Creation and Analysis of a Hybrid Wind Turbine

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***Abstract* - Horizontal axis wind turbines (HAWTs) are turbines whose rotating axis is parallel to the ground. Vertical axis wind turbines (VAWTs) rotate on an axis perpendicular to the ground. HAWTs and VAWTs each have their advantages and disadvantages, and are utilized in different situations. In this experiment, a hybrid of the two types was built in order to maximize energy gained in environments where both HAWTs and VAWTs can be accommodated. This research consisted of two main tasks: designing a mechanism by which the two systems could be placed on a single turbine in real world applications, and measuring the electrical outputs of that turbine. The proof of concept scale model of the hybrid was built along with a SolidWorks design of what a scaled up turbine would look like.**

NOMENCLATURE

Variables and Operators

A	Blade area (meters squared)
I	Current (amps)
P	Power (watts)
ρ	Air density (kilograms/meters cubed)
R	Blade radius (meters)
V	Voltage (volts)
v	Wind velocity (meters/second)
ω	Rotor rotational speed (radians/second)

I. INTRODUCTION

Human use of fossil fuels as an energy source has had a detrimental effect on the Earth's environment, including rising atmospheric temperatures, melting glaciers, and rising ocean levels. Over the past few decades, there has been an increasing interest in reversing this trend and using more renewable energy. In 2012, the world produced approximately 13.2% of its energy supply from human use of fossil fuels. Over the past few decades, there has been an increasing interest in reversing this trend and using more renewable energy. In 2012, the world produced approximately 13.2% of its energy supply from renewable sources. The next year, this Fig. jumped to 22% [1].

Wind power is a type of variable renewable energy source, which is a type of energy based on sources that fluctuate throughout the day or the season; other types of variable renewable sources include solar and hydroelectric energy. Wind power costs around the same or less than conventional fuels, in the range of 5 to 6 cents per kilowatt-hour. The wind power sector is also growing and -comprises 4% of the world's energy production. It is estimated that this percentage could increase to 20% by the year 2030 [2]. This proportion has already occurred on a national scale; in the year 2015, "wind power accounted for 20.2% of electricity generation" in Spain [3].

The concepts governing wind energy technology are harnessing the kinetic energy of wind, which is the movement of air from high pressure areas to low pressure areas, and the conversion of that to electrical energy using a generator. This required uneven pressure distribution is caused by unbalanced heating of the planet by the Sun. Unlike fossil fuels or petrol, wind energy produces no byproducts harmful to the environment [4]. Once the turbine is built, operational costs are minimal due to the prevalent availability of wind; no air or water pollutants are emitted as well [5].

An important facet of wind energy technology is its scalability. Small wind machine, with blades between 8 and 25 feet wide and a height of up to 30 feet, can be used to power homes and small businesses [5]. Industrial wind turbines can be very large; the common General Electric 1.5-megawatt model consists of 116 foot long blades atop a 212 foot tall tower [6]. These large industrial turbines often sit in wind farms, which can be tens or sometimes hundreds of turbines, and generate bulk electrical power which then enters the grid [5].

The area of land for a wind farm varies considerably, and depends on the desired energy output of the farm, the number of turbines, and the local topography [7]. The spacing of the turbines is usually determined by the blade diameter; estimates state that horizontal axis turbines should be spaced between five and ten diameters apart, depending on the environment. Proper spacing is required because of a phenomenon called *the wake effect*. When a turbine absorbs energy from the wind, there is an area of reduced wind speed behind the blades. Any turbine in the wake effect zone would then have reduced power output. Thus, turbines are spaced on farms in order to minimize each turbine's wake effect on adjacent turbines. This creates large amounts of wasted space which could otherwise be used to benefit industries such as farming [8].

In addition, there are legal limitations placed by local governments on the spacing of turbines. For example, in the state of Massachusetts, a wind turbine must be "one and a half times the overall blade tip height of the wind turbine from the nearest existing residential or commercial structure and 100 feet from the nearest property line and private or public way." Other limitations include regulations on proximity to airplane zones and to nearby electrical substations [9].

If an energy company were attempting to place a maximum number of turbines in a given area, they would be restricted by the horizontal distance needed by the turbines as well as regulations. The objective of this research is to explore the benefits of taking advantage of the remaining space on the tower of the turbine.

II. Overview of Turbine Function and Aerodynamics

A. *Structure and Functionality of Horizontal and Vertical Axis Wind Turbines*

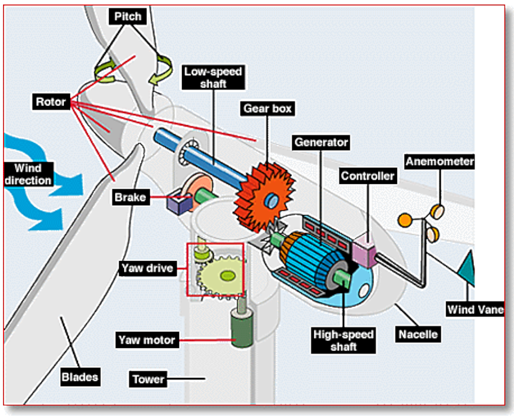

Fig. 1: Diagram of HAWT [10]

In a horizontal axis wind turbine, energy is transferred through a series of gears and shafts. As shown in Fig. 1, wind pushes the rotor blades, which turn a low-speed shaft; the low-speed shaft is connected to a drive train, inside of which is a large, slow-moving gear that turns a small gear quickly, increasing the rotational speed of the high-speed shaft in the generator. The drive train and the generator are housed in back part of the turbine head, the nacelle. On the exterior of the nacelle is a wind vane and an anemometer, which detect wind direction and speed respectively; they provide sensory input into the controller, which uses a yaw motor to turn a series of gears, called the yaw drive, that rotates the blades to face the wind at the ideal perpendicular angle [11].

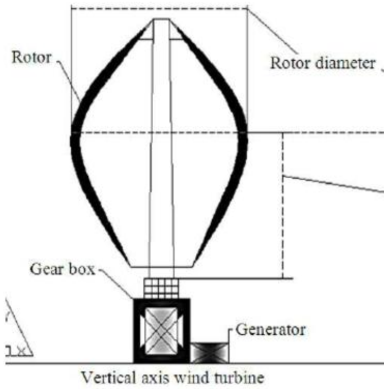

Fig. 2: Diagram of VAWT [12]

The design of the vertical axis turbine has fewer components because there is no particular angle that the wind must make when hitting the blades, eliminating the need for a yaw drive, making the VAWT ideal for turbulent conditions. The drive train and the generator lie at the bottom of the system, turned by the spinning blades.

The primary reason that vertical axis turbines are used less in industry is due to their decreased efficiency; while all three blades of a horizontal turbine are pushed by the wind, only one blade is pushed on a vertical turbine, while the other two simply inhibit the rotation, as they are not pushed by the wind. However, VAWTs are still occasionally used, as their more compact nature make them ideal for fitting in tight places [13].

B. *Wind Turbine Efficiency*

Wind turbines are not capable of converting 100% of the wind's kinetic energy into usable electrical energy. This is because much of available energy is lost through friction, heating, and energy retained by the wind. Wind turbine efficiency (C_P) can be measured through Equation 1:

$$C_P = \frac{P}{\frac{1}{2}\rho A v^3} \qquad (1)$$

(

The value of the power coefficient should theoretically be between 0 and 1.

(1) leads to the Betz criterion, which states that the absolute maximum power that can be converted from a wind turbine is 59.26% of the total available wind energy [14]. Though this may seem too inefficient, the average horizontal axis wind turbine produces about 6 million kWh a year, which can supply around 1,500 homes with constant electricity [2]**.** On average, horizontal axis turbines run at around 45% efficiency, while vertical turbines can only run at around 10% efficiency.

C. *Ideal Blade Number*

Wind turbine efficiency also depends heavily on the tip speed ratio, which is the ratio of velocities of the blade tips and the wind speed. The higher the tip speed ratio, the more energy that can be converted. Tip speed ratio (λ) can be calculated by using the following equation:

$$\lambda = \frac{\omega R}{v} \qquad (2)$$

An optimum tip speed ratio for the typical three-blade wind turbine is between four and five. The more blades a wind turbine has, the greater the tip speed ratio; if the tip speed ratio is too large, however, the wind turbine may not be able to function correctly and the blades could experience rapid damage. For example, a tip speed ratio of 10 on a three blade turbine could mean a dangerous blade tip speed of around 200 mph. Usually, the more blades a turbine has, the greater its tip speed ratio can be [14].

Placing more blades on the turbine increases torque. However, in most cases, producing power from wind energy requires more blade speed than torque. Blade speed is reduced when more blades are added to the turbine because more blades produce more drag. Three blades on a horizontal wind turbine produce optimal power; this number strikes a balance between stability and high rotational speed [14].

D. Effect of HAWT Blade Shape on Aerodynamics

Along with the number of blades on a wind turbine, the shape of the blade will also affect the power output of the turbine. Each blade will experience a number of forces, including lift, drag, and thrust.

The lift force "F_L" is always exerted perpendicular to the direction of the wind. Lift force is a direct result of the Bernoulli Effect, which states that an increase or decrease in speed happens simultaneously with a decrease or increase in pressure. A turbine blade, which is an airfoil, functions due to the curvature on one side; wind moves more quickly across this curved surface, creating an area of low pressure on one side of the blade and an area of relatively high pressure on the other side; this pressure difference pushes the blade. The equation for lift (F_L)is modeled by Equation 3:

$$F_L = \tfrac{1}{2} C_L \rho v^2 A \qquad (3)$$

A higher lift force will allow the wind turbine to produce more power and be more efficient [15].

Blades also experience drag force, exerted at a perpendicular angle to the lift force. Turbine blades are designed as elongated, aerodynamic tear shapes to minimize the drag coefficient. These airfoil shapes have a very low drag coefficient of around 0.04; in context, a common car's drag coefficient is 0.27-0.35 [15]. Similar to lift, drag (C_D) will increase with the square of the wind velocity:

$$F_D = \tfrac{1}{2} C_D \rho v^2 A \qquad (4)$$

This is similar to the equation for lift force, except "C_D" is the drag coefficient [14]. The drag force, along with the lift force, will form the components of the resultant thrust force "F_T", which is the force that turns the blades and powers the wind turbine [1].

E. Stall

Stall is defined as a decrease in lift force, which then causes a reduction in thrust. Stall is created when the angles of the blades are too steep or when the shape of the blade becomes altered. When the angle of attack is too steep, air stops clinging to the top of the blade, resulting in a flow separation, which creates a vacuum-like area at the top of the blade. Stall can also occur if the surface of the blade is not smooth enough, with something as little as a piece of misplaced tape being able to precipitate stall. Despite this, wind turbines can use stall to their advantage. Because stall in turbines causes the rotor and generator to stop, turbine operators will sometimes purposely cause stall by increasing the blade's angle of attack during high wind speeds or high turbulence in order to avoid damaging or destroying the wind turbine [15].

By graphing the coefficient of lift versus the blade's *angle of attack*, which is the angle at which the wind hits the length of the blade, the exact angle of attack to create stall can be calculated. While low to medium angles of attack produce a linear relationship, higher angles of attack generate a large amount of dead air around the blade, a flow separation, reduction in lift and an increase in drag. Therefore higher angles of attack produce a nonlinear curve, and the maximum point on this curve represents the minimum angle of attack to initiate stall [15].

III. PROCEDURE

A. Overview of the Experiment

This work consisted of designing the mechanism by which a real-world hybrid turbine would function, and gathering experimental electrical data, which includes voltage, current, and power, to estimate what the benefits of building this turbine would be. The data was gathered by building two blade systems separately, one horizontal and one vertical, in order to better facilitate data collection. The final proof of concept was built by combining these two blade systems into the final hybrid turbine.

B. Designing 3D Model of Hybrid Turbine

The inherent issue of placing a vertical axis blade system on the shaft of a horizontal turbine is that the vertical blades should be able to spin and turn the generator inside of the shaft, but the parts of the shaft below and above the turbine cannot spin. In a scaled-up model of the turbine, the planetary gear mechanism, a mechanism containing a large moving ring gear and smaller inner gears, would be used to keep these parts static.

SolidWorks, 3D modelling software, was used to design the planetary gear mechanism by which the two blade systems would be integrated into a single turbine in a scaled up version. To make solids, a two-dimensional sketch is first drawn, and then extruded to make a three-dimensional piece. Gears were made using the Toolbox add-in, and interlocked using a function called mechanical mate. To create animations of the blades spinning, Motion Capture was used.

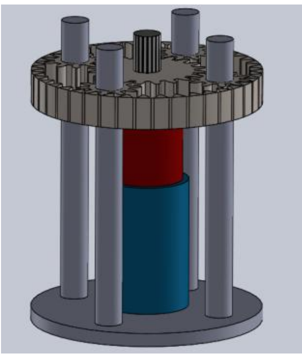

Fig. 3: Planetary Gear Mechanism

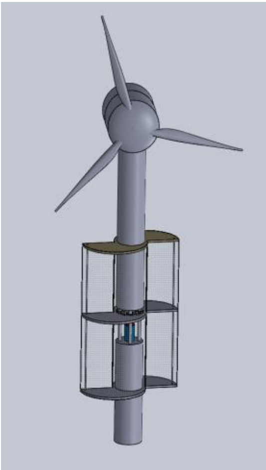

Fig. 4: Final Model of Hybrid Turbine

As the vertical blades are pushed by the wind, they turn the outermost gear of the planetary gear system, shown in Fig. 3. The rotating large gear drives four smaller gears that rotate on four axles rising from the base. The four gears turn the central gear, which spins the axle of the generator, producing electrical power. The generator shaft is shown in stripes, and the generator is the red cylinder. Everything in the planetary gear system is dynamic except for the four axles; it is these axles that support the upper part of the turbine.

In Fig. 4, the vertical axis blades are transparent in order to enable better viewing of the inner mechanism; in the real-world version, the blades would be made of fiber-reinforced epoxy or unsaturated polyester, as these materials have high tensile and flexural strength [16]. Horizontal axis turbines turn to face the wind using the yaw drive mechanism. This mechanism can be emulated in our model using a servomotor, which is a rotary actuator powered by an external source. In the model, the servo was coded to turn the generator and blades toward the wind, as shown in the code in Fig 6; the computing power required to run the code was provided by an Arduino mini-computer. The servo is wired to a stepper motor driver, which is in turn wired to the Arduino; two of wires, the ground and power wires, are connected to a power socket. The Arduino itself is connected to a computer, for power and data exchange.

The Arduino was coded in C++, labelled SAC. AccelStepper was included in order to be able to use viable methods for this servo. The servo is connected to the Arduino, one pin at a time, and is then initialized all together via the code. After that, the servo's parameters are set to run. A safe starting speed, acceleration, and max speed are set for the servo so it doesn't break under stress. Since no viable anemometer could be found with the available budget, it was opted instead that the servo would be manually controlled and steered towards the wind. This manual control is exerted by writing a different value in the move() method depending on how much rotation is desired. A negative value turns the servo clockwise, while a positive value turns the servo counter-clockwise. Then the servo runs until it has moved the set distance stated prior in the code.

Some problems were presented in how the servo responded to the code, such as how the servo executed more rotations when it was moving clockwise than counter-clockwise, written in SAC line 15. Another issue was that the greater the distance that was needed to be travelled, the more inaccurate the end location of the servo became. Thus, movement must be done in more concise, numerous bursts

C. Horizontal Axis Blade Construction

Fig. 7: First Generation HAWT Blades

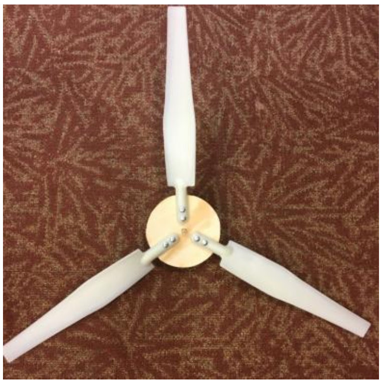

Fig. 8: Second Generation HAWT Blades

Two generations of horizontal axis blades were made. Both generations had three blades, as that is the ideal blade number for maximum power output. The hub of the first generation was eight inches in diameter and cut from sheet metal; sheet metal was chosen as it was lightweight and easily cut. The blades were made of foam board for similar reasons. However, there was a critical flaw in this generation's design. Due to the lack of curvature in the foam board blades, no lift force was generated and the turbine did not spin.

The hub of the second generation blade was cut from plywood, to increase the sturdiness of the final turbine. The polymer blades with proper curvature were purchased and installed onto the hub. The plywood hub and polymer blades made the horizontal turbine too heavy to be pushed by a regular box fan; higher speed winds are necessary to generate power. In the center of the wooden hub is a square hole, through which a square rod is inserted. The circle shape was avoided to prevent the hub from spinning on the axle rather than spinning the axle enough; the square shape prevents slippage on the axle and ensures full rotation.

E. Vertical Axis Blade Construction

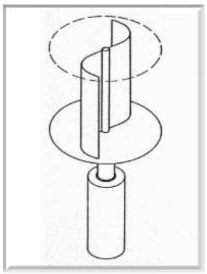

Fig. 9: VAWT with Savonius design [16]

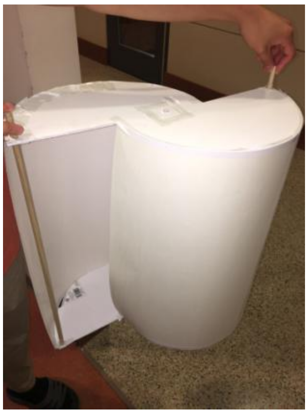

Fig. 10: Model VAWT Blades

The vertical axis turbine, based on a Savonius design (Fig. 9), was made by connecting two symmetrical foam boards with wooden dowels. The Savonius design, a design based on two disconnected semicircle bases, was chosen as it was the most feasible one to build. The vertical section is also draped in paper, which act as the blades of the turbine. In the center of the foam board pieces is a square key, through which a square rod is inserted.

F. Drive Train Construction

As in a real-world turbine, our blades do not spin fast enough to be connected directly to the generator. Real-world turbines use a series of gears to connect low speed shafts, which are rotated by the spinning blades, to high speed shafts, which spin the generator; this system is called the drive train. The gear system in a turbine commonly have a gear ratio of about 90, increasing the rotational speed by 90 [17].

Fig. 11: Gear System for Turbine

The gear system was designed by joining the square rod, which is spun by the blades, with a 120-tooth gear. This is then used to spin a 20-tooth gear connected to the generator, thus increasing the rotational speed of the generator input by a factor of six, which is the tooth ratio between the two gears.

G. Measuring Power Output

The gear mechanism was in place while gathering the data for both the VAWT and HAWT blades, which were built separately to facilitate this data collection. The square dowel connected to the 120-tooth gear was first inserted into the hub of the HAWT blades. These blades were spun by hand, as wind of sufficient speed was not available. A camera was used to measure rotations per minute (RPM), a volt meter was used to measure voltage, and an ammeter was used to measure current. From voltage and current, power was calculated using the Equation 5, where "P" is power, "I" is current, and "V" is voltage.

$$\mathbf{P = IV} \tag{5}$$

A similar system was used for testing the vertical axis blades; instead of placing the square rod attached to the drive train through the hub of the HAWT, the rod was placed through the foam board pieces of the VAWT. Since vertical axis blades require lower wind speeds to turn, data was able to be gathered by spinning them with a room fan, instead of manual rotation.

H. Constructing the Final Proof of Concept

Fig. 12: Final Proof of Concept

The horizontal axis generator system was placed at the top of the PVC tower by inserting the generator into a PVC elbow. The vertical axis blades were integrated by placing bearings on top and below the blades, and inserting the system into the piping, with the bottom and the top sections attached to the static parts of the bearings. Because connecting the vertical axis blades to a generator using the planetary gear mechanism is unfeasible, the VAWT blades will not generate power in the final proof of concept. Finally, a wooden frame was constructed to keep the proof of concept upright, as shown in Fig. 12; the frame would be removed in a more stable real-world version.

IV. Results

A. Power Output

The goal of this project was to create a hybrid turbine that integrated both a horizontal axis and vertical axis turbine in order to produce more voltage while conserving resources, such as space or money. The hybrid turbine produced a power output of 1.56 watts. This was 34.6% more power than the individual horizontal axis turbine and 291% more than the individual vertical axis turbine.

While this hybrid turbine will initially cost more than a mainstream individual horizontal or vertical wind turbine, this extra cost will eventually be offset. However, the hybrid turbine could substantially decrease need to build new wind turbines in order to keep up with energy demand, therefore saving money. Additionally, as the hybrid turbine produces more energy, more income will come as a result of this.

B. Evaluation of Design

The design goals set at the beginning of the project were mostly accomplished. The base and the tower of the turbine are stable. The fitting of the horizontal axis turbine to the generator through a square key could have been tighter, but overall the horizontal turbine spun on a nearly flat plane parallel to the PVC tower. For the vertical axis wind turbine, higher quality materials would have been appreciated in contrast to paper, foam, tape, and wood. An ideal material to use could have been a light aluminium sheet metal paired with plywood bases; although this would increase heaviness of the product thus requiring higher wind speed to push the blades, the improvement in structural rigidity would enable a more sturdy proof of concept.

V. Conclusion

A. Benefits of Hybrid Design

An average 2.5-3 MW turbine produces more than 6 million kilowatt-hours per year [2]; according to our estimates, if our design was integrated into a turbine this production could increase by 34.6%, or around 2 million kilowatt-hours. Though the calculated estimates might be slightly inaccurate, any increase in this ballpark would mean tens of thousands of dollars more in revenue per turbine, as the selling price is around 4-7 cents per kWh [17]. Wind farms, which can have hundreds of turbines, can incur millions of dollars more in revenue year over year.

Though the improvement of current turbines is very profitable, the increase in versatility could allow immense growth in the wind sector. As our hybrid functions better in areas where conditions vary than a regular turbine, having the capability to be more efficient in areas where at times conditions are turbulent and at times unidirectional, wind farms could be placed in new areas.

Additionally, if one of the turbines in the hybrid breaks down, the entire turbine is not shut down, as the other turbine can continue producing electricity. This increases the reliability of wind power.

B. Potential Improvements

If research on the hybrid turbine were to continue, there are many possible steps to improve design. One future test is the use of a wind tunnel to test for cut-out speed, the speed at which the turbine blades are brought to rest to avoid damage from high winds, as well as efficiency, optimal spacing between turbines, and blade aerodynamics. The wind tunnel's ability to simulate multiple wind conditions and high wind speeds will allow for greater understanding of the capabilities of this hybrid turbine.

A proper gearing system could also have been built for the horizontal axis turbine, while overall the turbine could be constructed from higher quality materials, rather than the predominant materials of wood, foam, and plastic. Overall, these would most likely give a better reflection of the design implemented in this project.

Another possible test is constructing differently designed blades for the turbine. This will show which blade design and blade material is most effective for the turbine, whether it be a horizontal or vertical blade design.

In addition, a servomotor and Arduino computer can be programmed to rotate the horizontal turbine to perpendicularly face the wind, emulating a yaw drive; the components would be physically connected by cutting the top of the PVC pipe to house the servo, and 3D printing a casing for the generator that would connect it to the servo. Higher quality materials could also be used to completely rebuild the turbine to make it more stable. Lastly, the addition of the planetary gear system modelled in SolidWorks would allow the connection of a generator to the vertical axis turbine, allowing it to produce electricity when integrated into the overall hybrid turbine.

Despite these potential improvements, however, the overall goals set at the beginning of the project have all been achieved; a hybrid wind turbine was designed, both with modelling software and physically, and the possible benefits of a real world hybrid were estimated.

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