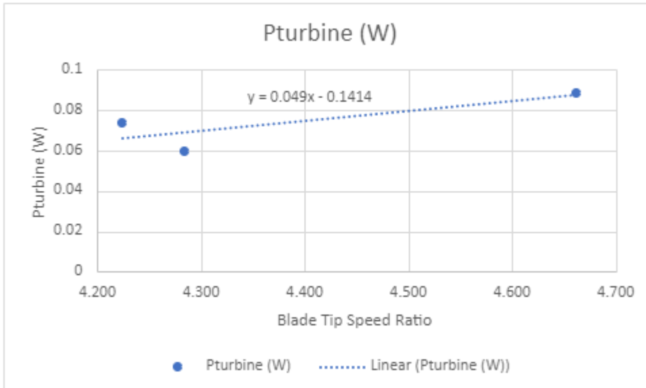

Figure 3. Turbine Power - Tip Speed Ratio Plot

4 Discussion

With these results it can be concluded that blade radius/shape and motor selection matters severely in the design of wind turbines. As the blade tip speed is determined by the radius which correlates to the speed the shaft of the motor spins. Motor selection matters to get the most generation of energy per rotation. So as in (table 1) optimal blade radius was 2.75in which gave us a blade tip speed of 951-978 m/s between all three trials as seen in (table 2.5). Blade shape matters to catch the wind although it wasn't studied as in depth as blade radius and blade numbers.

The way the results behaved is to be expected as in the design process the best turbine option was the one that lit up the LED. The change came from the motor which was found to produce too much resistance to push it to the final LED test of 3 volts. The reason the motor could have had this issue was because of faulty manufacturing or some flaw in the motor winding causing the inappropriate motor flux. Otherwise the blades remained the same from preliminary testing.

The results themselves changed when compared to the distance from the fan except for the blade tip speed ratio for the 20 cm test being 4.22 which is lower than the 11 or 30 cm test. This strange phenomenon could be explained by the way the air speed was 3.8 m/s or the faulty measuring equipment. The air speed is also a factor in calculating the blade tip speed ratio. All the other results calculated or collected were to be expected because as the turbine was pulled away from the fan the other results decreased. Efficiency as the speed of wind dropped increased which means that the turbine is more efficient at slower speeds. Which is a good thing because the testing was with a slow fan. The safety and health of the public was taken into consideration by making the structure of the wind turbine both waterproof and freestanding. The wind turbine also meet the power requirements for the public use. Economically speaking the wind turbine was cheap to make and is easy to manufacture in mass.

5 Conclusion

After three trials of the wind turbine testing, the rotational speed reached 11.32(rev/sec) or 679.3(rev/min) with a wind speed of 3.5(m/s) at a distance of 11(cm) from the fan. While the first and second trials put out similar results starting with a 660.0(rev/min) rotational speed and then a 668.3(rev/min) rotational speed it was not until the turbine was moved from 35 to 11(cm) from the fan that produced the best results. Once the proper calculations were made, the final trial had a 978.9(m/s) blade tip speed as well as a 4.66 blade tip speed ratio. All trials were able to light the LED with the third trial delivering a 6264(W) wind power, 0.03(A) Current, 2.95(V)

Voltage, 0.0855(W) turbine power, and a final efficiency of 0.0008%. The objectives were met with this turbine by lighting the LED as a free-standing model made out of waterproof materials such as resin and PVC piping. This was done after a group analysis of which parts of the individual designs would be used for the final model. The decision was to use Mustafa's 6 blade orientation and motor as well as a modified design of Alex's tower and shaft by shortening the height, and making the overall presentation smaller.

By testing this model the information learned was how much current and voltage a turbine could produce at a size of 2.75(in) blade radius, and a 6 blade resin orientation. Along with this, the DC motor stored the wind-powered energy from a rotation of the rotor converted into electricity which lit the LED bulb. Another objective that was completed and learned was how to make a sturdy base out of PVC piping to stop the model from tipping over after a fast wind speed was produced from the fan. Once all the testing and calculations were done, it was concluded that the motor selection and blade radius were the most important factors when designing a wind turbine. Another big factor that was learned is the distance from the fan, as to be expected when the turbine was moved closer to the fan it produced a higher revolution speed.

5.1 Future Work

To continue this design the DC motor must be changed to a motor that has a higher voltage output as well as a better harness to hold the blades and motor together in replace of the current harness. While the base of the tower was sturdy sitting on a metal disk extra measures can be taken to secure the whole turbine to add extra resistance and durability, by drilling the disk into a large piece of wood the overall structural integrity would increase. Further research in this area may include adjusting the blade size as well as the orientation to produce better results in fields such as the wind power, current, voltage, and turbine power. With advancements in these fields, the efficiency would grow to higher percentages and the overall product would be better performing. For example, instead of using the 6 blade 2.75in radius, experiments could be taken to tell if a smaller radius would perform better with more or less blades.

The next step for this project would be to make the minor improvements that will boost the development of the turbine to produce a higher efficiency to be used to capture more energy. The turbine would be useful as a good clean source of energy and can be kept running with little to no management, other than regular inspections to ensure the quality of the turbine. With advancements in technology the turbine can be improved over time to continue to produce a consistent energy output in rural areas where power is harder to acquire. The turbine can be set up in a field or on top of a mountain/hill to capture the wind and power multiple buildings to help expand an agrarian area.

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