Effect of Variable Speed on Power Generation of Vehicle Mounted Wind Turbine

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Abstract— **the growing need for sustainable energy sources has drawn a lot of interest to the integration of renewable energy solutions in transportation networks. This study examines how varying vehicle speeds affect a vehicle-mounted wind turbine's ability to generate electricity. The turbine serves as an additional energy source for on-board equipment by using the relative wind flow produced by the motion of the vehicle to make electricity. Important factors were examined, including energy conversion rates, vehicle speed range, wind turbine efficiency, and aerodynamic drag. The relationship between vehicle speed and wind turbine power was assessed using experimental testing and computational fluid dynamics (CFD) simulations. The findings show that power generation follows a quadratic relationship with vehicle speed, while it is constrained by airflow directionality and turbulence.**

Keywords: **HAWT, RRA (Required rotor acceleration), TSR (Tip speed ratio), VAWT, CFD**

INTRODUCTION

In daily life, energy is essential for doing any work. These days, the term "complete energy fulfillment" primarily refers to non-renewable energy sources like coal, oil, and gas. However, the main problem with non-renewable energy sources is that they are not sustainable and produce carbon dioxide that is bad for the environment. Solar, tidal, and biogas are examples of renewable energy sources that are abundant in nature and free to use for the purpose. Wind energy is the cleanest kind of energy for generating power and has no negative effects on the environment. It is the process by which wind energy is transformed into mechanical power in wind turbine systems. Grain grinding and water pumping are two examples of tasks that can be accomplished with mechanical power, much like in the past. Minor WT is typically installed for minor production needs, rural locations, or residential applications. The possibility of modifying vehicle-mounted wind turbines to include HAWT and VAWT is being investigated in a research study. It is not advantageous to use VAWT on an automobile because of the vehicle's narrow collision area, high weight, and size restrictions. Conversely, HAWT is more affordable, lighter, and has a smaller impact area than the larger swept area. More RPM, torque, and superb execution are all provided by the same advantage. In a similar vein, HAWT that is appropriate for two-wheelers is crucial for utilizing energy when necessary. As explained below, a thorough literature review was conducted in order to get the concept and development.

This paper will focus on wind turbine technologies that increase a vehicle's range by mounting the turbine atop the vehicle. When the car is moving, the turbine's operating principle is used to generate electricity. Here, the generated electricity is either directly linked to power the accessories or stored in the alternator, which is used to run the vehicle for additional range. The following chapter discusses the model's design and necessary materials.

LITERATURE REVIEW

Luis Alfonso Moreno-Pacheco (1) studied initially examines the aerodynamic characteristics of residual air currents created by vehicle movement and evaluates their potential for energy generation in order to build a vertical axis wind turbine. The characteristic velocity profile, the durations of the disturbances, the average and maximum velocities, and the probability of these disturbances recurring are some of the factors that are assessed. The data is used to estimate the amount of electrical energy that a wind turbine operating under such wind conditions could produce. Hassnaa Hasan Shaheed (2) focuses on creating a new model of a Savonius wind turbine and installing it on a car. By capturing the potential wind energy generated by a moving vehicle, the wind turbine revolves. The energy generated by this turbine is stored in the battery and can be used for many purposes. Using this method, a wind turbine's installation atop a car is tested to see if it produces the desired output and efficiency High vehicle speeds and self-starting have been found to increase the Savonius wind turbine's efficiency. Gashaw A. Anagie (3) aims to investigate the performance of a tiny horizontal axis wind turbine mounted atop a pickup truck. The power produced by the wind turbine is utilized to recharge the vehicle's batteries. For the experiment, a permanent magnet generator and a blade of the NACA 4412 type with a 6° angle of attack have been used. Using Qblade software, the angle of attack is calculated at the NACA 4412 airfoil's maximum lift to drag ratio.

PROBLEM DEFINITION:

The growing demand for sustainable and efficient energy solutions in the transportation sector has led to an increased interest in integrating renewable energy technologies into vehicles. One promising approach is the use of vehicle-mounted horizontal-axis wind turbines (HAWTs) to generate supplementary electrical power. However, the performance of these systems is significantly influenced by variable vehicle speeds, aerodynamic drag, and airflow behavior. Despite advancements in renewable energy technologies, there is limited research on the optimization of wind turbines for variable-speed vehicle applications and their real-world performance. Addressing these gaps is essential to maximize power generation efficiency, minimize aerodynamic losses, and ensure structural stability under dynamic operating conditions.

OBJECTIVE

Designing and creating a horizontal-axis wind turbine (HAWT) that can capture wind energy produced while the vehicle is moving is the main goal of this project. In order to sustain the vehicle's utilities, including climate control systems, entertainment systems, lighting systems, and other auxiliary electronics, this renewable energy will be transformed into electrical power. The system seeks to lessen dependency on the vehicle's battery or the traditional fuel-driven alternator by using wind energy as an extra power source. This can result in increased range efficiency for electric or hybrid vehicles and better fuel economy for fuel-powered vehicles.

I. WIND ENERGY GENERATION CAPACITY AND ITS OUTPUT STUDY

The energy contained in the wind is its kinetic energy. Hence,

$Kinetic\ energy = 1/2 \times m \times V2$……….. (1)

Where m is in kilograms and V is in meters per second (m s-1) and mass of air is given by,

$Mass(m) of air = Airdensity \times area \times velocity$

$m = \rho \times A \times V$……………………… (2)

Therefore, substituting in the above equation (1) of kinetic energy we get,

$Kineticenergypersecond = 0.5 \times \rho \times A \times V3$ $(joulespersecond)$… (3)

Where ρ is in kilogram per cubic metre (kg m-3), A is in square metres (m2) and V is in metres per second (m s-1)

As energy per unit time is equals to power,

The power in the wind is P (watts) =Kinetic energy in the wind traversing the circular ring per second (joules per second), that is:

$P = 0.5 \times \rho \times A \times V3$……………………………. (4)

The main relation that is apparent from the above calculations is that the power in the wind is proportional to:

• The density of air

• The area through which the wind is passing (i.e., through a wind turbine rotor

• The cube of the wind velocity

STUDY AND ANALYSIS OF ELECTRICITY CONSUMING COMPONENTS IN THE VEHICLE

Various Electrical components in a car that uses electricity for its operation are as follows:

1. Headlights, taillights, blinkers, Brake lights, Cabin, and Trunk light.

2. Wipers

3. Power window

4. Stereo music system

5. Air conditioner

Starter motor

7. OBC (onboard computer)

- Power Consumption of Electrical components

1. Headlight, taillight, blinker, Brake light, Cabin, and Trunk light.

Sr. no	Light Type	Traditional bulb(in Watt)	LED(in Watt)	Halogen(in Watt)
1.	High beam	70	34	65
2.	Low beam	60	54	55
3.	Brake light	53	11.2	35
4.	Cabin light	5	2	3.5

2. Wipers
• 4 wiper motors each of 50 W

• Total power consumption = 50W (each motor)*4 = 200W

3. Power window
• 4 Power window motors each of 50 W

• Total power consumption = 50W (each motor)*4 = 200W
4. Stereo music system
• A typical stereo system is of 200W 4 channel

• 50W peak by single channel

• Average power consumed is 13-18W per channel depending upon volume

• Total maximum consumption = 4×25W (each channel) =100W

5. Air conditioner
• Car Ac consume 1/4th of H.P i.e., 1/4*746=186.5W on low speed

• It consumes approximately 10 H.P at high speed.

• Total power consumption at high speed = 10×746 = 7460W.

II. THEORETICAL CALCULATIONS OF SAMPLE DESIGN OF HAWT FOR ELECTRICAL POWER GENERATION MOUNTED ON THE VEHICLE

Wind power calculations:

$$P_w = 1/2 \times \rho \times A \times V^3$$

Case 1:

V = 25km/hr

l = 1200 mm

h = 150 mm

$\rho = 1.2\ kg/m^3$

$\therefore P_w = 1/2 \times 1.2 \times (1.200 \times 0.150) \times (\frac{25\times1000}{3600})^3$

$\therefore P_w = 37.14W$

Case 2:

V = 50km/hr

l = 1200 mm

h = 150 mm

$\rho = 1.2\ kg/m^3$

$\therefore P_w = 1/2 \times 1.2 \times (1.200 \times 0.150) \times (\frac{50\times1000}{3600})^3$

$$\therefore P_w = 288.79W$$

Case 3:

V = 75km/hr

l = 1200 mm

h = 150 mm

$\rho = 1.2\ kg/m^3$

$\therefore P_w = 1/2 \times 1.2 \times (1.200 \times 0.150) \times (\frac{75\times1000}{3600})^3$

$$\therefore P_w = 976.09W$$

Case 4:

V = 100km/hr

l = 1200 mm

h = 150 mm

$\rho = 1.2\ kg/m^3$

$\therefore P_w = 1/2 \times 1.2 \times (1.200 \times 0.150) \times (\frac{100\times1000}{3600})^3$

$$\therefore P_w = 2312.87W$$

DESIGN AND DEVELOPMENT

Figure 1 shows the project's exploded assembly. We can see the alternator, turbine, base, and nozzle, among other project components. The final shape of the assembly is shown on the left side of the picture, while the diagram's right side shows the exploded components and the dots that indicate how each component is attached to the others. The base is the main element that sustains all other elements. The fan has 10 blades that are mounted to the shaft and is connected to the alternator's connection and base holder. The circular chamber that is connected in the middle of the base covers the fan. The alternator is placed above its rectangular base and connected by 4 nut bolts to the base. Also, it has a coupling connected to the rotating shaft.

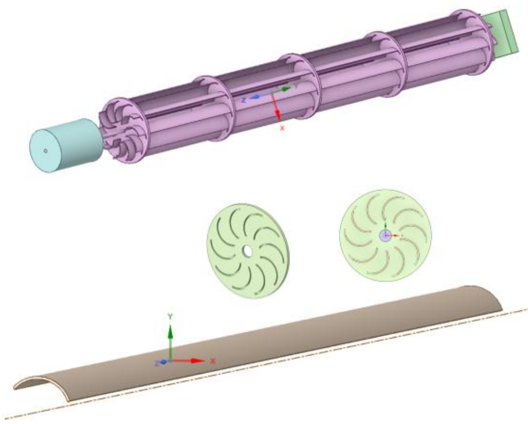

Figure 1 Design of Wind turbine prototype

Numerical Analysis of Horizontal Axis Wind Turbine

The numerical analysis of a Horizontal Axis Wind Turbine (HAWT) typically includes stress, modal, and airflow analyses. The objectives of these analyses are to optimize the design, ensure reliability, and improve performance.

Stress Analysis for the Horizontal Turbine Requirements:
Air Flow Velocity = 80 km/hr

$=(\frac{80\times1000}{3600})$

= 22.2 m/s

Turbine RPM = 300 rpm

$=(\frac{300}{60}\times 2\pi)$
=31.4 Rad/s

Cd – Drag Coefficient = 0.25

Drag Force $=(\frac{Cd}{2}\times \rho \times V^2 \times A)$

Where, ρ = Density of the air which is, 1.2 kg/m^3

Drag Force = $\frac{0.25 \times 1.2 \times 22^2 \times (2A)}{2}$

Where, 2A Taken for Calculation (Projected) Drag

Force = 148.14 N/m^2

Structural Analysis HWT

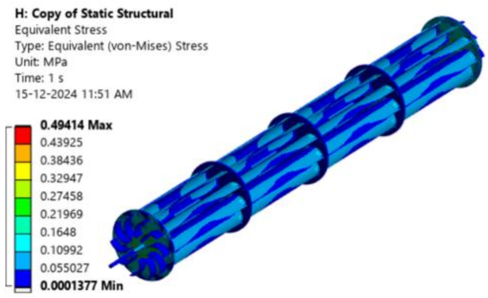

Figure2: Equivalent stress for HWT

The unit of stress is in MPa (megapascals). The color scale on the left indicates the range of stress values from 0.0001377 MPa (minimum) to 0.49414 MPa (maximum), with blue representing low stress areas and red highlighting regions with maximum stress. The component itself is cylindrical with reinforcing rings and internal structural elements, and the stress distribution shows varying intensities depending on the geometry and applied forces. Most of the components remain in the blue to green regions, indicating low to moderate stress, with no significant high-stress concentrations near failure thresholds. This analysis shows design is structurally sound and safe under the specified loading conditions.

Total Deformation of HWT

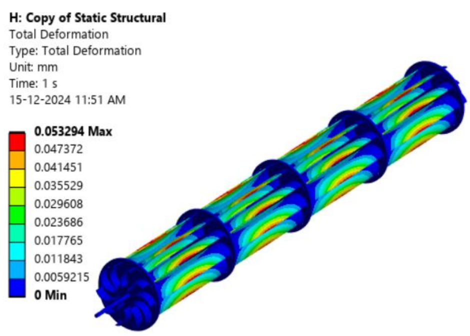

Figure 3: Total Deformation for HWT

PVC Sheet Material Properties

- Ultimate Tensile Strength: 9.81 MPa
- Elongation at Break: 100%

The color gradient scale, which highlights regions where the component undergoes the most displacement under loading, goes from 0 mm (blue, minimum deformation) to 0.053294 mm (red, highest deformation). Given the material's 100% elongation at break, PVC appears to be extremely flexible.

Modal Analysis of HWT

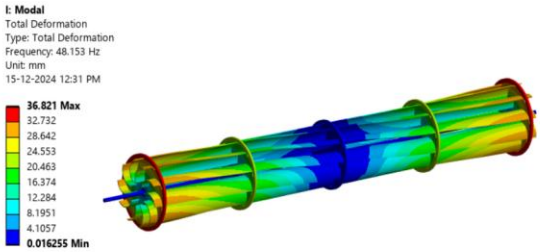

Figure 4: Modal analysis at 48 Hz for HWT

The core part of the structure exhibits little deformation, as shown by the blue regions, whereas the sections at each end of the structure undergo the greatest deformation, as seen by the red colour. This pattern suggests that the structure is undergoing a bending mode, where the ends are vibrating more significantly compared to the centre, which remains relatively stable. Modal analysis helps in understanding the dynamic behaviour of the structure, allowing to identify critical areas with excessive vibrations and take necessary design measures to improve stability and performance.

Modal Analysis Result of HWT

The following bar chart and table indicates the frequency at each calculated mode.

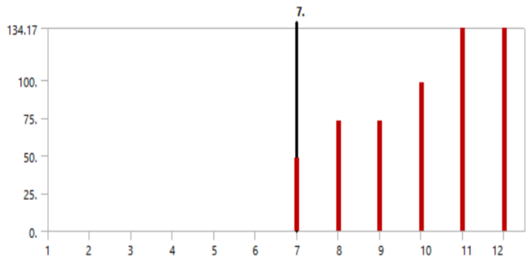

Chart 1: Bar chart indicates the frequency at each calculated mode

Modes 1–6: The frequencies are very low (close to zero), indicating these modes may not be significantly active or could represent lower vibrational states.

Mode 7: A sharp increase in frequency (48.153 Hz).

Modes 8–12: Frequencies increase steadily, with Modes 11 and 12 reaching the highest values, around 134 Hz.

First Mode at 48 Hz: This is well above the operational frequency range, ensuring no resonance issues during operation. Since the operating frequency is far lower than the first natural frequency, the system is safely designed to avoid resonance-related damage or instability.

Airflow Analysis of HWT (CFD Analysis)

The CFD case setup involves simulating airflow over a rotating wind turbine using the SST k-ω turbulence model and the total energy model for heat transfer. Air is modelled as an ideal gas, and boundary conditions include a velocity inlet with speeds ranging from 25 to 100 km/h, an outlet at ambient pressure (101,325 Pa), and an opening also at ambient pressure. The turbine's rotating domain, which includes the blade cavity and shaft, is given a rotational speed of 300 RPM about the global x-axis, while the stationary domain remains fixed, matching real-life conditions.

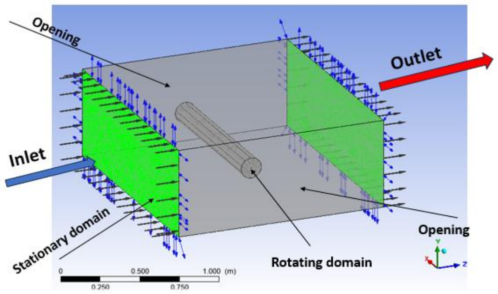

Figure 5: CFD Case setup and Boundary conditions

CFD Results for different inlet velocity

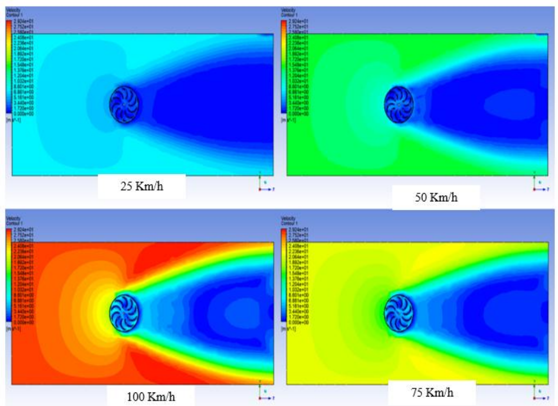

Figure 6: Velocity Contour at various speed

The contours illustrate the distribution and gradients of velocity as the flow interacts with a central turbine. At lower velocities (25 km/h and 50 km/h), the flow exhibits slower acceleration and more uniform velocity gradients. As the velocity increases to 75 km/h and 100 km/h, the contours demonstrate steeper velocity gradients and higher flow acceleration, particularly near the central geometry, indicating stronger aerodynamic interaction.

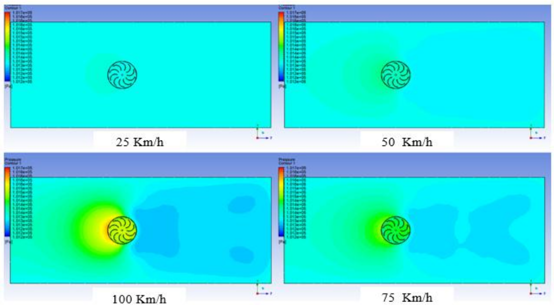

Figure 7: Pressure Contour at Various Speed

At 25 km/h, the pressure gradients are minimal, indicating a relatively uniform and low-pressure variation around the geometry. As the velocity increases to 50 km/h and 75 km/h, the pressure distribution starts to exhibit more distinct gradients, particularly near the central component, reflecting stronger aerodynamic interactions. At 100 km/h, the pressure difference becomes significant, with high-pressure regions forming upstream of the geometry and low-pressure zones downstream, indicating pronounced flow separation and wake effects.

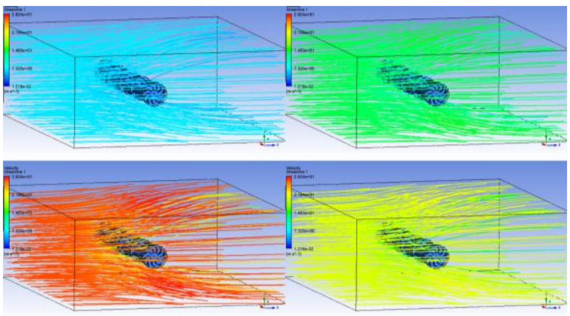

Figure 8: Velocity Contour at 25 km/h, 50 km/h, 75 km/h, 100 km/h speed

Figure 8 displays velocity streamlines at inlet velocities of 25 km/h, 50 km/h, 75 km/h, and 100 km/h, showing how airflow interacts with a central turbine. The streamlines illustrate the path of the airflow and the velocity variations in the domain. At 25 km/h, the streamlines are less dense and exhibit gradual acceleration around the turbine, with minimal turbulence. At 50 km/h, the airflow becomes more streamlined, showing increased velocity gradients near the turbine. At 75 km/h and 100 km/h, the streamlines demonstrate higher density and stronger curvature, indicating intensified aerodynamic effects, such as higher velocities and more noticeable wake regions.

Manufacturing, assembly

- Blade Fabrication (PVC Pipes)
- Circular Discs (Stainless Steel)
- Shaft Manufacturing
- Mounting Frame (Wooden Plank)
- Assembly

Figure 9: Final Assembly of HWT

System Testing

Testing the prototype in controlled conditions to measure power output, drag, and overall efficiency. To test how much voltage blades can produce, an external source of wind was needed. An Air Blower was used to depict this external wind source. With the help of a non-contact digital Tachometer, the rpm of blades was noted. At different rpm, the voltage produced was also noted down.

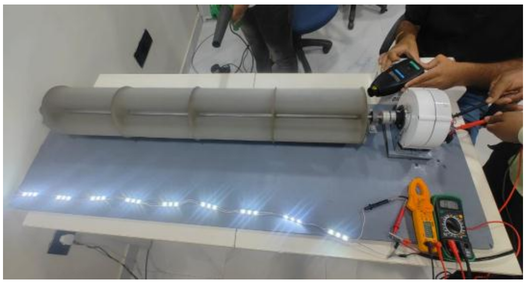

Figure 10: Lab Setup of HWT for testing

Table 1: Test Setup Readings

Wind Velocity (km/hr)	Turbine RPM	Voltage (V)	Current (A)	Electrical Power (W)
60	250	11	6.3	69.3
80	300	17.3	9.08	157.084
100	380	28.5	16.4	467.4
120	450	35	19.3	682.5

On -Road Testing

Figure 11: Actual Test photos for HWT

Car Velocity (km/hr)	(V)	(A)	(W)	Load
60	9	0.8	7.2	LED Strip
80 - 120	12	4	48	Car Head Light

Table 2: On Road Teats Results using Load

RESULTS AND DISCUSSION

The Horizontal Wind Turbine (HWT) mounted on a vehicle efficiently generates electrical power from wind energy, showing significant performance gains with higher wind speeds. At 60 km/hr, it generates 69.3 W, increasing to 682.5 W at 120 km/hr, reflecting the cubic relationship between wind speed and power output. On-road tests demonstrate its practical utility, producing 7.2 W at 60 km/hr, enough for an LED strip, and 48 W at 80–120 km/hr, sufficient for a car headlight. While highly efficient at higher speeds, its performance at lower velocities suggests room for blade design and system optimization. Overall, the HWT offers a sustainable power solution for vehicles, with potential for further improvement through aerodynamic enhancements and energy storage integration.

CONCLUSION

The Horizontal Wind Turbine (HWT) demonstrates structural integrity through low stress and minimal deformation, with von Mises stress values well below the material's tensile strength. Modal analysis confirms the system avoids resonance issues with the first natural frequency at 48 Hz, ensuring stability during operation. CFD analysis reveals significant aerodynamic interactions at higher velocities, with well-defined pressure gradients and streamlined airflow. System testing indicates an exponential increase in power output with rising wind speeds, producing 69.3 W at 60 km/h and 682.5 W at 120 km/h in laboratory conditions, and supporting real-world applications like LED lights and car headlights during on-road tests. These results validate the HWT's reliability, scalability, and efficiency, making it a promising sustainable energy solution for vehicular applications. Further optimization in blade design and energy storage integration could enhance performance across a broader range of wind speeds.

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