Performance of an Omnidirectional Wind Energy Harvesting System for Low Wind-Speeds

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Abstract

Modern in-field wind turbines are large structures designed with advanced features of long towers with heights of up to 100 m, large blades of about 54 m long, flexible rotors with control systems for blade pitch, generator torque, and machine yaw. These towers are tall enough so that the large blades can capture more wind speeds at a higher elevation for improved electrical power generation. However, the operation and maintenance of wind turbine systems are challenging and more expensive due to frequent structural damages to their towers and blades by powerful storms activity such as hurricanes. In addition, wind turbines do not operate at low wind speeds. This paper discusses a wind energy harvesting system with a low elevation height and short tower. This system overcomes the problem of low wind speeds by applying the continuity equation, which significantly amplifies natural wind normally at low speeds. It is shown in this paper that 91 percent area improvement can be achieved by selecting a rectangular inlet and a circular exit. The future work includes the implementation of the preliminary results in designing and fabricating a wind energy harvesting system with a low elevation height and shorter tower.

Introduction

Wind energy harvesting systems have gained significant attention in exploiting wind energy in recent times. According to WoodMac [1], the world-installed wind power capacity is projected to be over 1,756 GW by 2030, with an increasing cumulative annualized growth rate (CAGR) of 9% between 2021 and 2030 [1]. Because wind energy is sustainable, clean, and does produce greenhouse emissions and U. S is planning to generate 20% of its electric power from wind energy by 2030 [2]. According to the Global Wind Energy Council (GWEC) 2021 report [3], the installed wind power capacity was 743 GW in 2021, which prevented over 1.1 billion tonnes of carbon dioxide emissions annually. The research report by the Irish national grid says that "producing electricity from wind energy reduces fossil fuels consumption and therefore leads to emission savings" [3]. The wind's kinetic energy exploited by wind harvesting systems that transform mechanical power into electrical power can serve many purposes [3]. The electrical power can be stored (battery) or connected directly to various loads. Wind turbines are generally huge and tall, with tower height close to 100 m, having long blades up to 54 m [4].
The operation and maintenance of wind turbines are very costly. Developers' reports have shown that approximately half of the turbines in U.S farms are more likely to be damaged by storms activity in the next 20 years [5]. The effects of storms activity pose a significant challenge for wind turbines’ in generating improved electric power output. The growing demand for wind power has brought about major technological innovations in wind energy systems. The current wind power generators are not effective at low wind speeds [6]. The main motivation of this work is to develop a system that will capture and amplify the naturally low wind speeds for improved electrical power generation. This paper will discuss monthly average wind speed in the U.S and in Prairie View, Texas. The wind speeds estimation at low elevation will be calculated and graphically compared to wind speeds at high elevation. The improvement in the area of the square and triangular input sections will be discussed. In addition, the continuity equation will be used to show how low wind speed is transformed into high wind speed for areas with low wind speeds.

**Literature Review**

Many studies on structural damages caused to wind turbines blades and towers by storms activity have been reported. The reported research studies [7-12] overcame these problems by designing wind energy harvesting systems with low elevation height change and increasing low wind speeds for improved power generation. A novel wind tunnel was designed and fabricated with a conical and elevation shape for power generation by A. Atieh et al. [7]. The elevation height change was 1.5 m, and their simulation flow results showed that modifying an open conical tunnel shape with slight modifications in altitude between the entrance and exit areas resulted in optimum power generation. Numerical simulations were performed to investigate the wind speeds at different sections in a novel wind tunnel by A. Shariff et al. [8]. The wind tunnel was designed with an elevated height of 1.5 m. S. Taecharoenwiriyakun et al. [9] designed a model wind tunnel that simulates the naturally low wind speeds for improved power generation. Their results showed that the prototype wind tunnel model successfully improved low wind speeds within the wind tunnel but could not operate omnidirectionally. N. M. Kumar et al. [10] designed and fabricated a funnel-based wind energy harvesting system for low wind speeds. The results from the experimental setup indicated that the system improved inlet low wind speeds from 0.5 m/s to 7.89 m/s at the turbine section and generated power in the range of 0.0001 W to 9.93 W using the venturi effect. Design and flow simulation of a wind tunnel was reported by Serhat et. [11]. The flow results of their simulation showed that the output power generated was improved due to increased wind velocity in the wind tunnel but their system was unable to exploit wind speed from all directions. Catherine et al. [12] designed and fabricated a wind tunnel with a flange (wind enhancement device) at the inlet and exit sections to enhance the flow of low wind speed for generating electrical power for sensor node battery charging. Their results showed that the generated voltage output of the wind turbine model with wind enhancement device improved considerably.
Fig. 1 shows the monthly average wind speed in the United State of America (USA) and Prairie View, Texas. In 2021, the monthly average wind speeds in the USA range between 9 mph and 10.4 mph, whereas those of the Prairie View were between 5.5 mph and 8.1 mph [13]. The wind speeds in Fig. 1 were obtained at the height of 15 ft. at Prairie View, Texas, is one of the low wind regime areas in the USA with a monthly average wind speed that is insufficient for the wind turbines to generate electrical power that will meet the electricity demand of the residences when compared to that of the USA.

**Fig. 1 Monthly Average Wind Speed in U.S. and Prairie View Texas 2021 [13]**

**Improving Area of Short Tower Wind Turbine at Constant Height**

The inlet area of the wind turbine may be circular, square, or rectangular, as shown in Fig. 2. The wind power generator systems described in Section 2.0 [7-12] have a circular input.

**Fig. 2 Area Relationship in Wind Tunnel Intake**

The area of the proposed wind energy harvesting system with low elevation height and a short tower is improved by designing it to have a rectangular inlet and a circular outlet. In Fig. 2, the percent improvement in the area of the system is calculated as follows.
Table 1 Percent Improvement in Area

<table>
<thead>
<tr>
<th></th>
<th>Circle</th>
<th>Square</th>
<th>Rectangle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet cross-sectional area</td>
<td>$\pi r^2$</td>
<td>$4r^2$</td>
<td>$6r^2$</td>
</tr>
<tr>
<td>Calculated area improvement</td>
<td>Circle and Square</td>
<td>Circle and Rectangle</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\frac{4r^2}{\pi r^2} = \frac{4}{\pi}$</td>
<td>$\frac{6r^2}{\pi r^2} = \frac{6}{\pi}$</td>
<td></td>
</tr>
<tr>
<td>Percent improvement in area</td>
<td>27.3%</td>
<td>91%</td>
<td></td>
</tr>
</tbody>
</table>

Table 1 shows that the input area of the wind energy harvesting system increases considerably using a rectangular input section compared to a circular input section respectively.

**Continuity Equation**

The wind velocity at the turbine section of the harvesting system is appreciably higher due to the tunneling effect governed by the continuity equation [14] as in Eq. 1.

$$A_1 V_1 = A_2 V_2$$  \hspace{1cm} (1)

In the above equation, $A_1$ and $A_2$ are the cross-sectional areas of the inlet and turbine section of the wind energy harvesting system and $V_1$ and $V_2$, are the wind velocities at the inlet and turbine section.

**Flow Simulation Results**

In Fig. 4, the design and flow simulation was performed using the SolidWorks tool, the thermodynamic parameters used in this flow simulation were Pressure (101325 Pa) and Temperature (293.2 k).
The wind energy harvesting system was designed to amplify low wind speed for improved electrical power generation. The wind energy system had a rectangular inlet cross-sectional area of 10 inches x 8 inches, a circular exit diameter of 3.8 inches, and a length of 40 inches long. The simulated wind speed of 20 m/s was amplified to 138 m/s at the system exit using the continuity equation. The simulation results showed that wind speeds at the wind energy harvesting system exit increased by approximately 7 times compared to the simulated wind speed at the input.

Table 2 Calculated change in wind speed using Eq.1 and wind energy harvesting system specifications

<table>
<thead>
<tr>
<th>Rectangular inlet area</th>
<th>Circular outlet</th>
<th>Simulated wind speed</th>
<th>Calculated output wind speed</th>
<th>SolidWorks Simulation wind speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_1 = 1^{st}w$ 10 inch x 8 inch = 80 inch$^2$</td>
<td>$A_2 = \pi r^2$ $\pi(1.9)^2 = 11.34$ inch$^2$</td>
<td>$V_1 = 20$ m/s</td>
<td>( \frac{A_1}{A_2} \cdot \frac{V_1}{20} = 141.09$ m/s</td>
<td>138.207 m/s</td>
</tr>
</tbody>
</table>

The generated electrical energy is enough to meet the electricity demand of low wind speed regime areas in the USA, such as Prairie View, Texas. From Table 2, it can be seen that the SolidWorks simulation result is similar to the calculated wind speed at the output. The dimensions of the inlet and those of the turbine sections were selected to conform to the prototype system to be built.

![SolidWorks Simulation of Wind Energy Harvesting System](image)

**Fig. 4** SolidWorks Simulation of Wind Energy Harvesting System
Wind Speed Computations at Different Elevations

Wind speed change with elevation is based on Hellmann's power law [18-19] which is shown in Eq. 1.

\[
\frac{V_2}{V_1} = \left(\frac{H_2}{H_1}\right)^\alpha
\]

(2)

where \(V_1\) and \(V_2\) is the wind velocities at the turbine heights \(H_1\), and \(H_2\) respectively. Experiments performed on the campus of the Prairie View A&M University (PVAMU) showed that \(\alpha = 1.3\), the wind speed gradient [18]. Modern wind turbines towers are designed based on this principle, and their towers are very tall and up to 100 m above the ground with large blades of about 54 m long. These design features come with challenges. Powerful storms frequently damage the towers and blades; this makes the operation and maintenance of modern wind turbine systems more expensive, and this calls for the assessment of a cost-effective omnidirectional wind energy harvesting system with low elevation height change. The fence height (reference intake) requirement is between 6 feet to 8 feet. 7 feet was selected based on fencing height regulations [21].

Table 1 shows the calculated wind speeds at 7 feet low elevation height. The calculated low wind speeds from Prairie View, Texas, are insufficient to generate electrical power because wind turbines do not operate a low wind speed. A smart approach to overcoming this problem is to design a wind energy harvesting system that amplifies the low wind speeds using the continuity equation, as shown in Fig. 5. Table 3 shows the result from the continuity equation, where the calculated low wind speeds are multiplied by a factor of 7 whereas Fig. 5 shows the plot of the wind speeds at 15 feet, 7 feet, and from the those calculated continuity equation.

Table 3 Wind Speed Calculations Based on Elevation

<table>
<thead>
<tr>
<th>Months</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monthly average speed (V_1) (mph) at 15 ft</td>
<td>7.5</td>
<td>8</td>
<td>8</td>
<td>8.1</td>
<td>7.5</td>
<td>6.3</td>
<td>5.9</td>
<td>5.9</td>
<td>5.5</td>
<td>6.6</td>
<td>7.1</td>
<td>7.5</td>
</tr>
<tr>
<td>Wind turbine speed (V_2) (mph) at 7 ft</td>
<td>2.79</td>
<td>2.97</td>
<td>2.97</td>
<td>3.01</td>
<td>2.79</td>
<td>2.3</td>
<td>2.19</td>
<td>2.19</td>
<td>2.04</td>
<td>2.45</td>
<td>2.64</td>
<td>2.79</td>
</tr>
<tr>
<td>Flow simulation (Continuity Equation) system exit to inlet wind speed increased by a factor of approximately 7</td>
<td>19.53</td>
<td>20.79</td>
<td>20.79</td>
<td>21.07</td>
<td>19.53</td>
<td>16.1</td>
<td>15.33</td>
<td>15.33</td>
<td>14.28</td>
<td>17.15</td>
<td>18.48</td>
<td>19.53</td>
</tr>
</tbody>
</table>
Conclusions

Electrical power generated is relative to wind speeds, and at low elevation height, the wind speed reduces. The wind energy harvesting system designed with a low elevation height can capture and significantly amplify low wind speeds by the continuity equation. In addition, 91% improvement in system design in terms of the area can be achieved by selecting a rectangular inlet and circular exit. The result of this work shows that a wind energy harvesting system with low elevation height can be used in areas with low wind speeds. This paper's study does not address the effects of shorter blades length. However, future work will discuss the economic impact of shortening the length of the blades.

References

15. Continuity for Fluids (aplusphysics.com), (Assessed: February 2022)