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The Effect of Varying Number of Blades on the Efficiency of a Small-Scale Wind Turbine

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Motivation

Throughout my life, I have had a deep interest in the efficiencies of machines and generators. I was filled with a fascination towards efficiency, even trying to move more efficiently with least loss of time and energy. This led me to try and pursue physics and mathematics in high school and join the International Baccalaureate program. My fascination with the topic leads to me choosing my extended essay on physics and the topic to be the examination of efficiencies of wind turbines with different blade numbers.

Introduction

Wind turbines are renewable energy generators that convert kinetic energy into electrical energy. When designing turbines many factors come into play; structural loads, noise levels, drag of the wind on the blades and the aspect this essay plans on focusing, the number of the blades on the turbine. Most large-scale wind turbines use three blades as that number is considered a fair compromise between unwanted effects like noise and structural load and power output. Lower number of blades lead to lower drag and higher speed, and additional blades lead to an increase in swept area of the turbine and torque, especially at lower wind speeds however at higher speeds the positive returns are diminished due to drag and wake interference. Smaller scaled wind turbines might benefit from a blade count different from three. This extended essay explores the question "How is the energy output of a small wind turbine in constant wind conditions affected by varying numbers of blades?". By isolating the blade count as the variable, the study's goal is to determine whether higher number if blades truly increase the power output of the turbine, and if there is an optimal number of blades for the experimental conditions of the paper. This topic plays a significant role in optimizing small scale wind turbines, which are used in rural areas to provide energy for both quality of life technologies, and technologies that are essential to life like water pumps. If an optimized version of this small scaled turbine can be created, life in such areas can be improved.

Theoretical Side

The power available in the wind is calculated by the formula:

$$P_{wind} = \frac{1}{2}\rho A v^3$$

Where A is the area swept by the rotor and ρ is the air density. However, this is an idealized version where the wind is entirely captured. This is not applicable in the real world or in this experiment, which is why a different equation can be used to calculate power.

$$P_{wind} = \frac{1}{2}\rho A \upsilon^3 \times C_p$$

The difference in this equation is the power coefficient, C_p. This value can simply be called the efficiency of the wind turbine. In the real world the maximum efficiency of a wind turbine is given by Betz's Law, which states that in the most ideal conditions, the maximum efficiency of wind turbines is 59.3%. This paper will use the variance of this value for the effectiveness of the number of blades as it is directly correlated with power and affected by the number of blades. The closer the value of efficiency gets to this number the better the turbine. To get the power coefficient the equation below will be used.

$$C_p = \frac{P_{turbine}}{\frac{1}{2}\rho A \upsilon^3}$$

The power generated by the turbine is calculated by connecting the turbine to a resistor, a voltmeter, and an ammeter. By multiplying the mean of the values found by the multimeter, we can get the value of the power.

$$P_{turbine} = V \times I$$

The symbol "υ" is the average air velocity at the turbine plane. This velocity is calculated by the formula below.

$$\upsilon = \frac{Q}{A}$$

Q is the volume flow rate and A is the cross-sectional area of the tube. Q is measured by tightly attaching an empty bag with a known volume to the air dryer and measuring the time required for the bag to be full. The cross-sectional area of the tube is calculated by the regular formula for the area of a circle which is as below.

$$A = \pi r^2$$

In this equation, r is the radius of the tube, measured by diameter of the tube and dividing it by two, as it is hard to measure from the middle of the tube.

It is also important to mention that power coefficient has a relation to the tip speed ratio. Tip speed ratio is the ratio of the speed of the tip of the turbine to the speed of the wind. For a given turbine set-up C_p reaches a maximum at an optimal tip speed ratio, beyond which efficiency decreases due to many factors. Tip speed in the context of my experiment is already a factor of the efficiency and throughout the experiment it can be soundly claimed that these turbines are not at optimum tip speed ratio necessarily. While it is not measured directly, it is also a important component of the explanation of the variance of efficiencies and should be mentioned.

Materials

- Small scale motor
- Tape measure and ruler
- Hair dryer
- Tube
- Turbines with respectively 1,2,3,4 and 5 blades
- Voltmeter and ammeter and or a multimeter
- Hair dryer stand
- 10 Ohm Resistor

Methodology

The investigation was conducted by using a small horizontal-axis wind turbine with a modular hub that allows different turbines to be attached. All the blades were identical in shape, size and angle so that only blade counts could matter. Configurations of 1,2,3,4 and 5 blades were tested. A hair dryer provided a steady airflow at approximately 5.24m/s in an indoor setting through a tube to ensure constant wind conditions could be created. The wind speed was measured 5 times. The wind speed was also kept the same for each trial. For each blade configuration, the turbines' power output was connected to a resistor which was connected to an ammeter and voltmeter. The turbine was allowed to reach steady rotational speed to get more stable values.

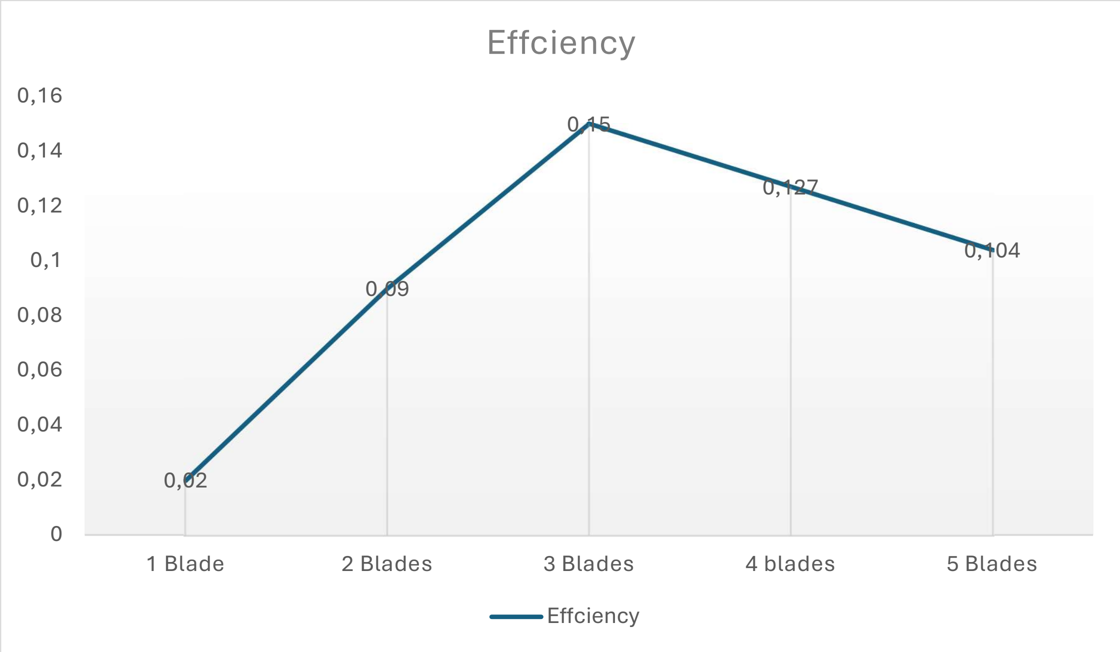
A hair dryer was chosen as the wind source not only because of its general availability allowing the experiment to be repeatable easily, but also due to its ability to produce continuous and repeatable airflow conditions under laboratory conditions. The tube being attached to the end of the hair dryer ensured that the air flow direction and cross-sectional area was the same throughout the trials.

Procedure

- Hair dryer was mounted securely using a stand and was set at constant speed and temperature.
- A long tube was attached to the end of the hair dryer
- A small-scale electric motor was attached at a fixed distance within the tube, mounted with changeable turbines.
- The small-scale motor is connected to a multimeter to measure the power generated
- The measurements are done by measuring the power output of the turbine for 20 seconds and the means of the measurements are taken, and these values are noted down
- These processes are repeated for each turbine.

Data

Number of blades	Voltage(V)	Current(I)	$P_{electric}$=V×I (W)	P_{wind} (W)	C_p (Max. 0.593)
1	0.55±0.023	0.055±0.0036	0.030±0.002	1.33±0.21	0.02±0.004
2	1.10±0.026	0.110±0.0041	0.120±0.005	1.33±0.21	0.09±0.01
3	1.41±0.027	0.141±0.0044	0.200±0.007	1.33±0.21	0.15±0.02
4	1.3±0.027	0.130±0.0043	0.169±0.007	1.33±0.21	0.13±0.02
5	1.18±0.026	0.118±0.042	0.139±0.006	1.33±0.21	0.1±0.02



Calculations

For each configuration, values are calculated by the formulas below.

- $P_{electric} = V \times I$
- $P_{wind} = \frac{1}{2}\rho A v^3$ (1.33 using the measured value)
- $C_p = P_{electric}/P_{wind}$

Using the findings from the three-blade turbine we can calculate.

$$P_{electric} = 1.41 \times 0.141 \cong 0.200$$

$$C_p = \frac{0.200}{1.33} \cong 0.15$$

Uncertainty Example

Uncertainties for each measurement and derived quantities were calculated to present more accurate results. The electrical output was measured by multimeter that measures voltage and current. The power available in the wind was calculated using measured wind speed, calculated area swept by the turbine and assumed air density.

Voltage and current were measured by a multimeter for which the manufacturer had given no specific uncertainty, so a conservative uncertainty was accepted. For the voltage, the assumed uncertainty was "±0.5% of the reading + 2 digits" and for the current an uncertainty of "±1% of reading + 2 digits" was assumed. The uncertainty for power was calculated by adding the respective uncertainties of voltage and current since they are multiplied in the formula.

Wind speed was measured by seeing how fast a bag is filled with air using a chronometer of 0.01 second increments, the radius of the turbines was measured by using a ruler with 1 cm increments and air density was assumed to be 1.20 kg/m^3 at room temperature and standard atmospheric conditions.

The uncertainty of the power available in the wind was calculated by using the relative uncertainties of the wind speed and swept area. Since the wind speed is cubed, the uncertainty of the wind speed is multiplied by 3.

Finally, the uncertainty of efficiency was obtained by combining the uncertainties of electrical power and the power available in the wind.

For example, the uncertainty for the three bladed turbine is calculated below:

$$Uncertainty\ of\ V = (1.41 \times 0.5\%) + 0.02 = 0.02705$$

$$Uncertainty\ of\ I = (0.141 \times 0.5\%) + 0.002 = 0.002705$$

$$Uncertainty\ of\ power = \frac{\Delta P}{P} = \sqrt{\left(\frac{0.02705}{1.41}\right)^2 + \left(\frac{0.002705}{0.141}\right)^2} = \pm 3.8\%$$

$$P_{turbine} = 0.2 \pm 0.0072$$

Uncertainty of the swept area was calculated below:

$$Radius\ of\ the\ turbine = 0.07 \pm 0.005 = R$$

$$\Delta A/A = 2 \times (\Delta R/R\ ) = 2 \times (0.005/0.07) = 0.142$$

Uncertainty of the wind speed was calculated by doing the measurement multiple times and dividing the spread with the mean of the measured times, which was found to be 2.45%.

$$\Delta v/v = 2.45\%$$

The relative uncertainty of the power available in the wind was calculated below:

$$\Delta P_{wind}/P_{wind} = \sqrt{(\Delta A/A)^2 + \left(3 \times (\Delta v/v)\right)^2} = \sqrt{}(0.142)\text{^}2 + (0.0735)\text{^}2 = 0.159$$

$$\Delta P_{wind} = 1.33 \times 0.159 = 0.21$$

$$P_{wind} = 1.33 \pm 0.21$$

The uncertainty of the power coefficient for the three bladed turbine is calculated below:

$$\Delta C_p/C_p = \sqrt{(\Delta P_{wind}/P_{wind})^2 + (\Delta P_{turbine}/P_{turbine})^2} = \sqrt{(0.159)^2 + (0.38)^2} = 0.163$$

$$\Delta C_p = 0.163 \times 0.15 = 0.02445$$

$$C_p = 0.15 \pm 0.02445 \cong 0.15 \pm 0.03$$

Discussion

The experimental data has shown that the efficiency of the turbines vary greatly with the efficiency being at maximum when the turbine has 3 blades. This experiment thus leads us to the conclusion that, at the wind conditions within the tube, a three-blade configuration of the turbine is the most ideal with a four-blade configuration being next, then a five-blade configuration and lastly a one-blade configuration. There may be a list of reasons for this outcome, with one of the reasons for the one and two bladed configurations being less efficient when compared to their more bladed counterparts is the fact that those configurations allow a lot of wind to slip by and go unused while the more bladed counterparts are able to catch more wind. Another reason for the one bladed counterpart being less efficient may be because of the mechanical instability of the one blade requiring a counterweight leading to increased inertia, causing a loss in power. The two bladed configuration causes torque fluctuations, leading to the loss of power. The reason for four and five bladed counterparts being less efficient than the three bladed one might be because of aerodynamic factors like wake interference. Wake interference occurs when the turbines create a “wake” of turbulence with relatively lower air velocity. Because of the magnitude of the angles between blades in the four and five bladed turbines, these turbines interact more with this turbulent airflow, leading to a loss in power production. Another aerodynamic reason could be the fact that each blade creates both drag and lift. While lift contributes to the useful torque because of the geometry and angle of each blade, drag counteracts this, and as blade numbers increase the total drag profile increases, meaning more forces that counteract the rotation leading to power loss.

Comparison With Literature

These results correlate with both the literature and real-world examples. Both textbooks and real-world examples show that at the relatively high wind speeds that are similar to the conditions of the experiment, the three bladed turbines are the most efficient compromise between tip speed and aerodynamic stability.

Ethical Considerations

There were no major ethical considerations for this experiment, other than the electricity used for the hair dryer, the electricity used for printing the wind turbines and the plastic of the wind turbines all having a carbon footprint.

Strengths

This examination asks a relevant, real-life question about efficiency of turbines, making the findings applicable to real life.

The experiment uses cheap, readily available materials, with the only exception being the turbines, making the experiments repeatable and verifiable

The assumptions made were acceptable and relevant, making the examination more relevant and accurate.

The uncertainties were calculated using the RSS method, making it more accurate.

Limitations

The measured C_p values are relevant but due to the material for the experiment being insufficient, the values found by the experiment understate actual pure C_p.

Wind speed uncertainty is extremely dominant when calculating the power available, so using an anemometer can lower uncertainties significantly.

Due to the small scale of the turbines, the findings may change as the scale increases.

Improvements

A handheld anemometer can help lower uncertainty drastically by measuring the wind speed directly.

Measuring the internal resistance of the generator and efficiency of the generator can help lower the uncertainty and get more accurate results

Creating a more airtight connection between the tube and the hair dryer can help get more accurate results by lowering the amount of air slipping from the connection.

Wind turbines could be made from more readily available materials, making the experiment more accessible and repeatable.

Conclusion

The investigation examined how the power coefficient varies across different blade numbers on wind turbines. By keeping the wind conditions, the electrical load and the rotor the same throughout, the experiment isolated the number of blades as the only variable. The results showed that the power coefficient of the turbines is not directly correlated with the number of the blades on the turbine, reaching maximum efficiency at a three-blade configuration. The one and two bladed configurations showed especially lower efficiency as they had generated insufficient torque, had a lot of wind slip and had mechanical imbalances leading to fluctuations in torque. However, four and five bladed configurations also showed lower efficiencies though less than their one and two bladed counterparts. Their inefficiencies were caused by increased drag profiles and higher wake interference which caused the effective airflows' reduction, leading to lower power coefficients. This investigation showed that turbine efficiencies don't simply depend on the increase in interaction with wind, instead depending on the balance of compromises between many aspects like tip speed, torque and drag.