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Research Article
A Novel Wind Turbine Design for Electrical Power Generation

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Abstract
Pakistan's energy infrastructure is not well developed and energy consumption is met by mix of gas, oil, electricity and coal and LPG sources with different level of shares. Though Pakistan has potentials of wind energy ranging from 10000-50000 MW, yet power generation through wind is in initial stages in Pakistan. Wind energy is the possible clean renewable resources available in Pakistan. It provides opportunity to reduce dependence on imported fossil fuel. Pakistan is fortunate to have something many other countries do not, which is high wind speeds near major centers. Wind turbines that are situated in or near water enjoy an uninterrupted flow of wind but the biggest disadvantage of wind energy is that the wind velocity and direction is not fix and it varies from zero to maximum. This means that wind cannot produce constant power throughout and can fluctuate greatly. There will be times when they will produce no electricity at all. One of the biggest purpose of our idea is that the system should be capable of recovering a portion of the power consumption by the cooling tower fan motor. This system can be employed, in general, to any device that releases exhaust air with strong and consistent wind speed and in particular, to cooling towers. Although, the design parameters of turbines for different applications will change but optimum values of the parameters can lead to greater power output which will in turn benefit the organization.

Key words: Wind turbine, cooling tower, waste heat recovery, wind energy, exhaust air

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Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

A cooling tower is a device that extracts the waste heat from water by passing an air stream through it so that the cooled water can be used for various purposes. The type of heat rejection in a cooling tower is termed "Evaporative" in that it allows a small portion of the water being cooled to evaporate into a moving air stream to provide significant cooling to the rest of that water stream. The heat from the water stream transferred to the air stream raises the air's temperature and its relative humidity to 100% and this air is discharged to the atmosphere with an approximate velocity of 6.5-7 m sec^{-1}. Instead of rejecting this waste air into the atmosphere, it is aimed to use this air to drive the wind turbine. A wind turbine is a work producing device that converts the kinetic energy of the wind into electricity.

Proposed idea: The cooling tower exhausts air in vertically upward direction over which a vertical axis wind turbine with the shaft oriented horizontally is placed. Due to financial constraints, full scale experiment couldn't be performed therefore we worked on a prototype using a blower fan as a depiction of cooling tower with the air velocity of blower fan equivalent to that of a conventional cooling tower but with a small box size.

Regeneration: The exhaust air energy recovery wind turbine generator is an on-site clean energy generator that utilizes the advantages of discharged air which is strong, consistent and predictable. This study focuses on using the exhaust air for a cooling tower which is conventionally wasted. Utilizing this wind to produce energy thus can help in overcoming power demands to some extent. This is a renewable and never utilized energy source.

Parameters

Wind turbine: Vertical Axis Wind Turbine (VAWT) is preferred over Horizontal Axis Wind Turbine (HAWT) because the rotational axis is perpendicular to the wind direction or the mounting surface. Also, since the lift to drag ratio of VAWT is higher, therefore it is preferable to use Darrieus type VAWT over Savonius. Furthermore, VAWTs does not require a yaw mechanism due to its inherent omni-directional properties which further reduces the power lost required to run the yaw mechanism[1].

The blades of an H-rotor have the same shape along the length of the blade and are not twisted. The blade area is often larger for a darrieus type H-rotor than for a HAWT with the same rated power. In the H-rotor, the blades are mounted so they can rotate around their vertical axis. This allows the blades to be pitched so that they always have some angle of attack relative to the wind.

The absolute lift coefficient to drag coefficient ratio is higher for straight blade than the curved blade at lower range of wind velocity. For a small scale wind power generation, Straight Bladed-Vertical Axis Wind Turbine (SB-VAWT) is more popular because of its simple in design, low cost and also good maintenance. Also, at low to medium wind speeds, the lift to drag (Cl/Cd) ratio is higher for straight bladed then curved bladed and since the wind turbine in this proposed idea works on the principle of generating maximum lift, hence straight bladed H-rotor is preferred over curved bladed[2].

Finally, the wind turbine is designed to be velocity controlled rather than power controlled because in this type of controlling, the design considerations are limited by the velocity of the wind acting on the turbine blades. The power produced is hence dependent on the designed structure of the wind turbine.

Airfoil: An airfoil is the shape of a wing or blade. The lift on an airfoil is primarily the result of its angle of attack and shape. When oriented at a suitable angle, the airfoil deflects the oncoming air, resulting in a force on the airfoil in the direction opposite to the deflection. This force is known as aerodynamic force and can be resolved into two components: Lift and drag. Most foil shapes require a positive angle of attack to generate lift, but cambered airfoils can generate lift at zero angle of attack. Another division of airfoils is on the basis of straight blades or curved blades. The airfoil selection is based on the factors of supportability to generate lift as per requirement and highest availability. The options readily available are NACA 4-6 digits series.

The calculation criteria for the selection is the available wind velocity (free stream velocity), kinematic viscosity of the air, chord width, reynold's number and N-critical value. The reynold's number, on the basis of wind velocity, is approximated to be in the range of 50,000-100,000. And with a wind speed of 6.5 m sec^{-1}, kinematic viscosity of 1.4e-5 m^2 sec^{-1}, a chord of 5' (based on approximate diameter of a cooling tower fan), the best airfoil suited for this scenario is found to be NACA 4412. Furthermore, cambered airfoil should be chosen on the basis of better lift to drag ratio. The reason for selecting straight blades over curved blades is that for normal wind speed applications, straight blades provide better lift as compared to curved blade[3,4].

The number of blades has a direct impact to the amount of torque being generated on the shaft. Furthermore, increasing the number of blades depends on the size of the turbine. For small scale applications, the number of blades that ensure reduced torque ripples for darrieus turbines is three:

$$N = 3 \text{ blades}$$

The parameters that will be calculated based on the above set conditions are; chord of the blade is calculated with the help of AR and span as follows:

$$AR = \frac{L}{C} \quad (1)$$

$$c = 3.4 \text{ inches}$$

where, rotor Aspect Ratio (AR), ratio between the length of the turbine to the diameter of the turbine is normally taken as unity.

The rotor diameter, or the diameter of the turbine is calculated with the help of rotor aspect ratio and the span of the turbine:

$$D = 34 \text{ inches}$$

Solidity is defined as the ratio of blade area with rotor area. It is represented and calculated as:

$$\sigma = \frac{\text{Blade area}}{\text{Rotor area}} = \frac{NcD}{D^2} = \frac{Nc}{D} \quad (2)$$

$$\sigma = 0.32$$

Betz's law calculates the maximum expected power that can be extracted from the wind, independent of the design of a wind turbine in open flow.

$$P = ½ \, Cp \, \rho \, AU\infty^3 \quad (3)$$

$$P = 45.68 \text{ W}$$

The tip-speed ratio (λ) for wind turbines is the ratio between the tangential speed of the tip of a blade and the actual velocity of the wind:

$$TSR = \frac{4\pi}{N} = \frac{4\pi}{3} = 4.1 \quad (4)$$

After the study of different materials for the manufacturing of wind turbine blades, it was concluded that fiber glass reinforced with resin should be used because of its lower cost ease of availability, high strength and corrosion resistance. Since, this project is based upon the exhaust air from cooling tower, hence moisture is our primary concern. For these reasons, fiber glass was deemed the best material for the fabrication of wind turbine blades.

Also, after the study of different types of binders for glass fiber, epoxy was selected as the binder for the glass fiber blades due to its high water resistance and high mechanical and thermal properties.

Shaft and hub designing: Shaft is a rotating machine element used to transfer power from one point to the other. The resultant torque, as a result of supply of power to the shaft, helps in transmitting power.

The shaft that has been used in the prototype is based on the maximum stress theory. The reason for using this theory is that the material used for making the shaft is mild steel. As mild steel is a ductile material, hence this theory is best opted to fulfill the demands.

For a solid shaft the maximum bending stress is given by:

$$\sigma_{b,max} = \frac{1}{2}\sigma_b + \frac{1}{2}\sqrt{\sigma_b^2 + 4T^2} \quad (5)$$

Substituting:

$$\sigma_b = \frac{32}{\pi d^3} \text{ and } T = \frac{16T}{\pi d^3}$$

On solving:

$$\frac{16}{\pi d^3}\left[M + \sqrt{M^2 + T^2}\right] = \sigma_{b,max}$$

where, $M + \sqrt{M^2 + T^2}$ is referred to as the equivalent bending moment ME.

The ME is defined as the bending moment, which when acts alone, will produce the same bending stress as the normal bending moment.

Therefore, this formula may be used to find the diameter of the shaft where. Therefore, this formula may be used to find the diameter of the shaft where, σ_b: Bending stress, M: Bending moment, T: Torsion and d: Diameter of shaft.

In order to allow for safe operation, a factor of safety (FOS) has also been incorporated. Usually for small to medium scale wind turbine applications, the FOS is taken in between 2-3.5. Hence, It have adapted the value:

$$FOS = 3.5$$

The maximum allowable stress for mild steel is 250 MPa. The Torsion may be calculated as follows:

$$P = T\times w$$

$$T = \frac{P}{w} = \frac{45.68}{16} = 2.855 \text{ Nm}$$

The bending moment may be calculated which accounts for all the weight of the components. The bending moment has been calculated as:

$$M = \frac{\text{Total weight}}{\text{Total shaft length}/2} = \frac{5}{21\times 0.0254} = 9.37 \text{ N m}$$

Substituting these values and solving for the diameter we get:

$$d = 10 \text{ mm}$$

But according to the standards of shaft diameters used throughout the world we had to take the next available diameter. Hence the diameter was selected as:

$$d = 19 \text{ mm}$$

Selection of suitable material for shaft designing depends upon more than one factor and the most important one is the application. Therefore, factor rating method, as shown in Table 1, is applied to decide the best material of shaft for our project.

The component on which the shaft is mounted and the weight of the entire assembly rests on is known as the Hub. The diameter of the hub was selected on a trial basis, where the least possible diameter which was assumed to withstand the entire assembly load was selected. The specifications are enlisted:

Diameter = 8 inches

Supporting structure: The major problem faced in the construction of a structure was that the structure was to be

Thickness = 0.25 inches

Weight = 2 kg

Rotor arms design: The rotor arms were calculated on the basis of the available data. The diagram to justify the dimensions of the arms is given in Fig. 1. The dimensions of the arms are as follows:

Rotor arm length	= 17.2 inches (via pythagoras theorem)
Volume of arm	= $17.2\times 2.54\times 100\times 2\times 4 = 3495$ mm^3
	= 3.49×10^{-6}
Density of mild steel	= 7850 kg m^{-3}
Mass of one arm	= $7850\times 3.49\times 10^{-6} = 0.027$ kg

The selection of bearing was in between ball bearing and thrust bearing and ball bearing was chosen. The reason for not using thrust bearing is that there was no axial movement in the shaft hence, we were free to use the bearing that met our requirement. The size of the bearings used is in collaboration with the size of the shaft i.e., 19 mm.

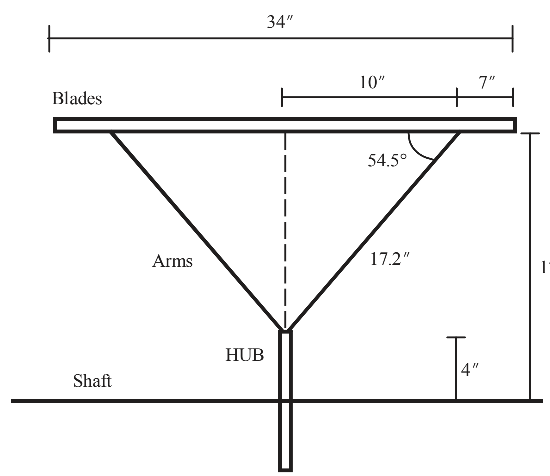

Fig. 1: Rotor structure geometry

Table 1: Factor rating method for material selection

	Materials											
	Mild steel			Cast iron			Stainless steel			Aluminum		
Factors	Rating (R)	Weight (W)	Factor rating (R×W)	Rating (R)	Weight (W)	Factor rating (R×W)	Rating (R)	Weight (W)	Factor rating (R×W)	Rating (R)	Weight (W)	Factor rating (R×W)
Ease of operation	10	0.3	3.0	8	0.3	2.4	8	0.3	2.4	7	0.3	2.1
Strength to weight ratio	7	0.2	1.4	5	0.2	1.0	10	0.2	2.0	9	0.2	1.8
Corrosion resistance	4	0.2	0.8	4	0.2	0.8	10	0.2	2.0	10	0.2	2.0
Availability	10	0.3	3.0	10	0.3	3.0	2	0.3	0.6	3	0.3	0.9
Total weight score			8.2			7.2			7.0			6.8

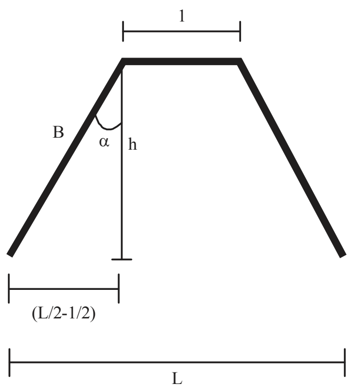

Fig. 2: Shaft support nomenclature, l: Length of base plate over which the bearing is mounted, L: Distance between the two legs, h: Height of the support and B: Length of the legs

made in such a manner that it does not interfere with the blades and is capable enough of supporting the entire load in a static position.

The supporting structure chosen for the turbine was a triangular shaped. The U-section beams were joined together to form the structure. The dimensions of one support were to be determined which could be used on both the supports that are placed on opposite ends. The nomenclature used is shown in Fig. 2.

The dimensions of the base plate was determined on basis of the dimensions of bearing pedestal. The length of the base plate was set as 1′ whereas the width was 2″.

For the length of the support's leg, consideration had to be placed on the fan below the turbine that was also in between the legs. The blower fan used was a square 3.5′×3.5′×1.5′ box. The minimum vertical clearance between the fan and the legs was set, randomly, as 6″. The total distance between the two legs was then measured to be 7.5′.

The height of the support structure was set as 3.5′ taking into account the total height of the blower fan and the rotor radius. Therefore:

$$l = 1'$$

$$L = 7.5'$$

$$h = 3.5'$$

$$\frac{L}{2} - \frac{L}{2} = \frac{7.5}{2} - \frac{1}{2} = 3.25'$$

By using pythagoras theorem, the length of the legs was calculated as:

Fig. 3: Final assembly

$$B = \sqrt{\left(\frac{L}{2} - \frac{L}{2}\right)^2 + h^2}$$

$$B = \sqrt{(3.25)^2 + (3.5)^2}$$

$$B = 4.94'$$

The supporting structure which comprises of channel beams was entirely made up of mildsteel because of its availability and ease of fabrication process.

Fabrication: Blades are one of the main components of the wind turbine and extreme care was taken to choose the materials and core wisely for the intended application. The blades were fabricated by first shaping them into the desired airfoil shape by mapping the exact shape of airfoil on to the thermocol sheets. They were then subsequently cut by hot wire foam cutter and were then piled for close tolerances. The fiber cloth was then bonded using epoxy resins and were left to dry for three days in open air. Finally they were coated with vinyl polyester for good finish, strong chemical bonding between fibers and thermocol and to prevent the fibers from wicking.

Supporting structure for our prototype wind turbine was fabricated by first grinding the U channel beam for the removal of rust and other impurities that would otherwise affect the strength of the supporting structure and they were then sheared into various lengths. For the joining of beams to fabricate our design, they were electrically arc welded and then subsequently cooled for solidification. After the beams were grinded, sheared and welded, they were finally bent into the desired shape of our supporting structure at an angle of 44.80 as denoted by α in Fig. 3.

RESULTS AND DISCUSSION

The power extracted from the prototype was approximately 40 watts which is significant considering the size of the prototype and an overall cost, including transportation, of only 13000/= PKR. In addition, since there are a number of cooling towers of different sizes and capacity installed in industries, therefore, the power output by the turbine for each cooling tower will be different so that it can sum up to give a large amount of output that can be used to feed into the electricity grid.

CONCLUSION

Since the basic aim of our project was to evaluate and study the design and operating conditions of a vertical axis wind turbine powered by cooling tower exhaust, we therefore modeled a prototype of our project. As the power produced by our wind turbine is less, hence, a generator installation was not feasible. However, our vertical axis wind turbine is modeled to be operable in industrial cooling towers. Since, the industrial cooling towers are larger and have greater flow rates of air, hence the power production will be large enough for the installation of generator and extraction of useful power which would have been wasted otherwise.

Considering the current electricity crisis in our country and the rise in unit price of electricity, this idea would help in solving the problem as it does not require any fuel for generation of electricity thereby eliminating the fuel cost. As this system does not depend upon natural wind, this system can also be utilized in areas where natural wind speed is not a limiting factor.

Another contributing factor is that as this is a clean energy based system, hence it can also help by not producing greenhouse emissions and other pollutants resulting in a cleaner source of energy and higher certification in green building index evaluation.

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