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DESIGN AND IMPLEMENTATION OF VEHICLE MOUNTED WIND TURBINE

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ABSTRACT

Vehicle Mounted Wind Turbine (VMWT) is a mounted horizontal axis wind turbine system for vehicles. This paper presents design and implementation of VMWT to generate electricity from vehicle. VMWT has several smart features including high rpm turbine, convenient weight, practical shape and portability. In addition, this paper evaluates the VMWT performance in terms of power generation. It is shown that, with proper designing, VMWT can generate approximately 200 W of power at vehicle speed of 80 km/hr. A number of design considerations have taken into account for designing VMWT to ensure its proper functionality in practical environment.

Keywords: vehicle turbine, renewable energy, wind energy, VMWT, electricity.

INTRODUCTION

Renewable energy sources offer limitless resource and environment friendly operation compared to conventional energy sources. There are several forms of renewable energy such as solar energy, wind energy, geothermal energy, tidal energy, hydro energy and bioenergy. However, wind energy is the most valuable, safe and fastest growing renewable energy. At the end of 2013, wind energy has served approximately 318.13 GW (GWEC, 2013) which is 12% of world demand (Frede, Zhe, Remus, and Florin, 2006). Moreover, it is low cost (0.12/kWh) (Ravi *et al*., 2009), low carbon footprints (< 5CO2/kWh), minimum sound pressure level (50-60 dB from 100 feet) and easy integration with other energy sources. However, commercial wind turbine (WT) is not suitable for small scale application as it requires big land, high installation cost, lack of energy storage and not portable. Additionally, in some places wind speed is not sufficient to run a commercial or domestic WT. Hence, a modified WT system is necessary which can be efficient under this kind of circumstances. Consequently, the idea of mobile WT for vehicle came along for small scale energy harvesting (Christian, 1975).

Several attempts are taken to produce electricity by vehicle as a number of literatures are already exists (Sham, 2011; Ferdous *et al*., 2011). However, these proposals never meet the threshold of the practical implementation. In most cases, these proposed models either too inefficient or directly affect the aesthetic appeal of the vehicles (Jean, 1983; Jose, 2013; Cecil, 2012; Andrew, 2013; Peter, 2013; Keith, 1979; Tran, 2011). Therefore, electricity harvesting from vehicle is still an active area to explore.

From these motivations, this paper proposes a modified, portable and distributed wind turbine system for vehicles. It is possible to increase the incoming wind speed for a mounted WT artificially by using the vehicle speed. Hence, a WT is mounted with vehicle to use the benefit of modified speed, thus it is called Vehicle Mounted Wind Turbine (VMWT). For the places where the wind speed is not considerable to run a stand alone wind turbine, VMWT can be a good solution for producing electricity as well. In addition, VMWT can be operated in domestic environment for small scale production.

This paper presents VMWT as a distributed renewable energy source. A horizontal axis wind turbine (HAWT) is used for VMWT. Previous literatures found on this projection have used vertical axis wind turbine (VAWT). Using VAWT to mount on a car is appealing but not beneficial in the context of efficiency. The collision area of VAWT is much smaller than the HAWT. Moreover, the size of VAWT can not be increased due to physical constraints of vehicles and it increases the weight, cost, and very little performance. Inversely, for a HAWT, with the same weight and cost, the collision area is increased with more swept area. This results increased torque and rotation, i.e. better performance.

The reminder of this paper is organized as follows, section 2 describes the conversion of wind energy to usable electrical energy. In section 3, the design of the proposed VMWT is discussed in detail. Section 4 carries out the hardware implementation process and Section 5 is dedicated for performance evaluation. Lastly, section 6 concludes this paper with some prospective future agendas.

CONVERSION OF WIND ENERGY

Wind energy is available in the form of kinetic energy which can be transformed to energy by mechanical conversion. As it is intended to use wind power to produce electrical power, hence the conversion is mainly from mechanical to electrical. Thus wind is the primary energy source. However, the availability of wind energy in this case is different from the conventional WT operation. Instead of a stall stand alone WT, now it is a moving one. Therefore, the availability of energy from this WT needs to be calculated for this particular circumstance.

Wind energy and power

The kinetic energy available in wind is given by,

$$KE = 0.5 \times \rho \times V^3 \times A \times T \qquad (1)$$

Where ρ is the density of the air, V is air velocity, A is the area of the air parcel and T is the time required for the air parcel to move through the plane. Now, wind power can be expressed as follows,

$$P_w = \frac{KE}{T} = 0.5 \times \rho \times V^3 \times A \qquad (2)$$

For the cross-sectional area (A), availability of wind power for air parcel,

$$P_w = 0.5 \times \rho \times V^3 \qquad (3)$$

Now, wind power density (WPD) can be stated as,

$$WPD = \frac{1}{2} \times \frac{1}{n} \times \sum_{j-1}^{a} P_j \times V_j^3 \qquad (4)$$

Here, n is the number of wind speed reading, P_j, V_j are the j[th] (1[st], 2[nd], 3[rd], etc.) readings of the air density and wind speed. Simplification of this gives,

$$WPD = \frac{1}{2} \times \sum_{j-1}^{n} \rho(median\ of\ V^3 in\ class\ j \times frequency\ of\ occurance\ class\ j) \qquad (5)$$

As the air density is not a variable then,

$$WPD = \frac{1}{2} \times \rho \times \sum_{j-1}^{n} \rho(median\ of\ V^3 in\ class\ j \times frequency\ of\ occurance\ class\ j) \qquad (6)$$

$$WPD = \frac{1}{2} \times K \times \rho \qquad (7)$$

Where K is a value determined by the shape of the distribution pattern that the wind speeds follow.

Aerodynamics of Wind Turbine blade

The aerodynamic profile helps us to find the behavior of the blades under the conditions of when air flow and forces applied by the air (Barnes, Morozov, and Shankar, 2015). It determines precisely the right way to design rotor blades for WT (Wei and Feng, 2010). Now the rotor design lies on Bernoulli's law (Christoph, 1993), which is,

$$Pressure + \frac{Kinetic\ Energy}{Volume} = Constant \qquad (8)$$

$$P + \frac{1}{2}\rho V^2 + pgh = Constant \qquad (9)$$

where P is the static pressure (in N/m^2), ρ is the fluid density (in kg/m^3), V is the velocity of fluid flow (in m/s), h is elevation and g is the gravitational acceleration. Equation (6) leads to the maximum point of stress for WT and is called dynamic pressure equation. Equation (5) and (6) deals with the basic aerodynamics of the WT rotor. Nevertheless, drag and lift force, tip speed ratio & solidity and Betz limit directly affect the aerodynamic performance of WT rotor.

Drag force and lift force: Lift force is considered as the force that works as perpendicular to the direction of motion. Lift force is very essential for a WT and should be as strong as possible. Lift force can be found as,

$$d_L = \frac{1}{2} \times C_L \times \rho \times W^2 \times c \times dr \qquad (10)$$

Where d_L is called lift force and C_L is the coefficient. Drag force works as parallel to the direction of motion, inversely to the lift force. For a VAWT it is useful to note that,

$$d_d = \frac{1}{2} \times C_D \times \rho \times W^2 \times c \times dr \qquad (11)$$

Where d_D is the drag force and C_D is the coefficient of it. For both equations 10 and 11, ρ is Air density, W relative air speed, c is blade cord length, r blade radius. The experimental improvement shows that, with angle of attack of 10-15 degrees, the lift coefficient is found as highest and drag force within tolerable limit (Karthikeyan *et al*., 2015).

Tip speed ratio and solidity: Tip Speed Ratio (TSR) is one of the important factors in WT design. TSR refers to the ratio between wind speed and speed of the tips of the WT blades. TSR maximizes power output and efficiency of WT.

$$TSR, \lambda = \frac{Tip\ speed\ of\ blade}{Wind\ speed} \quad (12)$$

Solidity is the ratio of total rotor platform area to total swept area and can be stated as follows,

$$Solidity = \frac{3a}{A} \quad (13)$$

where a is total rotor platform area and A is total swept area.

Betz limit: All the energy from the moving airfoil fall on the blades cannot be transformed to mechanical power. The theoretical maximum power efficiency of any design of WT is 0.59 (i.e. not more than 59% of the energy carried by the wind can be extracted by a WT) (Martin, 2013). Hence, this factor needs to be addressed properly during the designing of the WT.

Electrical output from Rotor blades

The Blade Element Momentum (BEM) theory explains the factors related to the control of rotor blades rotating (Muller, Deicke, and Doncker, 2002). For better understanding, let us consider an object of mass M with velocity V . Hence, the kinetic energy is given by,

$$KE = \frac{1}{2} \times M \times V^2 \quad (14)$$

Where the unit of K.E. is in Joules. Again the power in the swept area of turbine rotor (Jamal, Venkata, and Andrew, 2007),

$$P = \frac{1}{2} \times \rho \times A \times V^3 \quad (15)$$

$$P = \frac{1}{2} \times \rho \times A \times V^3 \times C_p \times N_g \times N_b \quad (16)$$

Equation 16 demonstrates total power extracted by WT from wind (Martin, 2013), where P is power in watts, ρ is air density (kg/m^3), A is rotor swept area exposed to the wind (m^2), V is wind speed in m/s, C_p is coefficient of performance, N_g is defined as the efficiency of gearbox and N_b for efficiency of bearings.

SYSTEM DESIGN

The designing of VMWT need careful considerations. VMWT has the basic configuration of a HAWT. However, the field of application makes it different from conventional HAWT. VMWT has some additional design criteria over conventional HAWT. Namely, rotor, generator, gear box (optional) and storage system designs are different. Moreover, VMWT has to be light weight, high RPM, highly rigid, low cost unlike conventional designs. Hence, the VMWT has to be designed carefully to compromise with these aspects. The principle of this work is presented in figure 1. As the Figure-1 illustrates, a wind turbine is mounted on a running vehicle and an airfoil is coming through opposite direction. The direction of the airfoil can either be natural or artificially directed to the rotor. They collide and make a resultant force in a modified direction. This event follows the Bernoulli's Law (Grant, 2005).

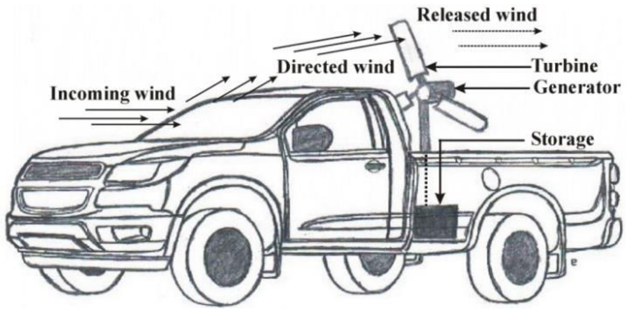

Figure-1. The VMWT system.

A generator is placed on roof of the vehicle and coupled with turbine shaft by a belt. Generator and turbine shaft are connected in parallel and belt is vertically coupled with two shafts. The output terminal of the generator is connected to a storage device (in this case battery). When the vehicle is in motion, the turbine rotates with a significant rpm and produces mechanical torque (i.e. mechanical input) to generator which produces electrical output and stored in the battery for the future use.

Additionally, the turbine blades efficiency with respect to the air force and vehicle speed is taken into account. Figure-2 represents the working principle of a WT blade. When two objects collide with each other in opposite direction, they produce a resultant force which can be stated as follows (Carol and John, 2001);

$$V_1' = V_1 \frac{\sqrt{m_1^2 + m_2^2 + 2m_1m_2 + \cos\theta}}{m_1 + m_2} \quad (17)$$

Where V_1' is the speed after collision for first object, V_1 is speed before collision for first object, m_1 is the mass for first object, m_2 is mass for second object, θ is the angle of deflection. Here, VMWT (including vehicle) is considered as first object and wind as second object.

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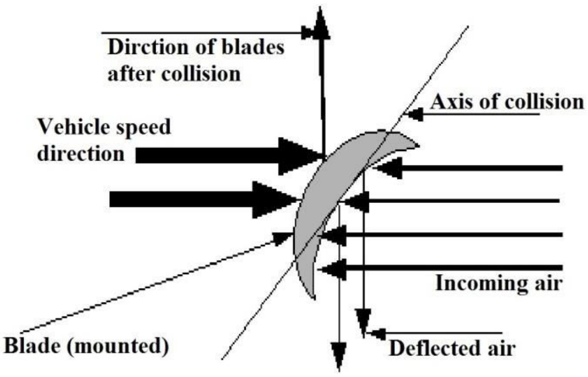

Figure-2. Working principle of a wind turbine blade.

HARDWARE IMPLEMENTATION

Practical implementation of VMWT is the crucial part of this work. The components are used for the implementation are given bellow,

Blades

The criteria for designing the blades is to provide high RPM, moderate torque, high tolerance and light weight. Hence, twisted blade is the first choice. However, twisted blades possess high cost. Therefore, modified half twisted blades are used to meet the requirements.

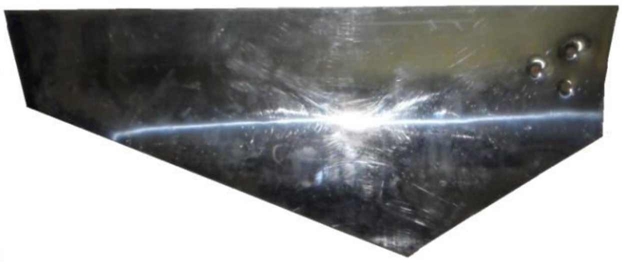

Figure-3. Blade of wind turbine (1 of 4).

All blades are made from a sheet of stainless steel (0.6 m × 3 m) to construct 3 blades. Each blade is 0.45 m long, 0.18 m wide and weight about 1 kg, i.e. 3 blades weigh about 3 kg. Figure-3 depicted the blades of VMWT and table I describes the physical details.

Belts

Two belts are used to couple the generator and turbine (made of shielded rubber). The belts attach the generator and turbine together. In this experiment, no gearbox used. However, a gearbox can be attached for the increment turbine rotation.

Turbine

Blades are assembled to construct the turbine of VMWT. A disc of 0.3 m diameter is used to assemble the blades (designed for six blades). Various kind of screwier and a 0.3 m long metal pipe have used to connect the disc with generator. Figure-3 shows the assembled WT. According to the design considerations, three blades design gives better performance than that of six blades, hence three blades are used. Table-1 summarizes turbine details.

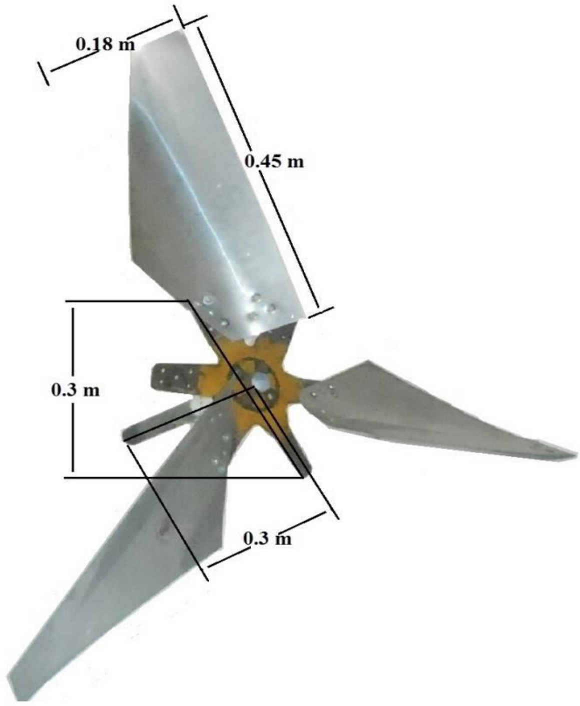

Figure-4. Turbine of VMWT.

Generator

A WTs mechanical output can vary a lot, from 0 to maximum based on maximum power point tracking (MPPT) method. Therefore, the choice of the generator is to be very careful. Hence, a permanent magnet DC (PMDC) motor as generator is the best choice to capture the output of turbine. This type of generator is very sensitive to rotation and able to give feedback at very low mechanical input. Figure-4 shows the used generator where Table-1 presents the rating. Assembled VMWT system is mounted on the roof of a vehicle as a HAWT fashion. For safety, the turbine needs to be covered by metal mesh on back side.

Figure-5. VMWT generator.

Vehicle

For VMWT the best choice is the Van or Truck type vehicle. They are suitable for their supporting shape which can provide a good amount of wind speed by reflecting air on wind shield. For the experiment a pickup truck of 150 horsepower engine is used. The wind turbine was mounted with the back of the vehicle. An attach mechanism was used to make the system stable under the active wind.

Table-1. Description of equipment.

Generator	Blades	Turbine
Model: HN1010B Input: 180V/5A RPM: 4000 Mechanical O/p: 2 hp Type: PMDC Efficiency: 60.35%	Length: 0.45 m Width: 0.18 m Weight: 1 kg (each) Total blades: 3 Orientation: Central	Swept area: 1 m Length: 0.45 m Weight: 6 kg (without generator) Type: HAWT Tail: No

RESULTS

The results in this work are collected through practical road test. Four cases depicted in Table-2 are considered for this experiment. From Table-2 it is clear that for case 1, 2 and 3, the power is insufficient to mention as either vehicle is stopped or air speed is too low. However, for case 4, both vehicle and air speed are in functioning mode. Hence, case 4 is the active case for VMWT. Therefore, for the experimental setup and data collection, case 4 is considered only.

Table-2. Vehicle speed and power.

Cases	Vehicle	Wind speed	Power status	Mode
Case 1	Stopped	≈ 0	≈ 0 (Negligible power)	Inactive
Case 2	Stopped	$\neq 0$	P (Negligible power)	Inactive
Case 3	Moving	≈ 0	P (Negligible power)	Inactive
Case 4	Moving	$\neq 0$	P (Maximum power)	Active

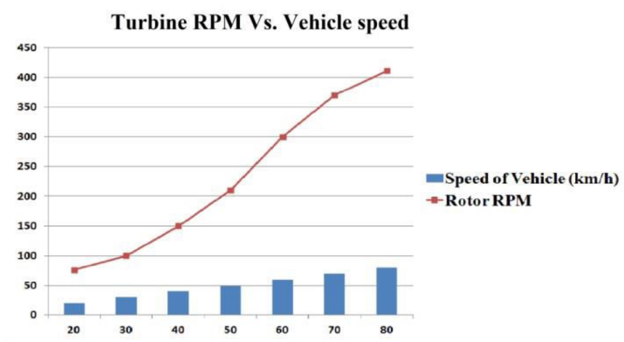

Figure-6. Turbine RPM Vs. Vehicle speed.

A WTs output power depends on several factors expressed as (Martin, 2013),

$$P = \frac{1}{2} \times \rho \times A \times V^3 \times C_p \times N_g \times N_b$$

Here, considered *ρ= 1.16 kg/m3* (experiment place), $A = 0.66\ m^2$, $V = 16\ m/s$, $C_p = 0.45$, $Ng = 0.604$, $Nb = 0.9$. These data were collected during the experiment which gives output of 383.55W of electricity. But practically the captured output is *150W-200W*. Results are recorded based on four considerations to measure, rotation of turbine, vehicle speed, produced torque & wind force and generated power. Rotor speed can be as high as above *400 rpm* when the vehicles speed of *80 km/hr*.

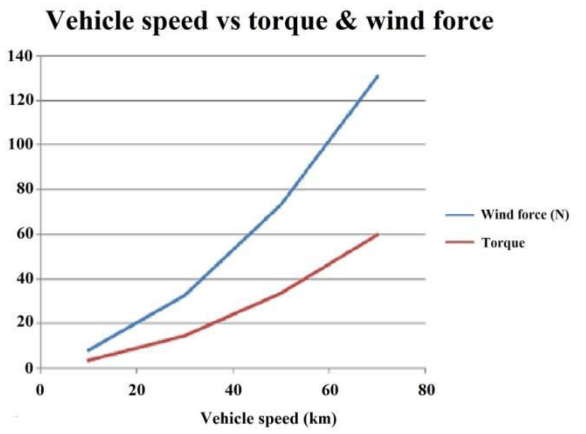

Figure-7. Vehicle speed vs. produced torque and wind force.

Variation in torque and wind force respect to the vehicle speed is listed in Figure-6. From figure it is clear that, torque and wind force depend on vehicle speed in principle. Higher vehicle speed produce high torque due to increased wind force which conclude increased power. Figure-7 illustrates the effect of vehicle speed on produced power. From figure it is evident that, produced power increases with vehicle speed.

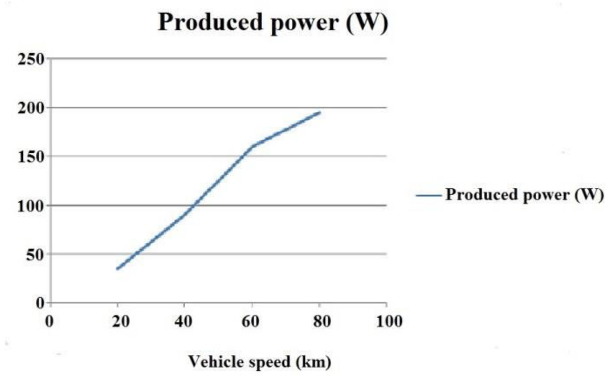

Figure-8. Produced power (w) vs. vehicle speed.

Figure-5 illustrates the variation of rotor rpm respect to vehicle speed. The fluctuations of the data due to vehicle speed are removed from results. It is well evident that, torque increases in respect to the increment of the vehicle speed.

The experiment was held through a public road. Hence, the vehicle speed for this experiment was limited to max 80 km/hr due to the public safety. Nevertheless, test can be done with higher speed by ensuring proper safety issue.

Public safety

Most of the vehicle whether commercial or private run through the residential area and public way, so a VMWT will be very closer to public exposure and be a sensitive issue for public safety. Usually for commercial WT system the total area is a restricted area for unauthorized person, however it is not possible for the VMWT. It is recommended to add a protecting case for the WT, it will increase the strength and protection. The case should cover the back side of the WT and should be opened in front side for the incoming wind. Technically, the case should be styled as mesh so that it can possess a lot of gaps to release the deflected air and stabilize the system from falling down. Moreover, sometimes sudden gust can come through the way. Hence, to control this situation an emergency manual break should be attached with the vehicle.

Converter for storage

The mechanical input of the system is not constant, it depends on the vehicle speed and wind speed. As both of the speeds vary, especially vehicle speed varies a lot depending on the traffic and surroundings, power generation will fluctuate as well. Therefore, a small, light weight and low cost converter is required to regulate output voltage level compatible with the storage. Therefore, a simple topology can be a best choice. A buck-boost DC-DC converter is recommended for regulated output (Rizzoli *et al*., 2014; Camara *et al*., 2010; Sivaprasad, Jijo, Kumaravel, and Ashok, 2015). Table-3 shows some DC-DC converter topologies for small scale operations (Robert, 1999).

Table-3. Several DC-DC converter topologies.

	Power range 1	**Power range 2**	**Power range 3**	**Power range 4**
Converter topology	0-100W/<5A	0-100W/>5A	200-400W	400-1200W
Single switch Flyback	√			
Double switch Flyback	√			
Single switch Forward	√	√		
Double switch Forward	√	√	√	
Half bridge			√	√
Full bridge				√

As the output of generator provide us V_{max} of 100V, I_{max} of 2A whether V_{min} is 0V, and power is varying within 0-200W. So it will be convenient to design a converter that is capable to provide,

- V_{out} of 12V
- I_{out} of 5A
- P_{out} of 60W

And this criteria of converter gives,

- Converter should be step-down converter
- Transformerless converter to reduce the cost and weight

CONCLUSIONS

A convenient system for energy harvesting with vehicle is proposed in this paper called vehicle mounted wind turbine (VMWT). The architecture and design of VMWT have been discussed in detail. It is shown that, VMWT possesses several attractive features including increased rpm and torque compared to conventional mounted WTs, along with light weight, small size, convenient and portable architecture. Moreover, VMWT has cheap installation cost and nearly zero maintenance cost. From experiment it is marked that, by VMWT upto 200 W of electricity is acquirable from a single vehicle (< 80 km/hr). With proper conversion technology, this power can be stored easily for future use. Nevertheless, some drag force is originated evidently. Hence, it is recommended to follow the Betz limit of efficiency properly. In conclusion, with proper design step VMWT can be an efficient source of small scale electricity for domestic and portable purposes. In this work VMWT is used to harvest wind energy only. However, a hybrid energy harvesting system for vehicle is our future agenda.

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