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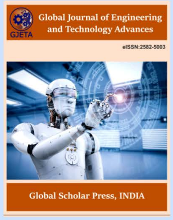

(REVIEW ARTICLE)

Design and development of a vertical axis wind turbine for slip stream energy harvesting

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Abstract

Zimbabwe has over the last decade witnessed a steady surge with regards to the demand of electric vehicles (EVs), and on the global scale as well, this has highlighted the need for innovative charging solutions. These innovative solutions are required more in the developing nations, which historically have depicted insufficient infrastructure to support the widespread adoption of EVs. The major challenges which have been observed have been the high ratio of EVs as compared to the available charging pots, the erratic nature as well as inadequacy of electricity as well as the heavy reliance by developing nations on fossil-based fuels for the generation of electricity. The factor associated with fossil-based fuels thus diminish the environmental benefits that are synonymous with EVs which include the reduction of greenhouse gas emissions. The research sought to address these highlighted challenges by designing a Vertical Axis Wind Turbine (VAWT) and integrating it with a charging station which then harnesses electricity from the slipstream associated with passing vehicles. This action thus effectively converts the nation's highways into renewable energy sources. The evaluation process of the design involved the analysis of aerodynamical forces, estimation of power generation potential, an assessment of operational loads, conducting Computational Fluid Dynamics (CFD) analysis and prototyping the system to demonstrate its practicability and potential scalability. The results of the research demonstrated the feasibility of implementing VAWTs along highways so as to provide a sustainable and decentralised power supply for EV charging stations, thus offering a much promising solution for the adoption of EVs in Zimbabwe.

Keywords: Vertical axis wind turbine; Computational fluid dynamics; Electric vehicles; Renewable energy; Slipstream; Charging stations

1. Introduction

Electric vehicles (EVs) have over the last decade, gained global traction due to the environmental benefits they offer, improved performance as well as reduced costs associated with maintenance. Global sales alone of EVs surpassed the 2 million marks in the first quarter of the year 2022 [1], which was an evident 75% increment from the first quarter of the previous year, 2021.

However, despite this noticeable milestone, there has been a lag in the adoption of EVs in developing nations such as Zimbabwe, and this hinderance has largely been due to the insufficiency of charging infrastructure [2], electricity supply as well as an over-reliance on fossil fuels for purposes of power generation. This research proposed a Novel solution: the integration of Vertical Axis Wind Turbines (VAWTs) with EV charging stations so as to seamlessly harness slipstream energy from passing motor vehicles. By converting the highways into renewable energy sources, the proposed system seeks to provide a sustainable and decentralised power supply for the charging of EVs, thus reducing

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the strain on the national grid and also ultimately minimising greenhouse gas emissions. The proposed system is designed in such a way that it can be seamlessly integrated into existing road infrastructure, thus providing a sustainable and renewable energy source.

Recent reports published by the International Energy Agency (IEA) have highlighted the rapid growth in terms of global EV adoption, with developing nations not being left out as they have embraced EVs as a sustainable transportation solution for their populations [3]. However, a significant barrier in the form of insufficient charging infrastructure, remains in the African landscape, and this has been exacerbated by the fact that electricity supply is inherently unreliable and the nations depend heavily on fossil fuels [4].

A slipstream is defined as a region behind a moving object in which a wake of fluid is moving at velocities comparable to that of the moving object, relative to the ambient fluid through which the object is moving [5]. Slipstreaming has found a popular use in formula 1 racing where the car in the front line pierces a hole through the wind and the cars behind it line up behind it to reduce the effect of air resistance [6]. The proposed principle of operation within this research is by virtue of harvesting high speed slipstream air to turn the turbine blades of vertical axis wind turbine which in turn produces electricity. This is achieved by generating electrical power through wind draft and lift forces produced by vehicles travelling on the road [7]. High speed vehicles push away air as they move, producing air kinetic energy ad heat. Placing wind turbines at the centre or the side allows this kinetic energy to be captured and converted in electrical energy. According to the Zimbabwean National Statistics Agency (ZIMSTAT), the number of registered vehicles in Zimbabwe reached approximately 1.5 million as of December 2022, with light motor vehicles accounting for 80.6% of the total [8]. Of these vehicles, the majority are concentrated in Harare, which is the Capital City. Over the years, the vehicle population has shown a consistent surge, with a recorded growth increment of 6.9% from 2021 to 2022 [8].

Each moving vehicle represents an opportunity to harvest the slipstream kinetic energy produced [9] [10] in order to generate electricity required to charge electric vehicles or to serve secondary functions such as lighting up street lamps, electrifying homes that are not connected to the grid or supplying lighting options that supplement electricity in the event of power cuts. Figure 1 shows the application of the slipstream principle.

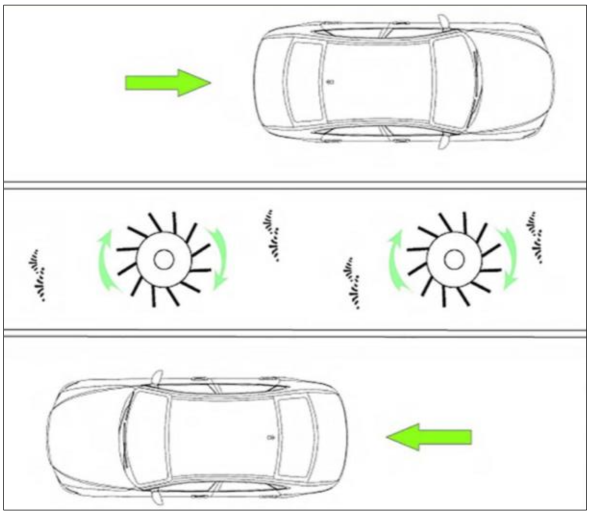

Figure 1 Slipstream Harvesting [11]

2. Design Parameters Determination

The rotor, shaft, power train parameters were determined using mathematical calculations to achieve the vertical axis wind turbine for electric vehicle charging.

2.1. Rotor design

The rotor of the turbine encompasses the rotor aerodynamics, air foil, the blades, swept area and tip speed ratio parameters.

The rotor aerodynamics parameters are derived from the blade acting forces and angles diagram as shown in Figure 2.

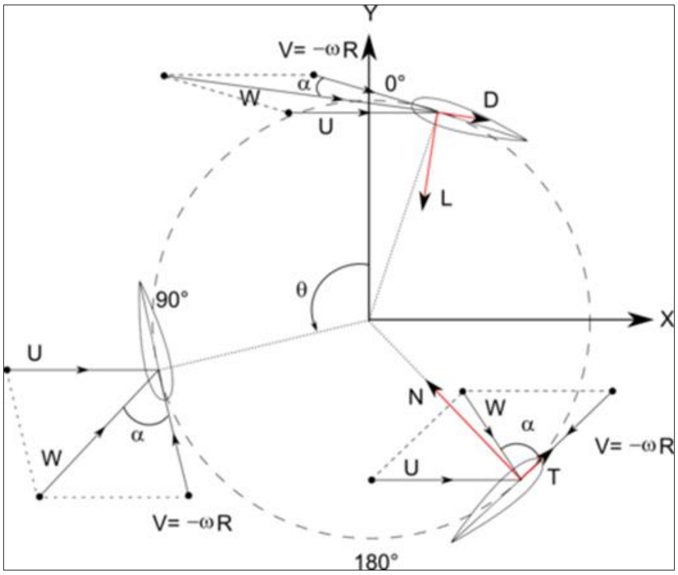

Figure 2 Acting forces and angles for rotor blade

The formulas applied on the turbine determine the parameters are given as follows [12, 13];

The relative velocity is given by;

$$W = V_\infty - R\omega \tag{1}$$

Where; W is the relative velocity, V_∞ is the free stream velocity, is the R is the radius of rotation, and ω is the turbine angular velocity

The resulting angle of attack and airspeed flow are determined geometrically as:

$$W_c = U + V\cos\theta \tag{2}$$

$$W_n = V\sin\theta \tag{3}$$

where: W_c is the chord wise direction, W_n the perpendicular direction to the chord.

Thus, the angle of attack for an unpitched and pitched blade is defined as:

$$\theta = \tan^{-1}\left(\frac{V\sin\theta}{R\omega} + V\cos\theta\right) - \alpha \tag{4}$$

The Rotor air foil, DU 06 -W - 200 air foil was selected due to its superior performance based on the performance curve chart given on Figure 3. This air foil model was used in the design of the rotor blades.

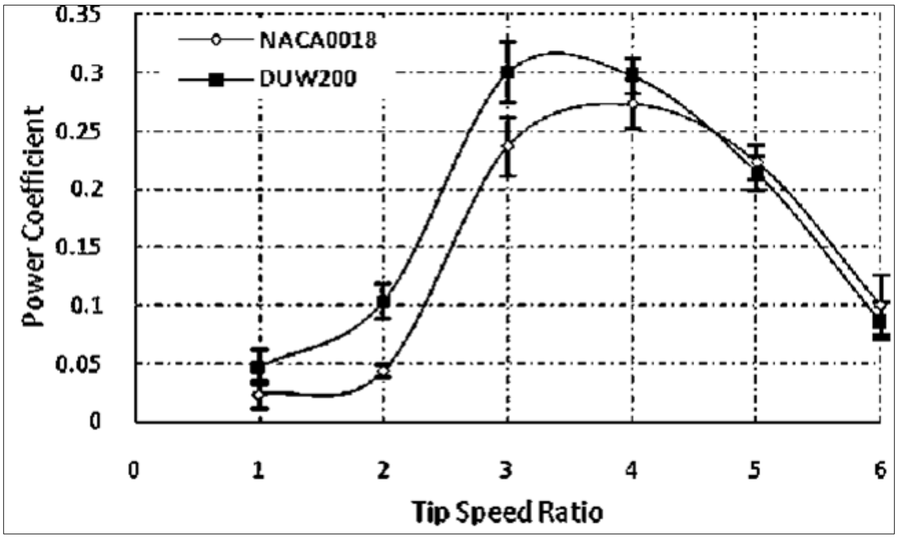

Figure 3 Performance curves comparison [14]

The selected number of blades was achieved using the performance curves obtained by varying turbine blade numbers as given on Figure 4 [14]. The 3-blade design was selected as it promotes stability, reduces torque ripple in the drive train and eliminates symmetrical loading.

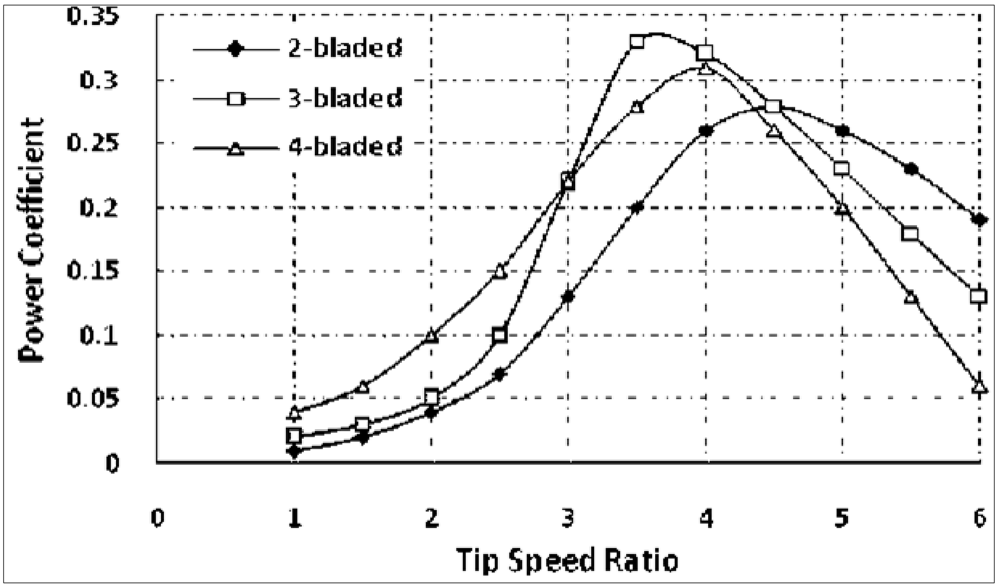

Figure 4 Varying blade number performance curves [14]

The solidity values selected were based on the standard graphs of the relationship between the power coefficient and the tip speed ratio as solidity values are varied curves as given in Figure 5 [14]. Solidity values between 0.3 and 0.5 were chosen as they are ideal in maximizing both the power coefficient and the tip speed ratio.

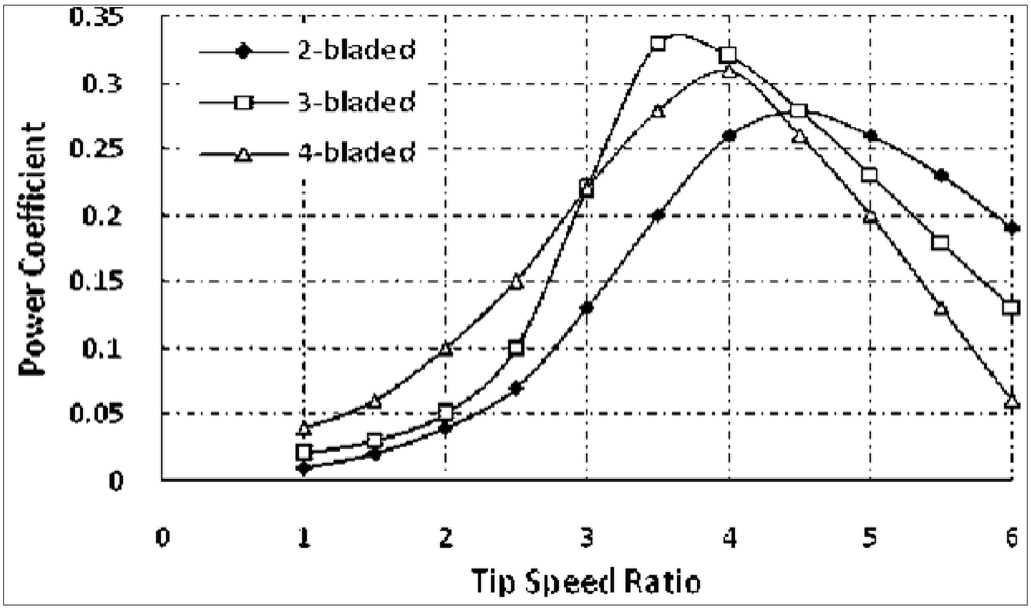

Figure 5 Effect of solidity on the power coefficient [14]

The turbine swept area is the space that encloses the turbine as it rotates and it is dependent on the shape of the rotor configuration and is determined as:

$$A = L \times d \tag{5}$$

Where; L is the blade length and d is the blade diameter

The tip speed ratio (TSR) is defined as the ratio of the tangential speed at the blade tip to the actual wind speed [15]. Values of TSR for VAWTs range between 2 and 2.5. The equation is below giving the TSR to be used for calculations;

$$TSR = \frac{\omega R}{v_w} \tag{6}$$

Where; ω is angula velocity, R is the blade radius and v_w is the wind speed

The turbine torque is a factor of the velocity, rotor swept area, air density and the efficiencies of the generator and the gearbox. The turbine torque is determined as:

$$\boldsymbol{T_t} = \frac{(\mathbf{0.5} \times \boldsymbol{C_p} \times \boldsymbol{\rho} \times \boldsymbol{A} \times \boldsymbol{v}^3)}{\boldsymbol{\omega}} \tag{7}$$

Where; C_p is the turbine power coefficient, ρ is the air density, ω is the angular velocity, A is the rotor swept area, $\boldsymbol{v}$ is the wind velocity.

The turbine power is determined as:

$$P_t = 0.5T_t \tag{8}$$

Glass fibre - epoxy resin was selected for the blade material. The Fiberglass composites are good insulators, and do not react to an electric field. This material allows to achieve light weight blades and the razor-sharp edges allow the blades to cut through the wind, making it relatively silent. Although the material has low tensile strength, it has a low tensile modulus which gives the blades the ability to bend and strain without breaking.

The chord length is determined as:

$$c_l = \frac{S \times \pi \times d}{N_b} \tag{9}$$

Where; S is solidity, d is the blade diameter and N_b is the number of blades

The wind load is obtained as follows:

$$W_L = P_d \times A_b \quad (10)$$

Where; P_d is the dynamic pressure and A_b is the blade area.

2.2. Shaft design

The shaft is subjected to two main forces and torque as a result of the blades rotation due to wind orthogonal to the shaft. The stress which the shaft is subjected in the x and y direction is determined as follows [16]:

$$\sigma_x = \frac{P_w}{A} \quad (11)$$

$$\sigma_y = \frac{W}{A} \quad (12)$$

Where; A is the shaft cross section, P_w is the wind load on the blade and W is the turbine weight

The torsion in the shaft is determined as follows:

$$\tau = \frac{T \times r}{j} \quad (13)$$

Where; T is the torque, r is the shaft radius and j is the polar moment of inertia

The principal stresses σ_1 and σ_2 are determined as follows [16]:

$$\sigma_1 \sigma_2 = \left(\frac{\sigma_x + \sigma_y}{2}\right) \pm \sqrt{(\frac{\sigma_x - \sigma_y}{2})^2 + \tau^2} \quad (14)$$

The Von Mises stress theory is used to determine the factor of safety as follows [16]:

$$\sigma_{ovm} = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_3 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2}{2}} \quad (15)$$

The factor of safety is then determined as [16]:

$$SF = \frac{S_y}{\sigma_{ovm}} \quad [16]$$

Where; σ_{ovm} is the overall stress and S_y is the yield strength

2.3 Spur Gears Design

The formulas applied in the gear system design are given as follows [16]:

The tangential tooth load W_T on the gear is determines as:

$$W_T = \frac{P}{v} \times D \quad (17)$$

Where; P is the permissible tangential tooth load, v is the pitch line velocity and D is pitch circle diameter.

The Lewis equation is used to determine the tangential tooth load on the pinion and is given as follows:

$$W_T = \sigma_w . b . p_c . y = \sigma_w . b . \pi . m . y = (\sigma_0 . C_v) . b . \pi . m \quad (18)$$

Where; b is width of gear face p_c is the pitch circle, m is the module, y is half of the thickness of the tooth; σ_0 is allowable static stress and C_v is the velocity factor.

The gear train dynamic load is determined using the Buckingham equation defines as:

$$W_D = W_T + W_I = W_T + \frac{21v(b.C + W_T)}{21v + \sqrt{b.C + W_T}} \quad (19)$$

Where, W_T is the steady load dur to transmitted torque, W_I is the incremental load dur to dynamic action, v is pitch line velocity, b is the face width of gears, C is deformation dynamic factor

The static toot load is determined as follows:

$$W_S = \sigma_e.b.p_c.y = \sigma_e.b.\pi.m.y \quad (20)$$

For safeguard against breakage, W_S must be greater than W_D and the maximum wear tooth load W_w should not be less than the dynamic load. The wear tooth load is defined as:

$$W_w = D_p.b.Q.K \quad (21)$$

Where; D_p is the pitch circle diameter of the pinion (mm), Q is ratio factor K is the Load stress factor.

3. Results and Analysis

Table 1 gives the determined parameters which were determined used in the development of the vertical axis wind turbine. The parameters include solidity, turbine swept area, number of blades, turbine solidity, swept area, tip speed rotation shaft diameter, power, torque shaft factor of safety, generated. Table 1 Design parameters of the vertical axis wind turbine.

Table 1 Vertical axis wind turbine parameters

Parameter	**Value**
Solidity	0.5
Blades	3
Shaft diameter	0.025 m
Swept Area	0.78 m^2
Tip speed ration	2.25
Code Length	0.5m
Torque	44.3 Nm
Power	6 919 Wh
Factor of Safety	20

The shaft material used is the 50 C 4 grade of carbon steel and the factor of safety of 20 indicates a safe project design which is able to sustain load at higher wind speeds.

Table 2 and Table 3 gives the bearing and gearbox specifications of the developed the vertical axis turbine.

Table 2 Bearings specifications

Parameter	**Value**
Bearing type	Angular contact bearing
Bore	25mm
Outer diameter	47mm
Width	12mm
Minimum static load	18.6kN
Maximum static load	31.9kN

Angular contact bearings were selected because they provide greater speed and they are able handle combined radial and axial loads.

Table 3 Gearbox Specification

Parameter	**Value**
Gear type	Spur
Gear ratio	10: 1
Rotational Speed	175 rpm
Shaft orientation	Vertical
Input horsepower	1.13
Efficiency	0.90

Spur gears application is due to their ability to transmit exact velocity ratios, transmit large power, are associated with high efficiency and are reliable.

3.1. Vertical axis wind turbine Simulation

Figure 6. gives the simulation outcome carried out to establish the velocity contour around the blade according to its shape.

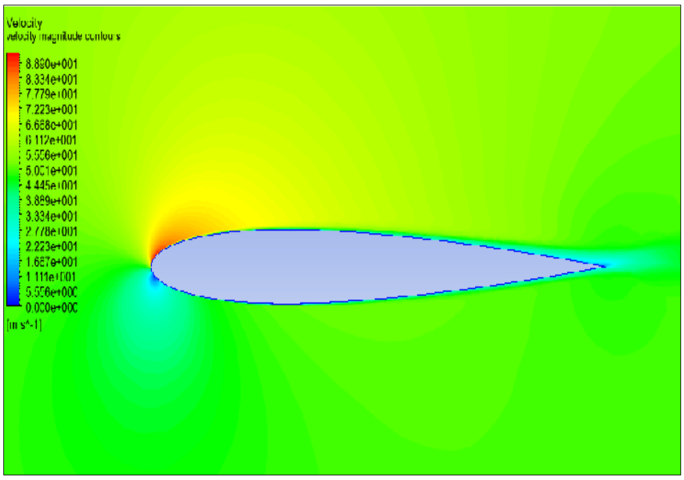

Figure 6 Characterisation of a single blade velocity contour

Figure 7 give the Multiple blade velocity characterisation of the three-blade vertical axis wind   turbine.

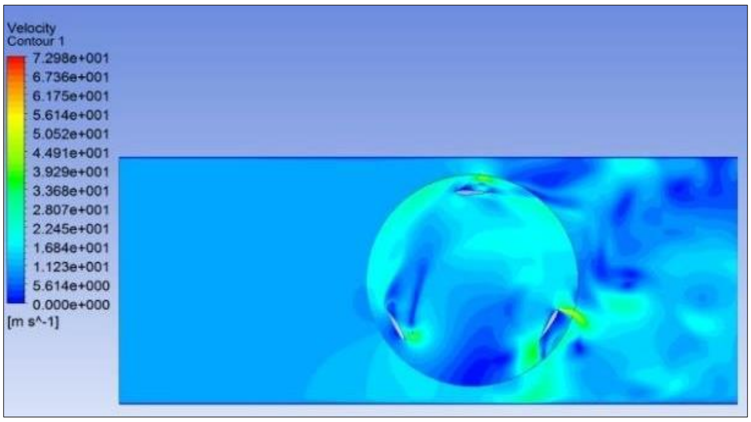

Figure 7 Multiple blades velocity contour characterisation

Table 4 Gives the simulated power achieved under varying wind speed from a minimum speed of 5m/s to a maximum speed of 25m/s.

Table 4 Simulated vertical axis wind turbine generated powered under variable wind speed

Wind Speed (m/s)	Wind speed (km/hr)	Power generated (W)
5	18.0	58.5
10	36.0	465.9
15	54.0	1 572.5
20	72.0	3 727.5
25	90.0	7 280.2

Figure 8 gives the simulation carried out to characterise the turbine fracture as a function of force induced by excessive wind velocities.

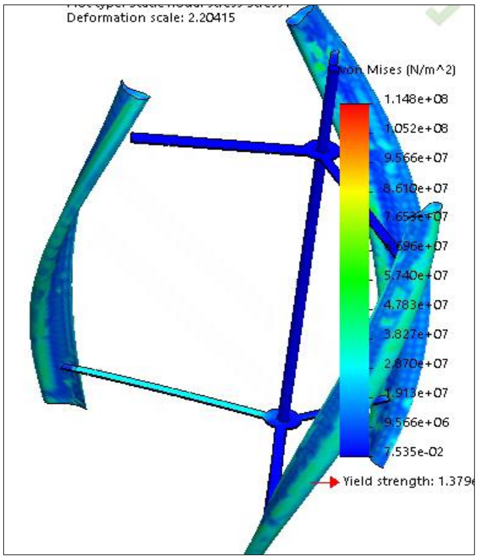

Figure 8 Vertical axis wind turbine fracture Simulation

3.2. Prototype Fabrication

The vertical axis wind turbine for slip Stream Energy harvesting was fabricated and installed as shown in Figure 9. The prototype uses the slipstream wind to rotate the blades. The shaft, containing two bearings, rotates with the blades transferring the motion. On the bottom section of the turbine a wheel is connected which transfers motion to the dynamo which generates power. The dynamo used in the building the prototype has a maximum power output of 50 Watts.

Figure 9 Vertical axis wind turbine prototype testing

The vertical axis wind turbine prototype was tested and the evaluation performance of the turbine is given in Figure 10 based on the generated power. The highest power output of 45 Watts was achieved during prototype testing.

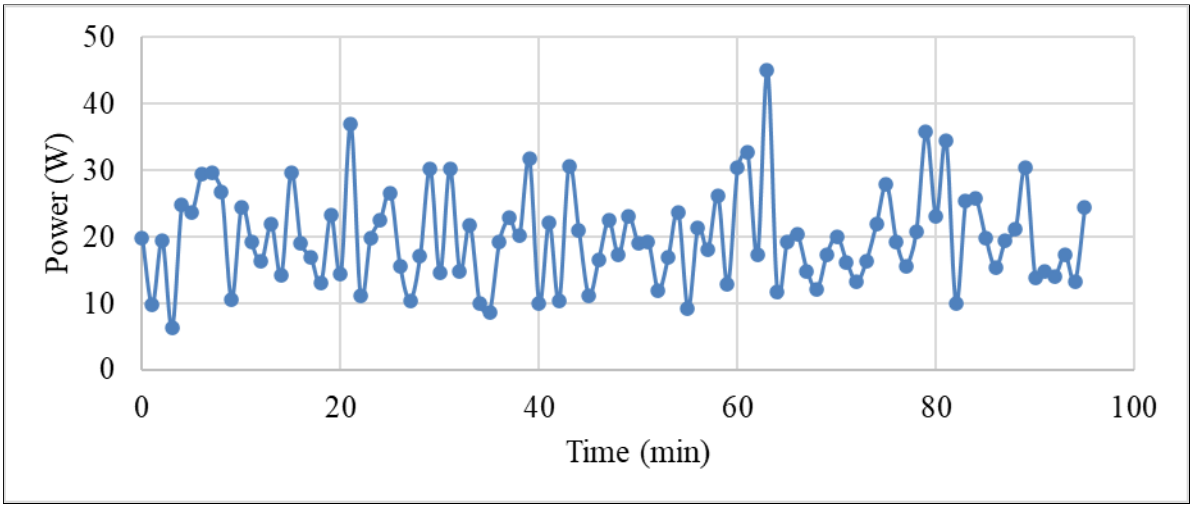

Figure 10 Prototype power output

4. Conclusion

In this paper, an investigation into the design of a slipstream harvesting system was conducted. The following research has proved that a vertical axis wind turbine can be used to harvest slipstream energy. The power produced is heavily a function of the velocity of slipstream wind and the efficiency of the power train. Further research can be conducted on the use of vertical axis wind turbines to power houses that are off the grid and placement on rooftops to produce electricity.

Compliance with ethical standards

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Disclosure of conflict of interest

No conflict of interest to be disclosed.

References

[1] W. Chege, „2022 Electric Vehicle Market Intelligence Report," 2022 Electric Vehicle Market Intelligence Report, p. 13, 2022.

[2] C. Tadya, Interviewee, Insights on Electric Vehicle Adoption in Zimbabwe. [Onderhoud]. 28 April 2025.

[3] IEA, „Global EV Outlook 2024: Moving Towards Increased Affordability," IEA - International Energy Agency, Paris, France, 2024.

[4] E. Etukudoh, A. Hamdan, V. Ilojianya, C. Daudu en A. Fabuyide, „Electric vehicle charging infrastructure: a comparative review in Canada, USA, and Africa.," Engineering Science & Technology Journal, vol. 5, nr. 1, pp. 245-258, 2024.

[5] T. A. Ismaeel, S. Aljabair, O. A. Abdulrazzaq en Y. A. & Abood, „Energy Recovery of Moving Vehicles' Wakes in Highways by Vertical Axis Wind Turbines.," FME Transactions, vol. 48, nr. 3, pp. 1-9, 2020.

[6] R. Dominy en M. Wilson, „The Aerodynamics of Slipstreaming," ATZ Autotechnol, vol. 8, pp. 56-60, 2008.

[7] M. Hennlock, „Strong link between charging infrustructure and adoption of electric vehicles," SustainableHorizons in Future Transport, vol. 1, nr. 1, p. 2, 2020.

[8] S. Munuhwa, K. M. J. P. T. Mandere en T. & Gabakaiwe, „Approaches for Reducing Urban Traffic Congestion in the City of Harare," Journal of Economics and Sustainable Development, vol. 11, nr. 4, pp. 1-12, 2020.

[9] M. H. Shah, G. O. Alandjani en M. Ashgar, „Energy harvesting using kinetic energy of vehicles," 3C Tecnología Glosas de innovación aplicadas a la pyme, vol. 9, nr. 2, pp. 113-126, 2020.

[10] R. De Fazio, M. De Giorgi, D. Cafagna, C. Del-Valle-Soto en P. Visconti, „Energy Harvesting Technologies and Devices from Vehicular Transit and Natural Sources on Roads for a Sustainable Transport: State-of-the-Art Analysis and Commercial Solutions," Energies, vol. 16, nr. 7, pp. 1-46, 2023.

[11] Y. Li, Straight-Bladed Vertical Axis Wind Turbines: History, Performance, And Applications, Rotating Machinery: IntechOpen, 2020.

[12] Z. Li, R. Han, P. Gao en C. Wang, „Analysis and implementation of a drag-type vertical-axis wind turbine for small distributed wind energy systems.," Adv. Mech. Eng., vol. 11, pp. 1-16, 2019.

[13] S. J. Deshmukh en S. Charthal, „Design and Development of Vertical Axis Wind Turbine," Internal Journal of Technology and Engineering, pp. 5 - 8, 2017.

[14] P. Sabaeifard, H. Razzaghi en A. Forouzandeh, „Determination of Vertical Axis Wind Turbines Optimal Configuration through CFD Simulations," Semantic Scholar, 2012.

[15] W. Tong, „Fundamentals of Wind Energy," WIT Transactions on State of the Art in Science and Engineering, vol. 44, pp. 6 - 8, 2010.

[16] R. S. Khurmi en J. K. Gupta, A Textbook of Machine Design, 14 red., New Delgi: Eurasia Publishing House (PVT) LTD, 2005.