Generation of Electrical Power by a Wind Turbine for Charging Moving Electric Cars

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Abstract
This research targets the design of a wind turbine that will be mounted on the electric car to generate electrical power to charge the car batteries when in motion. The turbine is positioned on the roof of the car near the wind screen, where the velocity of air flowing around the car is highest due to its aerodynamic nature. A portable horizontal axis diffuser augmented wind turbine is adopted for the design since that is able to produce a higher power output as compared to the conventional bare type wind turbine. The air current is generated by the car when it begins to move. A frame is provided on the roof of the car to serve as a support for the turbine. Through the theoretical calculation on the power generated from the wind, a significant amount of electrical power (about 3.26 kW) is restored to the batteries when the car is moving at a speed of 120 km/h.

Keywords: Wind Turbine, Diffuser, Power, Electric Car, Batteries.

1. Introduction

1.1 History of Electric Cars

The electric vehicle has been around for over 100 years, and it has an interesting history of development that continues to the present. France and England were the first nations to develop the electric vehicle in the late 1800s. It was not until 1895 that Americans began to devote attention to electric vehicles. Many innovations followed and interest in motor vehicles increased greatly in the late 1890s and early 1900s. In 1897 the first commercial application was established as a fleet of New York City taxis. The early electric vehicles, such as the 1902 Wood's Phaeton (Fig.1), were little more than electrified horseless carriages and surreys (Anon., 2013a). Since the invention of electric car, it has been developed till date. Despite this fact, the major challenge which is their short driving range still exists.

Fig. 1 1902 Wood's Electric Phaeto
(Source: Anon., 2013a)

Fig. 2 Typical 2011 Model of Electric Car
(Source: Anon., 2011)

1.2 Major Components in an Electric Car Driving System

Electric vehicle driving system is made up of three main parts; namely, the motor, the controller and the battery.

1.2.1 Electric motor

The motor (Fig. 3) is the most important part of the vehicle; it is the part responsible for the propelling of the car. There are three different types of electric motors; these include, DC wound, Permanent magnet DC and AC motor (Altaf, 2010).

1.2.2 Battery

The number two major component of electric car parts is the battery (Fig. 4). While some cars would use the standard car batteries as a source of energy, the more advanced ones use the Li-ion batteries as more efficient energy source that gives extra range of operation for the vehicle. They require less time to be charged and provide more energy for the motor attached (Altaf, 2010).

1.2.3 Controller

The third part of the electric car parts is the controller (Fig. 5). This part is responsible for power management; it senses the amount of energy needed by the motor and supplies it directly from the batteries in order to get the car moving. The controller is very important because it synchronizes the operation of both the motor and the battery (Altaf, 2010).

1.3 Electric Car Charging

Electric car chargers are responsible for charging the battery pack in an electric car. These chargers are installed in homes, offices, shopping stores and public places to enable one to charge his/her car. Fully charging an electric car can take 6 – 8 hours.

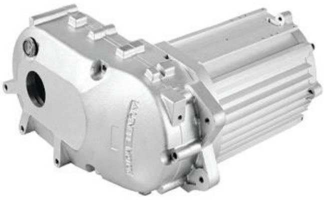

Fig. 3 Electric Car Motor
(Source: Anon., 2013b)

Fig.4 LiFePO4 Battery Pack (24 V-300 AH)
(Source: Anon., 2013c)

Fig. 5 Electric Car Controller
(Source: Anon., 2013d)

Fig. 6 On-street Electric Car Charging Station
(Source: Anon., 2010)

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1.4 Velocity Distribution Around a Moving Car

Fig. 7 shows a simulation conducted by Hu and Wong (2011), which reveals that the velocity distribution of air around a moving car is highest at the top of the roof. This helps to position the turbine at the point where the highest air velocity can be realised.

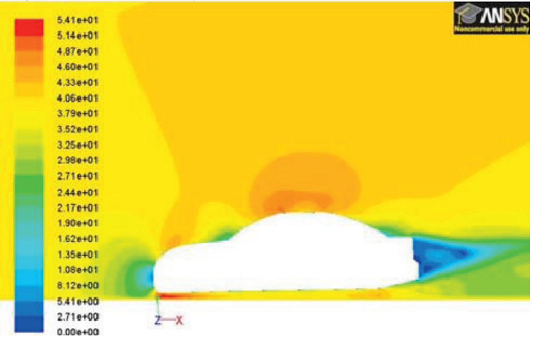


Fig. 7 Distribution of Velocity on the Symmetric Plane of a Typical Car
(Source: Hu and Wong, 2011)

1.5 Wind Turbines

A wind turbine is a device that converts kinetic energy from the wind into mechanical energy. If the mechanical energy is used to produce electricity, the device is called a wind generator. If the mechanical energy is used to drive machinery, such as for grinding grain or pumping water, the device is called a windmill or wind pump. The smallest turbines are used for applications such as battery charging or auxiliary power on sailing boats, while large grid-connected turbines are becoming large sources of commercial electric power. Wind turbines can be put into two basic categories: namely, vertical axis and horizontal axis wind turbines.

1.5.1 Vertical Axis Wind Turbine

The vertical axis wind turbine has its blades rotating on an axis perpendicular to the ground. Examples of this type of turbine are the Darrieus (Fig. 8) and the Savonius wind turbines (Fig. 9).

Fig. 8 Darrieus Wind Turbine
(Source: Anon., 2006)

Fig. 9 Savonius Wind Turbine
(Source: Anon., 2012

1.5.2 Horizontal Axis Wind Turbine

The horizontal axis machine has its blades rotating on an axis parallel to the ground. This type of turbine has the main rotor shaft and electrical generator at the top of a tower and must be pointed into the wind. Small turbines are pointed by a simple wind vane, whiles large turbines generally use a wind sensor coupled with a servo motor.

Fig.10 Danish Wind Turbine
(Source: Anon., 2006)

Fig.11Diffuser Augmented Wind Turbine
(Source: Yuji and Takashi, 2010)

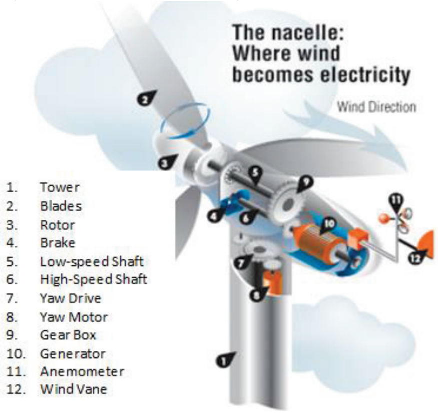


Fig.12 Details of Horizontal Axis Wind Turbine
Source: (Alexander, 2008)

1.5.3 Main Parts of a Wind Turbine

There are three major components that made up a wind turbine. These include, the rotor, the generator and the tower.

1.5.3.1 Rotor

The portion of the wind turbine that collects energy from the wind is called the rotor. Therotor usually consists of two or more wooden, fiberglass or metal blades which rotateabout an axis (horizontal or vertical) at a rate determined by the wind speed and the shapeof the blades. The blades are attached to the hub, which in turn is attached to the mainshaft (Anon., 2013e).

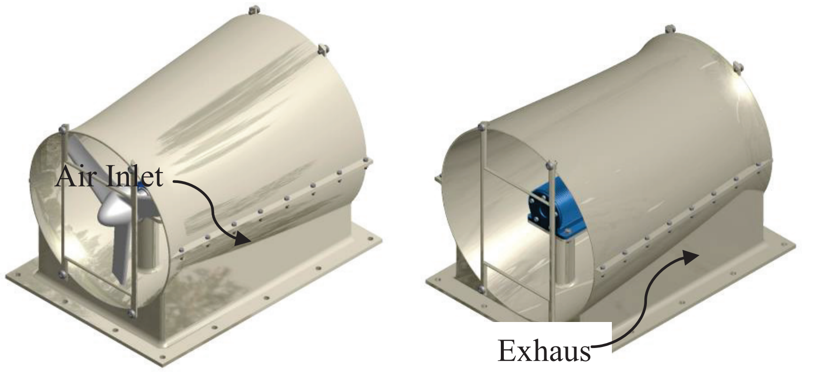
1.5.3.2 Generator

This part is what converts the turning motion of a wind turbine's blades into electricity. Inside this component, coils of wire are rotated in a magnetic field to produce electricity. Different generator designs produce either alternating current (AC) or direct current (DC), and they are available in a large range of output power ratings. The generator's rating, or size, is dependent on the length of the wind turbine's blades because more energy is captured by longer blades (Anon., 2013e).

1.5.3.3 Tower

The tower on which a wind turbine is mounted is not just a support structure. It also raises the wind turbine so that its blades safely clear the ground and so it can reach the stronger winds at higher elevations. Maximum tower height is optional in most cases, except where zoning restrictions apply. The decision of what height tower to use will be based on the cost of taller towers versus the value of the increase in energy production resulting from their use. Studies have shown that the added cost of increasing tower height is often justified by the added power generated from the stronger winds. Larger wind turbines are usually mounted on towers ranging from 40 to 70 meters tall (Anon., 2013e).

2. Proposed Design of the Wind Turbine



(a) (b)

Fig.13 Isometric Views of the Wind Turbine

The assembled turbine, Fig. 13 is fastened to a frame-like structure provided on the roof of the vehicle as shown in Fig. 14 by a set of bolts with the inlet facing the front of the vehicle. The shrouded diffuser augmented wind turbine is chosen for the design since that is the most efficient wind turbine.

Fig.14The Wind Turbine on a Model of Electric Car

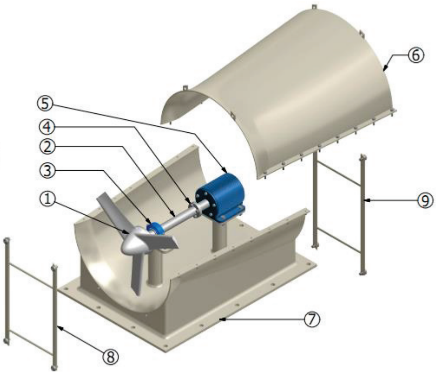


Fig. 15 Exploded View of the Wind Turbine showing the Main Parts

The main components of the proposed design are the rotor, main shaft, main bearing coupling, generator, top shroud, base shroud, inlet safety guard, exhaust safety guard. The rotor (1) is coupled to the main shaft (2) by a set of four hexagonal head bolts. The main shaft (3) and the generator (5) are fastened to the supports on the base shroud (6) by a set of hexagonal head bolts.

2.1 Rotor

The rotor (Fig. 16) collects the kinetic energy from the wind and converts it to rotational motion. The rotor consists of three blades and a hub made of fiber glass which rotates about an axis (horizontal) at a rate determined by the wind speed.

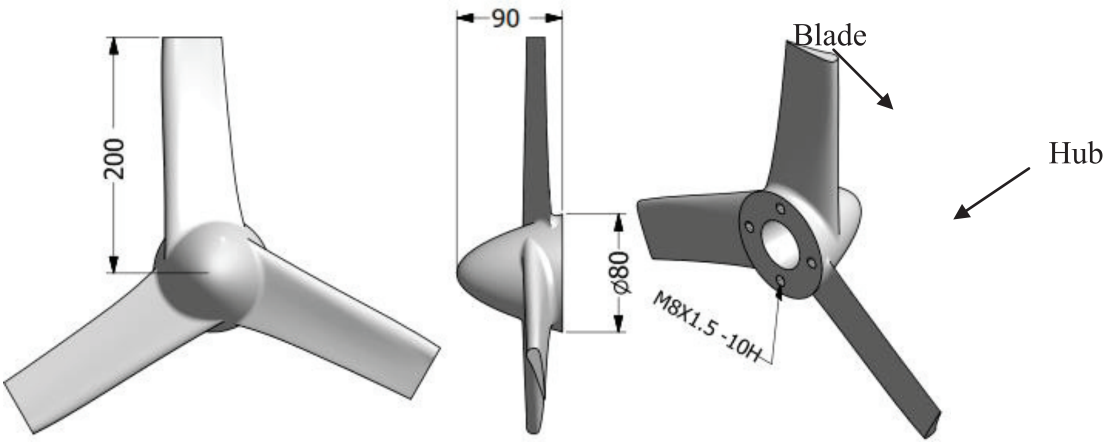


Fig. 16 Rotor (All Dimensions are in mm)

2.2 Main Shaft

The main shaft, Fig. 17, transmits the rotational energy of the rotor to the generator with the help of the main bearing (Fig. 19). In addition to the aerodynamic loads from the rotor, the main shaft is exposed to gravitational loads and reactions from the main bearings and the generator shaft. The purpose of the threaded end of the main shaft is to help detached the coupling during assembling of the main bearing on to the shaft. The material selected for the shaft design is SAE 1006 HR (carbon steel).

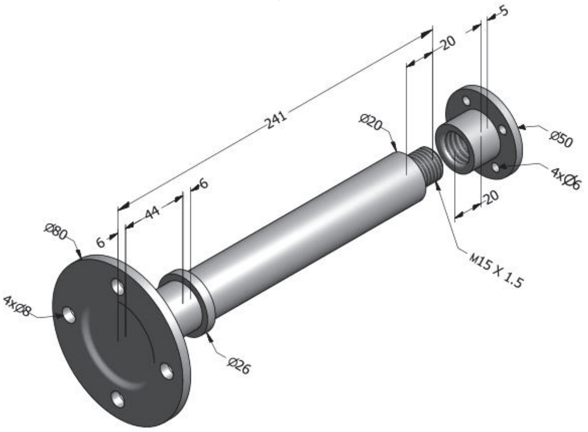


Fig. 17 Main Shaft with Coupling
(All Dimensions are in mm)

Fig. 18 Alternator

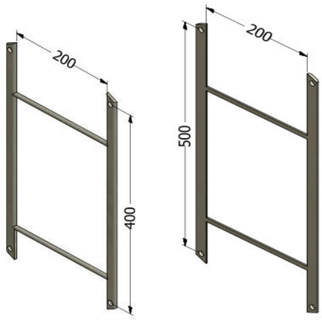
4.3 Generator

A high speed brushless alternator is used for the design. This is because; it has fewer moving parts. There is therefore less wear, and hence longer life span.

2.4 Main Bearing

The main bearing supports the main shaft and transmits the reactions from the rotor loads to the supports on the shroud. On account of the relatively large thrust (axial) and radial loads in the main shaft and the high speed involved, the spherical roller bearing is often used, see Fig. 19.Spherical roller bearings have two rows of rollers with a common sphere raceway in the outer ring. The two inner ring raceways are inclined at an angel to the bearing axis. The bearings are self-aligning and consequently insensitive to errors in respect of alignment of the shaft relative to the housing and to shaft bending. The material used is AISI 52100 steel because it is very hard and hence has the ability to withstand wear.

Fig. 19 Spherical Roller Bearing
(Source: Anon., 2013f)



(a) (b)
Fig. 20 Safety Guards (All Dimensions are in mm)

2.5 Safety Guards

The purpose of the inlet (Fig. 20a) and exhaust (Fig. 20b) safety guards is to prevent the rotor from coming out of the shroud in case it removes. They are made of aluminium.

2.6 Shroud

Researches have proved that the diffuser augmented wind turbine is the most efficient wind turbine. The wind enters the diffuser shroud (Fig. 21) at the inlet to the turbine, getting to the exit of the turbine there is a pressure drop which creates a partial vacuum that sucks more air into the turbine, thereby increasing the amount of wind flowing through the turbine blade and hence the output power is increased. In addition to the power augmentation, the shroud helps in protecting the turbine blade, the main shaft, the main bearing and the generator from external harsh conditions like rain fall and sun shine. The base of the shroud serves as the main support of the inner components of the turbine. The material for the shroud is aluminium alloy because of its high strength and light weight.

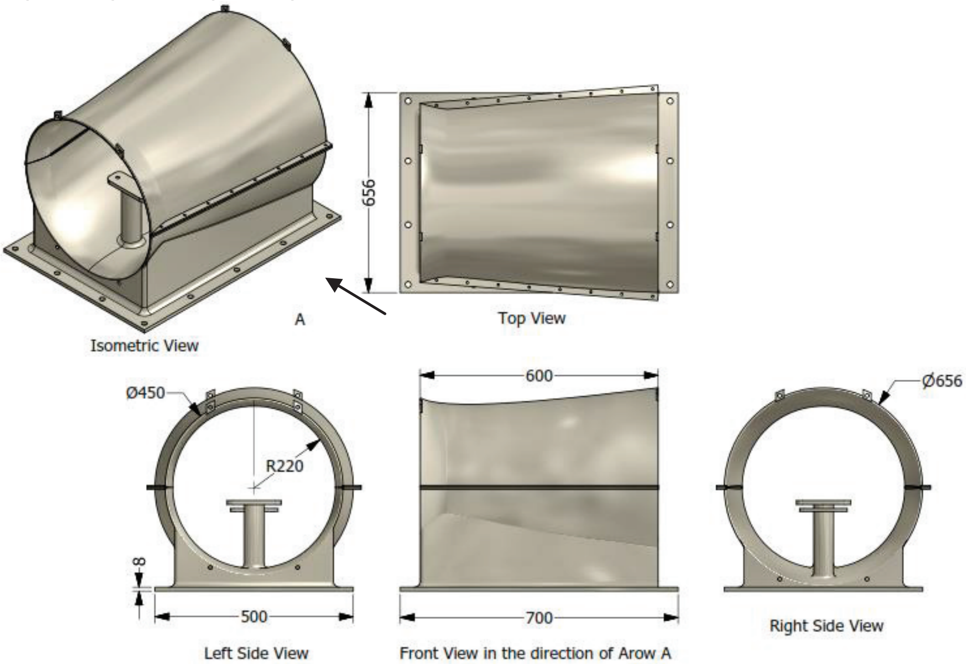


Fig. 21 A Third Angle Orthographic Projections of the Diffuser
(All Dimensions are in mm)

2.7 Principle of Operation

When the vehicle starts moving, it displaces the air which is directly in front of it. This causes the surrounding air to flow relative to the moving vehicle in a direction opposite to that of the vehicle. The opposing air stream directly in front of the turbine passes through the turbine blades thereby providing a torque which rotates the rotor. The rotational energy of the rotor is then transferred to the generator through the main shaft. The generator is electrically connected to the charging system of the vehicle. The batteries are therefore charged continually, while the vehicle is moving.

3. Design calculations

3.1 Diffuser Design

A research conducted by Phillips (2006) reveals that an augmentation of 1.38 is achievable by a diffuser of Exit-Area-Ratio (EAR) of 2.22 and an overall length to diameter meter (L/D) of 0.35. These values are used for the diffuser design.

$$\mathrm{EAR} = \frac{A_e}{A_i} \tag{1}$$

where, $A_e\left(=\frac{\pi D_e^2}{4}\right)$ and $A_i\left(=\frac{\pi D_i^2}{4}\right)$ are the exit and inlet areas of the diffuser respectively.

With a diffuser inlet diameter (Di) of 0.44 m;

$$A_i = \frac{\pi \times 0.44^2}{4} = 0.15205\ \mathrm{m}^2$$

From equation (4.1),

$$A_e = A_i \times \mathrm{EAR} = 0.15205 \times 2.22 = 0.33756\ \mathrm{m}^2$$

From above, the exit diameter (De) of the diffuser is:

$$D_e = \sqrt{\frac{4A_e}{\pi}} = \sqrt{\frac{4 \times 0.33756}{\pi}} = 0.656\ \mathrm{m}$$

The diffuser is therefore having an inlet and outlet diameters of 440 mm and 656 mm respectively. The length of the diffuser is taken to be 600 mm for it to cover the whole span of the turbine.

4.2 Power Calculation

It is assumed that the velocity of the natural wind is zero (still air), and hence the velocity of the air current flowing around the moving vehicle is equal to the vehicle's velocity. Also, the density of air is assumed to be $1.225\ \mathrm{kg/m^3}$ (the standard atmospheric value).

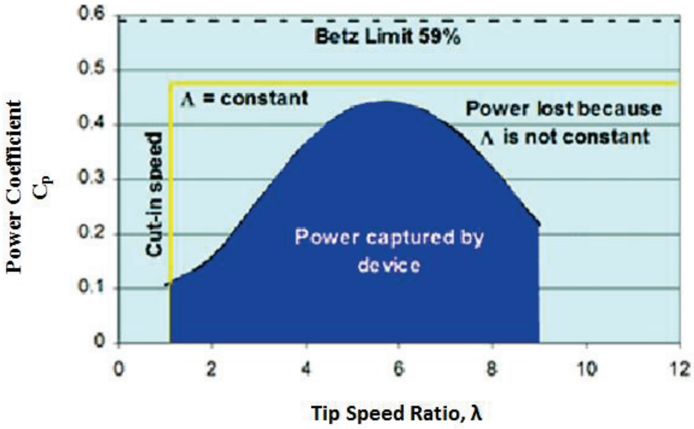


Fig. 4.1 Graph of Tip Speed Ratio against Power Coefficient
(Source: Anon., 2007)

The maximum tip speed ratio is given by:

$$\lambda = \frac{4\pi}{B} \tag{2}$$

where B $(= 3)$ is the number of blades.

$$\lambda = \frac{4\pi}{3} = 4.189$$

From the graph (Fig. 4.2) above, $\lambda = 4.189$ corresponds to a power coefficient:

$$C_p \cong 0.38$$

With an augmentation of 1.38, $C_{p_s} = 0.38 + 1.38 = 1.76$, where C_{Ps} is the shaft power coefficient.

Kinetic Energy $(KE) = \frac{1}{2}\dot{m}V^2$, Mass flow rate $(\dot{m}) = \rho AV$, $KE = \frac{1}{2}\rho AV^3$

Wind Power $(P_w) = KE, P_w = \frac{1}{2}\rho AV^3$,

$$P_s = \frac{1}{2} C_{p_s} \rho AV^3 \tag{3}$$

where, P_s = shaft power.

ρ = density of air, A = swept area of the rotor blades, Cp = power coefficient, V = air velocity.

$$A = \frac{\pi d^2}{4} \tag{4}$$

With a rotor diameter (d) of 0.4 m: $A = \frac{\pi \times .4^2}{4} = 0.12566\ \mathrm{m}^2$

For design sake, a car speed of 120 km/h (33.33 m/s) is assumed.

$$\Rightarrow P_s = \frac{1}{2} \times 1.76 \times 1.225 \times 0.12566 \times 33.33^3 = 4.071\ \text{kW}$$

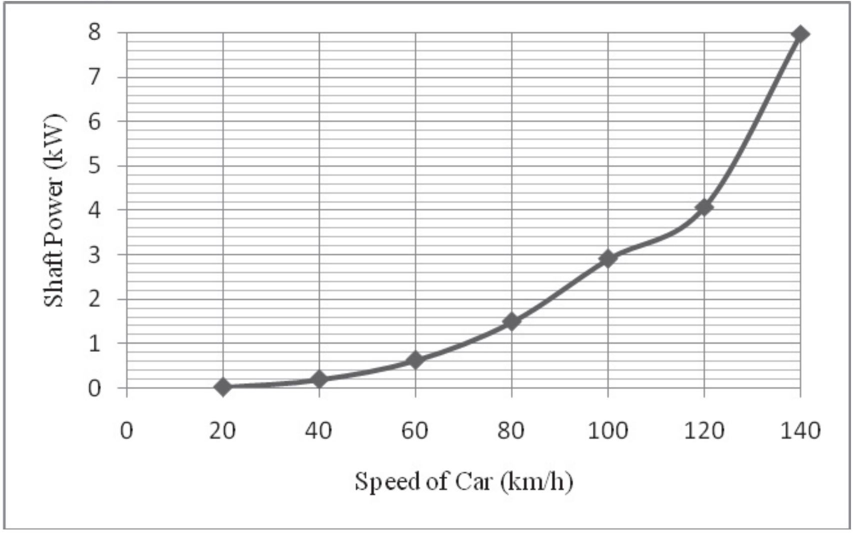


Fig. 4.2 Graph of Speed of Car against Shaft Power

3.2 Torque on Rotor

$$P_s = T\omega \Rightarrow T = \frac{P_s}{\omega} \tag{5}$$

where, T and ω are the torque and the angular velocity of the rotor respectively.

$$\omega = \frac{\lambda V}{R} \tag{6}$$

where, R = the blade length.

$$\Rightarrow \omega = \frac{4.189 \times 33.33}{0.2} = 698.1\ \text{rad/s}, \qquad \therefore T = \frac{4.071 \times 10^3}{698.1} = 5.832\ \text{Nm}$$

3.3 Rotor Design

3.3.1 Rotor Solidity

Solidity (S) is the ratio of the rotor projected area perpendicular to the flow to the rotor swept area (A). Low solidity, $(S = 0.10)$ produces high speed and low torque and high solidity, $(S > 0.8)$ produces low speed and high torque.

$$S = \frac{\text{Rotor Projected Area}}{A} \tag{7}$$

The rotor projected area, measured in Autodesk Inventor is 0.033 m2.

$$S = \frac{0.033}{0.12566} = 0.263$$

4.3.2 Blade Calculation

$$\emptyset = \tan^{-1}\left(\frac{\pi R N}{V}\right) \tag{8}$$

where, $\emptyset$ and N are the blade angle of twist and rotational speed of the rotor respectively.

$$N = \frac{60\lambda V}{2\pi R} = \frac{60 \times 4.189 \times 33.33}{2\pi \times 0.2} = 6666\ \text{rpm} \tag{9}$$

From equation (4.10): $\emptyset = \tan^{-1}\left(\frac{\pi \times 0.2 \times 6666}{33.33}\right) = 89.5\,^{\circ}$

$$\text{Lift force, } F_L = \frac{1}{2} C_L \rho V^2 A_t \tag{10}$$

$$\text{Drug force, } F_D = \frac{1}{2} C_D \rho V^2 A_t \tag{11}$$

where, A_t, C_L and C_D are the blade surface area, coefficients of lift and coefficient drug respectively.

The blade surface area, measured in Autodesk Inventor is; $A_t = 0.019738\ \text{m}^2$

From a designfoil workshop DEMO program, using altitude $= 1.58$ m, angle of attack, $\alpha = 15\,^{\circ}$, and a wind speed of 33.33 m/s yielded;

Renolds number $= 695375$, Mach number $= 0.0979$, $C_L = 2.034$, $C_D = 0.0297$

$$F_L = \frac{1}{2} \times 2.034 \times 1.225 \times 33.33^2 \times 0.019738 = 27.317\ \text{N}$$

$$F_D = \frac{1}{2} \times 0.0297 \times 1.225 \times 33.33^2 \times 0.019738 = 0.399\ \text{N}$$

$$F = F_L \cos(90 - \emptyset) - F_D \sin(90 - \emptyset) \tag{12}$$

where, F = thrust on each blade.

$F = 27.317 \times \cos(90 - 89.5) - 0.399 \times \sin(90 - 89.5) = 27.31$ N

The total thrust on the three blades, $F_T = 27.31 \times 3 = 81.93$ N

3.4 Main Shaft Design

The main loadings on the main shaft are the torque on the rotor, and the weight of the rotor blades and hob. SAE 1006 CD (carbon steel) with an ultimate tensile strength (Sut)of 330 MPa is chosen for the shaft design.

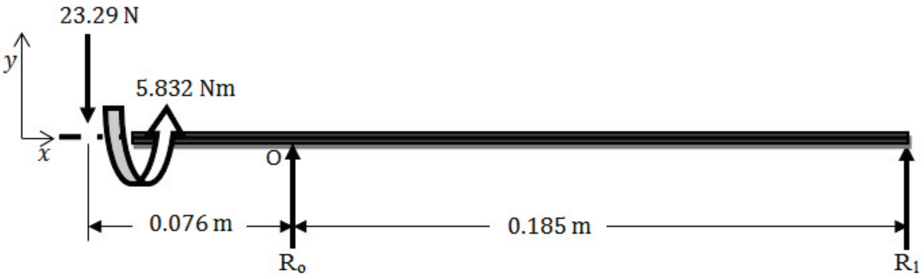


Fig. 4.3 Free-body Diagram of the Main Shaft

Fig. 4.3 shows the Free-body Diagram of the Main Shaft. R1 and R2 are the respective reactions at the bearing and generator supports.

By summing all vertical forces and taking moment about point o:

$$\sum F_y = 0, \Rightarrow R_1 + R_2 = 23.29, \tag{13}$$

$$\sum M_o = 0 \Rightarrow 23.29 \times 0.076 + R_2 \times 0.185 = 0$$

$\Rightarrow R_2 = -9.568$ N

Substituting $R_2 (= -9.568 \text{ N})$ into equation (4.15) above:

$R_1 = 32.858$ N

By using singularity functions:

$$q = -23.29\langle x\rangle^{-1} + 32.858\langle x - a\rangle^{-1} - 9.568\langle x - a\rangle^{-1} \tag{14}$$

$$V = -23.29\langle x\rangle^{0} + 32.858\langle x - 0.076\rangle^{0} - 9.568\langle x - 0.261\rangle^{0} \tag{15}$$

$$M = -23.29\langle x\rangle^{1} + 32.858\langle x - 0.076\rangle^{1} - 9.568\langle x - 0.261\rangle^{1} \tag{16}$$

where, x is the length of the main shaft. q, V, and M are the load, shear force and bending moment at distance a on the shaft respectively.

Table 1 Shear Forces (V) and Bending Moments (M) at Distances (a)

a (m)	0	0.076	0.261
V (N)	-23.29	9.568	---
M (Nm)	0	-1.77	0

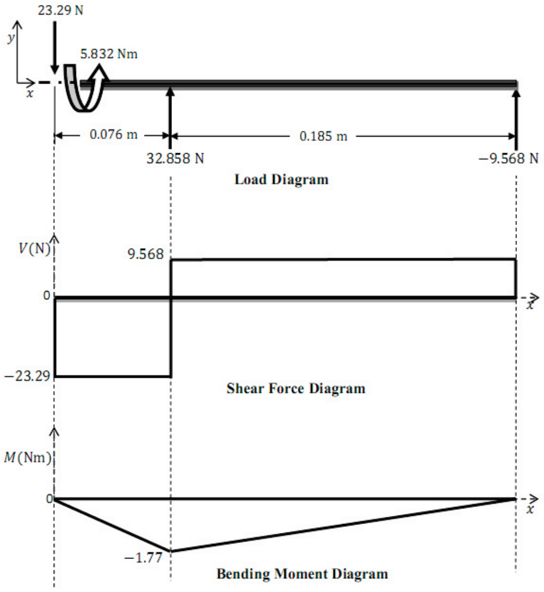


Fig. 4.5 Load, Shear Force and Bending Moment Diagrams

From the diagrams (Fig. 4.5) above, the magnitudes of the maximum shear force and bending moment are $23.29\ \mathrm{N}$ and $1.77\ \mathrm{Nm}$ respectively.
SAE 1006 HR (carbon steel) with an ultimate tensile strength (Sut)of 300 MPa is chosen for the shaft design.
By using DE-Goodman's criterion for shaft design:

$$d = \left\{\frac{16n}{\pi}\left(\frac{(2K_f M)^2}{S_e} + \frac{[3(K_{fs}T)^2]^{\frac{1}{2}}}{S_{ut}}\right)\right\}^{\frac{1}{3}} \tag{17}$$

where, d = Shaft diameter, Factor of safety (n) = 3
$S_e = k_a k_b S_e{}^1$, K_f and K_{fs} = Stress concentration factor for bending and shear respectively, k_a = Surface condition modification factor, k_b =Size modification factor,
$S_e{}^1$ =Rotary-beam test specimen endurance limit, Se = Endurance limit at the critical location of a machine part in the geometry and condition of used.
$k_a = aS_{ut}{}^b$(Budynas and Nisbett,2011)
For hot-rolled metals: $a = 57.7$ and $b = -0.718$ (Budynas and Nisbett, 2011)
$\Rightarrow k_a = 57.7 \times 300^{-0.718} = 0.9607$
$S_e{}^1 = 0.5S_{ut}, k_b = 0.9 \Rightarrow S_e = 0.9607 \times 0.9 \times 0.5 \times 300 = 129.6945\ \mathrm{MPa}$

$$K_f = 1.7, K_{fs} = 1.5 \Rightarrow d = \left\{\frac{16\times 3}{\pi}\left(\frac{(2\times 1.7\times 1.77)^2}{129.6945\times 10^6} + \frac{[3(1.5\times 5.832)^2]^{\frac{1}{2}}}{300\times 10^6}\right)\right\}^{\frac{1}{3}} = 17.14\ \mathrm{mm}$$

A standard shaft diameter of 20 mm is selected for the shaft design.

3.5 Bearing Selection

The design of a spherical roller bearing depends on the magnitude of the radial load, the thrust load and the design life.

$$P_d = VXR + YF_T, \tag{18}$$

where, Pd = Equivalent load, V = Rotation factor, X = Radial factor, R = Applied radial load
Y = Thrust Factor, FT = Applied thrust load
For rotating inner race bearing, Y = 1.5, V = 1, X = 1 and R = 32.858 N (the bearing reaction)
$\Rightarrow P_d = 1 \times 1 \times 32.858 + 1.5 \times 81.93 = 155.753\ \mathrm{N}$

$$C = P_d \frac{f_l}{f_n} \tag{19}$$

where, C = Basic dynamic load rating, fl = Life factor and fn = Speed factor
For a design life of 50000 hours, $f_l = 2.456$, $f_n = (0.03N)^{-\frac{3}{10}} = (0.03 \times 6666)^{-\frac{3}{10}} = 0.204$
$\Rightarrow C = 155.753 \times \dfrac{2.456}{0.204} = 1875.144\ \mathrm{N}$
Summary of data for selected spherical roller bearing:
Bearing number: 21304E, double roll, cylindrical bore, spherical bearing.
Bore, d = 20 mm, Outside diameter, D = 52 mm, Width, B = 15 mm, Maximum fillet radius, r = 1.1 mm and Basic dynamic load rating, C = 47 kN

3.6 Generator Selection

From catalogue, an alternator speed $24\ \mathrm{V}$, $7000\ \mathrm{rpm}$, power output of $6.6\ \mathrm{kW}$, an efficiency of 80% and a mass of $19.6\ \mathrm{kg}$ is selected.

$$P_e = \eta_g \eta_t P_s \tag{20}$$

where, Pe is the electrical power η_g and η_t are the generator and transmission efficiencies respectively.
For direct transmission (no gearbox), $\eta_t = 1$, $\eta_g = 0.8 \Rightarrow P_e = 0.8 \times 1 \times 4.071$
$= 3.2568\ \mathrm{kW}$

4. Conclusion and Recommendations

4.1 Conclusion

The wind turbine is appropriately designed to extract maximum amount of energy from the wind to power the electric car. Through the theoretical calculation on the power generated from the wind, a significant amount of electrical power (about 3.26 kW) is restored to the batteries when the car is moving at a speed of 120 km/h.

4.2 Recommendations

It is recommended that another research should be conducted to find out the extent to which the power generated by the turbine can increase the driving range of the electric car.
It is also recommended that more research should be done in order to incorporate the turbine design into the body of the electric cars.

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