Design and Simulation of Vertical-Axis Wind Turbine for Urban Environment

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Abstract. This work presents the modelling of a small-scale vertical-axis wind turbine (VAWT), designed to integrate wind-based power generation into an urban environment and reduce grid reliance. The turbulent and low-wind speeds characteristic of the built environment were taken into consideration. The selection of rotor type and airfoil was done taking cost into consideration; the Darrieus, straight-bladed H-rotor, being a lift-type device, was selected for its conversion efficiency, and the symmetrical, non-cambered NACA0021 airfoil to aid in the starting torque of the turbine.

1 Introduction

The increasing significance of wind energy in global energy production annually means that the share of fossil fuels and coal in conventional energy production is declining [1]. This elimination of the carbon footprint that would have been present in fossil fuel-run steam turbines is instrumental in realizing carbon emission goals set to mitigate climate change [2]. Wind turbines can be predominantly grouped into two categories, based on the axis of rotation [3]. The kind employed in large-scale wind farms is the one most are familiar with, i.e., the horizontal axis wind turbine (HAWT), as they have a higher conversion efficiency of wind energy to electricity, in comparison to a vertical axis wind turbine (VAWT) [4]. This trait is attributed to its ability to intercept winds of higher speeds and more laminar flow, allowing for the turbine to operate at much higher rotational speeds.

HAWTs, however, cannot be integrated into the built environment without objection, even if the sheer size, land requirement, and hence visual landscape obstruction are neglected [5]. The infrastructure of urban areas breeds low velocity, turbulent winds, thus reducing the potential output of an HAWT, had it been installed in a more ideal location [6]. The noise and resulting frequencies that arise from high-speed turbine rotations further prevent HAWT installation near industries and urban areas alike [7]. The VAWT is particularly advantageous for wind-based electricity generation in an urban environment; it outperforms HAWTs under its characteristic turbulent and low wind speed conditions, lending VAWTs an increasing potential in small-scale, residential applications [8]. The placement of electrical equipment in

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conjunction with the turbine results in reduced transmission losses and hence costs, allowing for seamless building integration [9].

The law governing the peak theoretical extractable power from the wind, i.e., converting the wind kinetic energy to rotational or mechanical energy through a wind turbine, is Betz's law, which comes out to be 59.3% [10]. This is reflected in the power coefficient (C_p) of a turbine; $C_{p\,max}$ is 0.593 for a wind turbine.

Tip speed ratio (TSR or λ) can be defined as the ratio of the tangential speed at the turbine blade tip to 'actual' wind speed, also known as free stream velocity [11]. Turbine Cp is related to this parameter; Cp max can be found at an optimum TSR specific to a turbine and the ambient wind speed. It is given by:

$$TSR = \frac{R\omega}{U} \qquad (1)$$

Where TSR or λ denotes tip speed ratio, ω represents the angular speed with units of rad/s, R is the rotor radius in units of m, and U denotes the free stream velocity in units of m/s [12].

The objective of the proposed VAWT design in this paper is a relatively simple, cost-effective solution to electricity generation by accessing the previously untapped wind resource and promoting a gateway building integration of wind-based renewable energy for urban residents in low wind speed environments.

2 Design and Simulation

The assessment of the wind resource was done for Dubai, United Arab Emirates (Latitude: 25.11° N, 55.41° E), and the mean wind speed was recorded to be 3.5 m/s, which served to be the basis for design and simulation. Secondly, to narrow down the type of vertical-axis wind turbine to be selected, the following were kept in mind:

- Mean wind speed – the basis for selection of the type of VAWT
- Cost – the basis for selection of the type of VAWT and airfoil

The resulting turbine selected was the straight-bladed H-rotor Darrieus VAWT and airfoil NACA0021. The Darrieus turbine, being a lift-type device, allows for faster rotational speeds, the geometry of a straight allows for simpler manufacture and hence reduced costs, in comparison to a helical Darrieus turbine. The downside of Darrieus turbines is their low starting torque; NACA0021 was the airfoil selected for its thickness to complement this. Symmetrical airfoils also contribute to a reduction in cost, which was an added reason for their selection.

A preliminary model of the H-rotor Darrieus turbine with specifications listed in Table 1, based upon which the calculated parameters as listed in Table 2 were found.

Table 1. Rotor design parameters.

Design Parameter	Value
Rotor height	0.66 m
Rotor radius	0.14 m
Rotor diameter	0.27 m
Number of blades	3

Chord length	0.125 m
Airfoil	NACA0021

Table 2. Calculated rotor parameters.

Calculated Parameter	**Value**
Swept area (S)	0.356 m
Solidity (σ)	0.694
Diameter-height (DH) or projected area	0.54 m – 0.66 m

An analysis of the NACA0021 airfoil was performed using Qblade to find the angle of attack (α) that refers to the highest lift-to-drag ratio. This angle can then be incorporated into the preliminary design, following which, rotor and turbine simulations can be conducted to find useful parameters relating to turbine output, as well as parameters such as pitch angle (β), rotational speed in rpm, and λ corresponding to the turbine's maximum output. The resulting design is presented in Fig.1.

Fig. 1. Vertical-Axis Wind Turbine design in Isometric View

Due to the turbulent nature of winds in the space of urban built environment, a Reynolds number value of 10^5 was selected. Design parameters employed for conducting the simulation are presented in Table 3.

Table 3. Parameters used in the simulation.

Simulation parameter	**Value**
Sea level air density	1.225 kg/m^3
Mean wind speed	3.5 m/s

Reynolds number	10^5

3 Results and discussion

An angle of attack (α) of approximately 7° was found to obtain the highest C_L/C_D ratio of 36.41, as shown in Fig. 2. Analysis conducted on the blades having an angle of attack of 7° showed an optimum C_P of 0.5, for which TSR was 2.5, shown in Fig. 3.

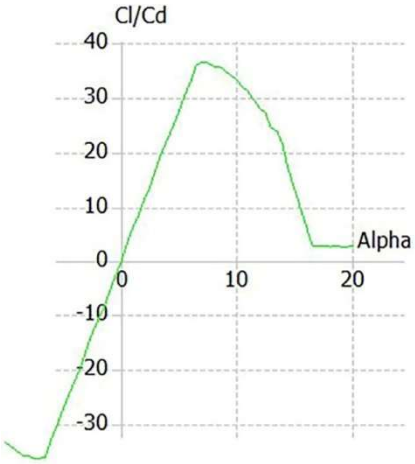

Fig. 2. C_L/C_D versus Angle of attack (α)

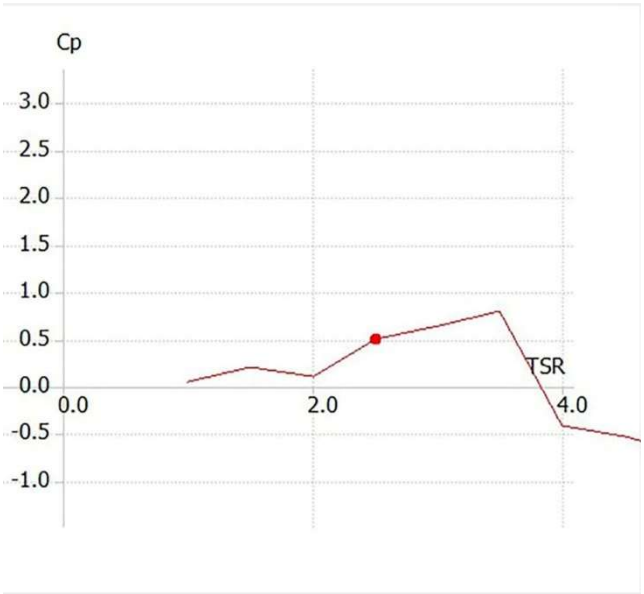

Fig. 3. C_p versus TSR

As the wind speed was the primary constraint, optimum rpm was the first parameter to be found – 400 rpm for 7.5 W of power – as in Fig. 4. Next, the power output incorporating 400 rpm for a TSR or 2.5 was found to be was approximately 7.5 W, as in Fig. 5. Lastly, pitch of 1 degree was found to be optimum for the aforementioned parameters, as in Fig. 6. Results of a turbine simulation are illustrated in Fig. 7, it was found that 6.5 W of power can be obtained from a wind velocity of 3.5 m/s. The values obtained in this simulation are comparable to recent works [13, 14].

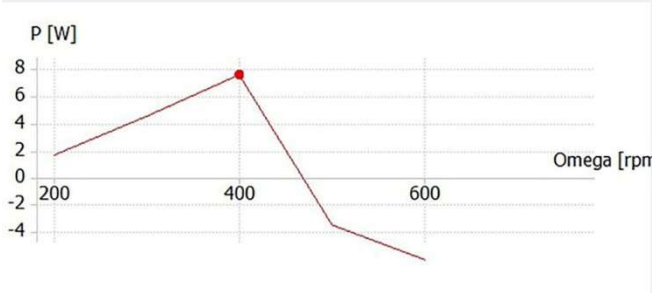

Fig. 4. Power versus rpm for wind velocity of 3.5 m/s

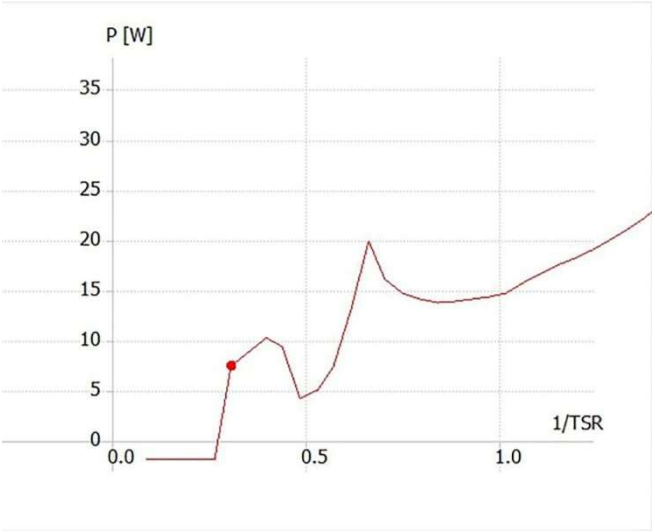

Fig. 5. Power versus 1/TSR at 400 rpm

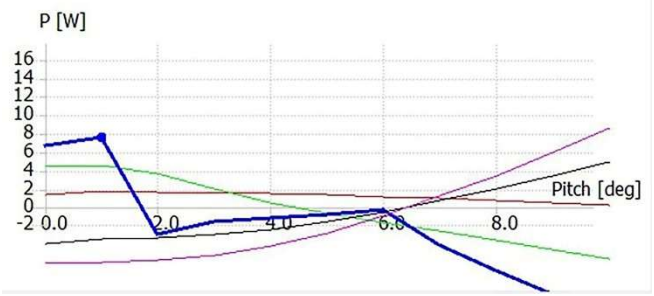

Fig. 6. Power versus pitch for wind velocity of 3.5 m/s at 400 rpm

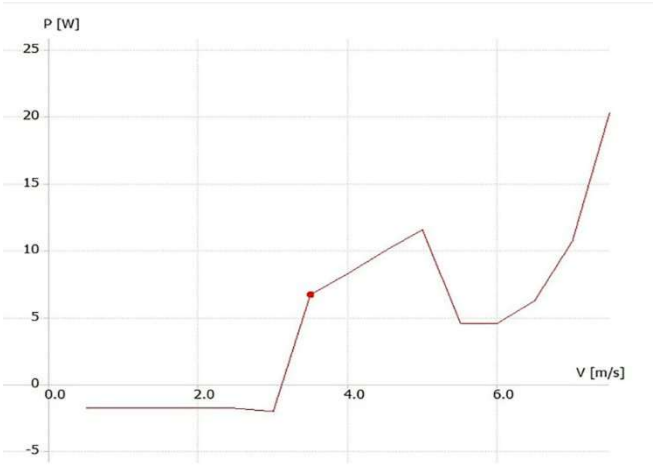

Fig. 7. Power versus wind speed

4 Conclusion

This paper illustrates the design of a VAWT that offers a potentially cost-effective solution for the integration of a small-scale wind-energy-based energy-generation source in an urban location where low wind speeds prevail. These are simulated results that were based on average wind speed data taken for a city 10 meters above ground level. There is potential for reaching an even higher power output by designing the rotor height to intercept much higher speed winds present above the boundary layer of a building. The nature of the geometry of a VAWT allows for a higher output by extruding vertically, whilst virtually occupying the same amount of space. Moreover, the straight-bladed design and symmetrical airfoil used imply relatively inexpensive manufacturing techniques (as opposed to, say, helical turbine designs), potentially allowing more turbines to be installed per unit area, and hence further stimulating the seamless integration of wind turbine-based energy generation in an urban setting.

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References

1. P. Sadorsky, *Wind Energy for Sustainable Development: Driving Factors and Future Outlook*, Journal of Cleaner Production **289**, 125779 (2021). doi: https://doi.org/10.1016/j.jclepro.2020.125779.
2. A. Kumar, *First and Second Law Thermodynamic Analysis of a Single and Dual-Stage Ignition Biomass Downdraft Gasifier*, International Journal of Hydrogen Energy **48**, 7582 (2023). doi: https://doi.org/10.1016/j.ijhydene.2022.11.194.
3. R. Bharani and A. Sivaprakasam, *A Review Analysis on Performance and Classification of Wind Turbine Gearbox Technologies*, IETE Journal of Research **68**, 1 (2020). doi: https://doi.org/10.1080/03772063.2020.1756936.

4. M. Ahmad, A. Shahzad, and M. N. M. Qadri, *An Overview of Aerodynamic Performance Analysis of Vertical Axis Wind Turbines*, Energy & Environment **34**, (2022). doi: https://doi.org/10.1177/0958305x221121281.
5. O. Apata, P. N. Bokoro, and G. Sharma, *Integration of Small-Scale Wind Turbines in Sustainable and Energy Efficient Buildings*, Natural Energy, Lighting, and Ventilation in Sustainable Buildings 111 (2023). doi: https://doi.org/10.1007/978-3-031-41148-9_6.
6. E. Voon and Elammaran Jayamani, *Study and Analysis of Challenges in Wind Energy Implementation*, Lecture Notes in Mechanical Engineering 177 (2022). doi: https://doi.org/10.1007/978-981-19-3307-3_15.
7. P. Škvorc and H. Kozmar, *Wind Energy Harnessing on Tall Buildings in Urban Environments*, Renewable and Sustainable Energy Reviews **152**, 111662 (2021). doi: https://doi.org/10.1016/j.rser.2021.111662.
8. K. Calautit and C. Johnstone, *State-of-The-Art Review of Micro to Small-Scale Wind Energy Harvesting Technologies for Building Integration*, Energy Conversion and Management: X **20**, 100457 (2023). doi: https://doi.org/10.1016/j.ecmx.2023.100457.
9. V. J. Reddy, N. P. Hariram, M. F. Ghazali, and S. Kumarasamy, *Pathway to Sustainability: An Overview of Renewable Energy Integration in Building Systems*, Sustainability **16**, 638 (2024). doi: https://doi.org/10.3390/su16020638.
10. P. Coelho, *The Betz Limit and the Corresponding Thermodynamic Limit*, Wind Engineering **47**, (2022). doi: https://doi.org/10.1177/0309524x221130109.
11. P. Bayron, R. Kelso, and R. Chin, *Experimental Investigation of Tip-Speed-Ratio Influence on Horizontal-Axis Wind Turbine Wake Dynamics*, Renewable Energy **225**, 120201 (2024). doi: https://doi.org/10.1016/j.renene.2024.120201.
12. F. Rezaei and Marius Paraschivoiu, *Computational Study of the Effect of Building Height on the Performance of Roof-Mounted VAWT*, Journal of Wind Engineering and Industrial Aerodynamics **241**, 105540 (2023). doi: https://doi.org/10.1016/j.jweia.2023.105540.
13. A. I. Altmimi, M. Alaskari, O. I. Abdullah, A. Alhamadani, and J. S. Sherza, *Design and Optimization of Vertical Axis Wind Turbines Using QBlade*, Applied System Innovation **4**, 74 (2021). doi: https://doi.org/10.3390/asi4040074.
14. Y. H. Mahmood and M. R. Badah, *Design Vertical Axis Wind Turbine Rotorblade and Simulation in (DMS) Approach by Q-Blade Software*, AIP Conference Proceedings **2593**, (2023). , doi: https://doi.org/10.1063/5.0113069
15. M. Ferencová, I. Jeleňová, and L. Kakalejčík, *Social Media Usage in Product Information Searching*, Applied Mechanics and Materials **795**, 69 (2015). doi: https://doi.org/10.4028/www.scientific.net/amm.795.69.