VOL. 5, NO. 1, JANUARY 2010 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

DRIVING FORCE CHARACTERISTIC AND POWER CONSUMPTION OF 4.75 kW PERMANENT MAGNET MOTOR FOR A SOLAR VEHICLE

Zahari Taha[1], Rossi Passarella[1], Nasrudin Abd Rahim[2] and Jamali Md Sah[1]
[1]Center for Product Design and Manufacture, Faculty of Engineering, University of Malaya, Kuala Lumpur, Malaysia
[2]The Center for Research of Power Electronics and Drives, Automation, and Control, Faculty of Engineering, University of Malaya, Kuala Lumpur, Malaysia
E-Mail: passarella.rossi@gmail.com

ABSTRACT

Electric, hybrid-electric and fuel-cell vehicles have received positive response from the market due to their environmental-friendly factors. However, an electric vehicle powered by a solar energy has not yet being produced commercially because of power reliability and also high production cost. At the moment, solar vehicles are being developed for individual use, demonstration and also for research activities. For example a solar vehicle is being developed for the World Solar Challenge (WSC) 2009. Most of the mechanical components and the electrical components such as the solar panels, batteries, permanent magnet motor, controller and maximum power point trackers (MPPT) are available off-the-shelf. In this paper, the driving force characteristics of the permanent magnet motor are described. The motor's torque, speed and current characteristics are used to analyze the potential power performance of the vehicle on the road. Road test has shown that the theoretically calculated performance matches the road test results very closely.

Keywords: solar vehicle, off-the-shelf components, driving force characteristic, power performance.

INTRODUCTION

Driving force is fundamental to acceleration and power performance of a solar vehicle. In order to drive a solar vehicle, induction motors, reluctance and permanent magnet motors are commonly used. Electric propulsion has been used for many years in vehicle, since early 1900s. When scientists found out that solar energy can be transferred to electric energy, many researchers have tried to develop an electric vehicle that is powered by the sun [1, 2, 3, 4, 5, and 6].

Since the introduction of the World Solar Challenge (WSC) in 1987, many universities and companies have taken part. The competition requires the participating teams to design and built a solar vehicle that is capable of racing over 3000 km through central Australia from Darwin to Adelaide. Various types of motor, photovoltaic and battery can be seen here, especial in motor technology.

In this paper, a permanent magnet (PM) DC motor was chosen for a solar vehicle. The motor has a power range from 2.2 to 7.2 kW and voltage range from 24 to 72 V DC. The temperature of the motor can affect its efficiency and hence it has a self cooling function [7]. In order to optimize the performance of the vehicle during the race, the driving force and power performance of the vehicle need to be validated. The driving force is calculated from the torque vs. speed characteristic curve and the power is calculated from force, speed and time. The driving force at the rear wheels is used to overcome the driving resistance and works as the propulsion power.

Solar vehicle system

The vehicle (Figure-1) consists of three main components, the photovoltaic (PV) or solar array which converts solar energy to electricity, the batteries for storing electric from PV, and the motor to drive the vehicle [8].

Figure-1. CPDM solar vehicle.

In recent years solar vehicle in the world solar challenge drive by teams from universities around the world are developed using new materials and advance aerodynamic designs and sophisticated electrical system [9]. These vehicle cost a lot of money [10], but the solar vehicle in this study is built based on a sustainable product concept where the total investment involved is small but the performance and safety are comparable to other solar vehicles and also the components are recyclable and reusable. The idea, behind this solar vehicle, is to use off-the-shelf components [11].

The vehicle uses lead acid battery, photovoltaic (PV) panels that are normally use for housing application (Sharp NUSOE3E) and motor and controller that are commonly use for a golf buggies. To maximize the current draw from the PV, MPPT controllers are used. The National Instrument compact Rio (cRIO) is used to monitor the battery voltage, current, voltage, and rpm, and the data sent by telemetry to lead vehicle [11].

The schematic diagram for the electrical system of the solar vehicle is shown in Figure-2. It consists of 4 PVs and 4 MPPTs, where each PV is linked to one MPPT. This subsystem is called a Small Generator Module (SGM) which can produce maximum current of 14 amps. The four SGMs are combined to maximise the current stored in the battery, this configuration will result to maximum power of 48V x 56 Amps which is 2.688 kW.

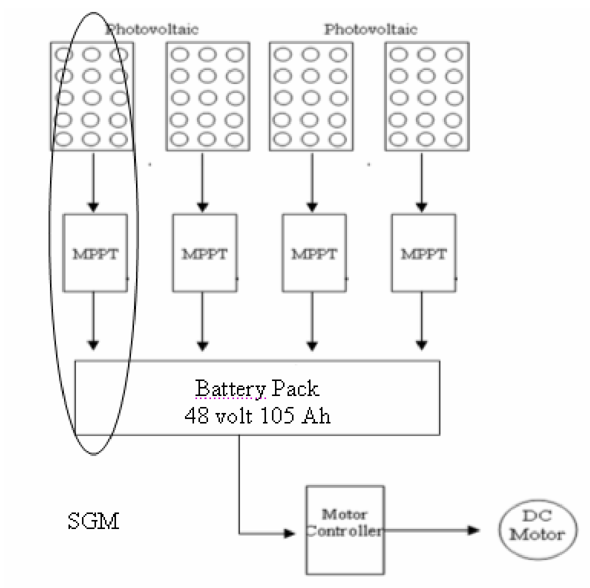

Figure-2. Electrical schematic diagram of solar vehicle.

The battery pack produces 48 volt, with a capacity 105 Ah. The controller takes 48 volts DC power from the batteries and delivers it to the motor. The accelerator is hooked to a potentiometer (variable resistor), and this potentiometer provides the signal that tells the controller how much power it is supposed to deliver. The controller can deliver zero power (when the car is stopped), full power (when the driver presses the accelerator maximum), or any power level in between.

Motor characteristic

The PMG 132 is a pancake style, brushed, permanent magnet DC motor manufactured by Perm Motor in Germany. As mentioned before the DC motor is designed to give a power range from 2.2 to 7.2 kW and a voltage range from 24 to 72 V DC for battery powered vehicles with speeds ranging from 1080 until 3480 rpm. There are openings on the body of the motor for self cooling purposes and the carbon brush is designed to be compact and ragged. The advantage of this voltage range is that the motor can be set based on the requirement of power and torque of the vehicle

Figure-3 shows the torque vs. speed characteristic at 48 volt of the motor used in this study. The torque remains at peak until 2340 rpm and then decreases. Figure-4 shows the efficiency of DC motor at 48 volt.

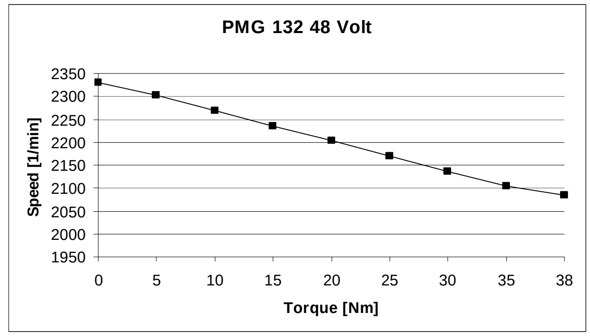

Figure-3. Torque vs. speed characteristic.

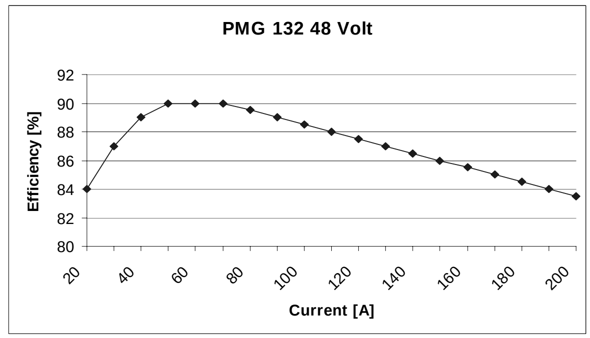

Figure-4. Efficiency of the PMG motor.

VEHICLE DYNAMICS

Driving resistance characteristic

Driving resistance or road load is important for the calculation involving the driving force of the solar vehicle. Driving resistance (F_{rm}) consists of rolling resistance force (f_{ro}), aerodynamic drag force (f_l), and climbing resistance force (f_{st}).

$$F_{rm} = f_{ro} + f_l + f_{st} \quad \text{.......................} (1)$$

The rolling resistance (f_{ro}) is caused by the tire deformation on the road:

$$Fro = \mu . M . g \quad \text{.........................} (2)$$

Where

μ The rolling resistance coefficient;
M the vehicle total weight;
G the acceleration of gravity;

Aerodynamic drag, *fl*, is the viscous resistance of air acting to the vehicle

$$Fl = \frac{1}{2} \rho . C_d . A . (v+v_0)^2 \quad \text{........................} (3)$$

Where

P air density;
C_d the air resistance coefficient;
A the frontal projected area;
V the vehicle speed;
$V0$ head-wind velocity;

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The climbing resistance (f_{st} with positive operational sign) and the down force (f_{st} with negative operational sign) is given by

$f_{st} = m . g. sin\ \theta$ ……………………………...……(4)

Where θ is the gradient angle

The driving resistance of the vehicle at 0 and 5 deg slope as a function of vehicle speed is shown in Figure-5.

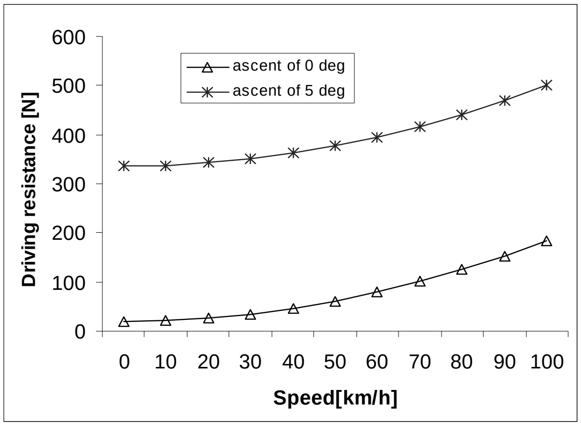

Figure-5. Driving resistances curves.

The solar vehicle parameters used in this study are listed in Table-1.

Table-1. Parameters used in this study.

Rolling resistance coefficient, μ	0.0055
Total Weight, m	370 kg
Acceleration of gravity, g	$9.8 m/s^2$
Air Density, ρ	$1.22\ kg/m^3$
Air resistance coefficient, Cd	0.35
Frontal projected area, A	$1 m^2$
Wheel radius, rd	0.345m
Gear ratio, i	4.174

Driving force

Acting as propulsion power, driving force is applied to the wheels in order to overcome the driving resistance. Therefore, a driving force which is lower than a driving resistance does not satisfy roll of the vehicle. Given the vehicle speed:

$$v = \frac{2\pi r_d \eta}{i} x \frac{60}{1000}$$ …………….... [Km/h](5)

The driving force is given by:

$$p = \frac{T.\eta.i}{r_d}$$ …………………………. [N] (6)

Where

Rd the wheel radius;

i the overall gear ratio;

η the transmission efficiency which is assumed to be 0.95 in this study;

T torque.

Figure-6 shows the driving force characteristics calculated from equations 5 and 6. This Figure represents the driving performance for a gear ratio of 96/23, the ratio of the sprocket at the rear wheel and sprocket at the motor.

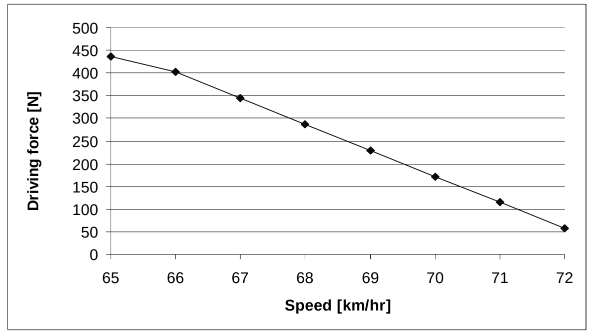

Figure-6. Driving force curves for a gear ratio of 96/23.

POWER CONSUMPTION

Cruising at maximum vehicle velocity

The power requirement to cruise the vehicle at maximum speed can be obtained as

$P_{vmax} = Pro + P_{st} + P_l$ ……………… (7)

$P_{vmax} = (f_{ro}.\ v_{max}) + (f_{st}.\ v_{max}) + (f_l.\ v_{max})$ ……….…..… (8)

Where

Fro rolling resistance force
f_{st} climbing resistance force
Fl aerodynamic drag force
V_{max} Velocity maximum

This power is obtained from the batteries to drive the motor to achieve certain speed as shown in Figure-7. The following assumptions are considered:

a) Zero head-wind velocity
b) Grade angle 0 = level ground
c) Without acceleration

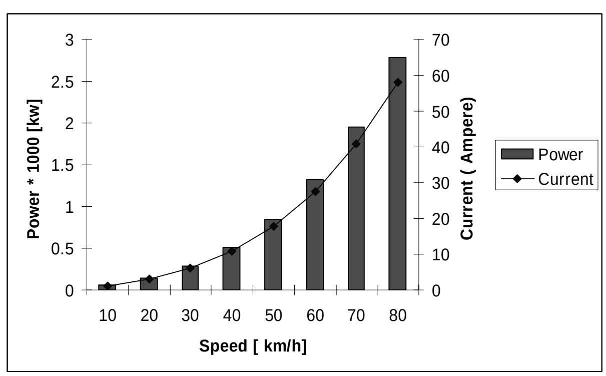

Figure-7. Power and current required for cruise at various speeds.

Acceleration is very important for the movement of a vehicle, therefore, the energy losses was caused by acceleration must be added in the calculation. Hence the power required to accelerate the solar vehicle given by:

$P_{accel} = m\ A.\ v$ …………….. (9)

Where

A instantaneous acceleration.
M mass vehicle
Therefore, the power that is used at the wheels is given by:

$P_{out} = m.A.\ v + P_{vmax}$ ……………. (10)

EXPERIMENTAL

Road test

A test was conducted on a public road with a distance of 10 km (Figure-8). An escort car follows the solar vehicle with in a distance of 100 m. The monitoring system is placed inside the Lead vehicle (Figure-9). The ideal condition for the vehicle was set before the test, the batteries pack was fully charged, and the tires pressure are 70 psi for rear, 80 psi for the front tires.

Figure-8. Solar vehicle test on a public road.

Figure-9. Data acquisition and telemetry system of solar vehicle road test.

Monitoring system

The data acquisition system that monitors the entire electrical system is installed inside the vehicle as shown in Figure-10. Lab view with compact Rio (cRIO) is used. The cRIO acquires data from the sensors. The basic data being monitored are the battery voltage, speed and current. However, the driver must interpret his instruments and his team members monitor the vehicle remotely using telemetry (wireless data transmission). The data received from the acquisition system is very useful in planning race strategy.

The front panel of the real time host at the receiving computer is shown in Figure-11. Indicators such as thermometers, current consumption, battery voltage, speedometer, waveform charts, LEDs and buttons are added in order to enhance the features of the monitoring system.

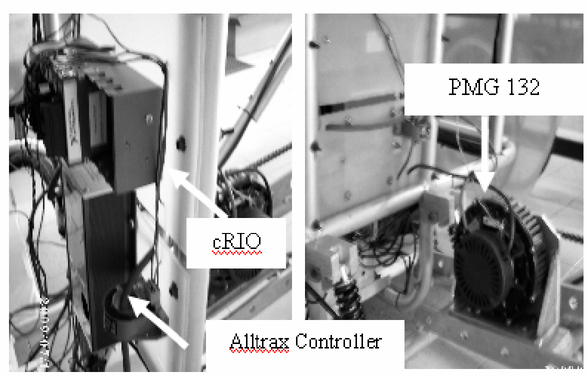

Figure-10. Motor, controller and data acquisition.

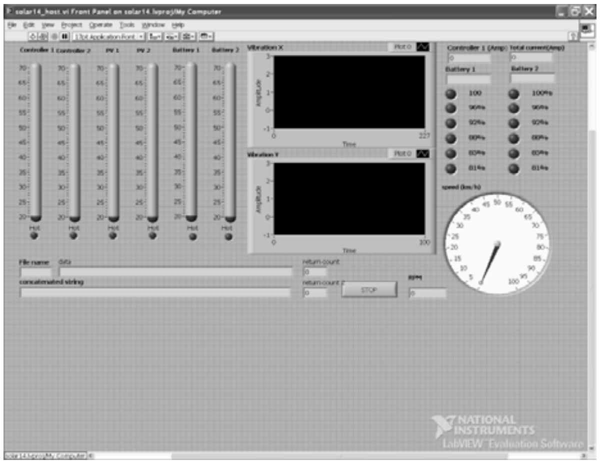

Figure-11. Front panel of real time host. vi.

RESULTS AND DISCUSSIONS

In the road test the driver increases the vehicle speed slowly until the maximum speed (Figure-12 (a)). He then maintains the speed at approximately 60 km/h before slowing down to a stop. Figure-12 (b) shows the current drawn by the motor, Figure-12 (c) is the battery voltage and Figure-12 (d) is the road slope.

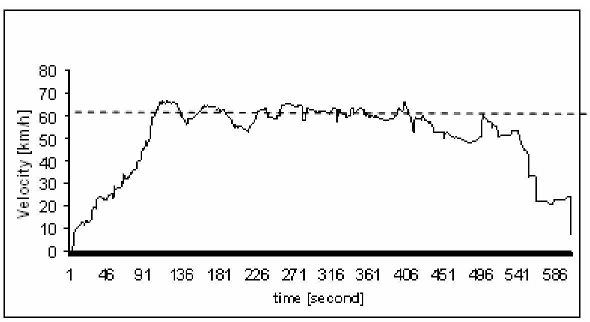

Figure-12(a). Velocity.

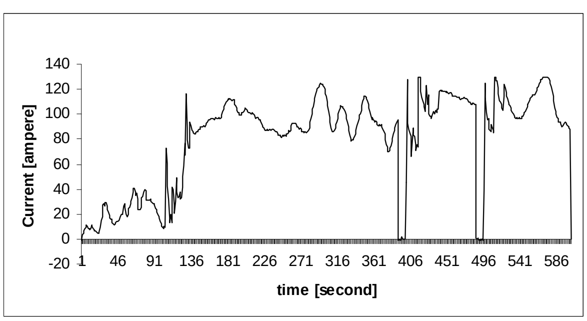

Figure-12(b). The current.

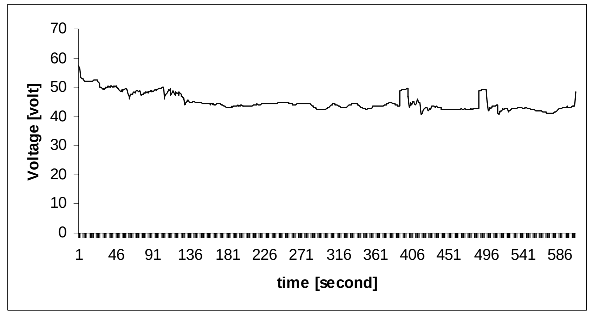

Figure-12(c). The voltage.

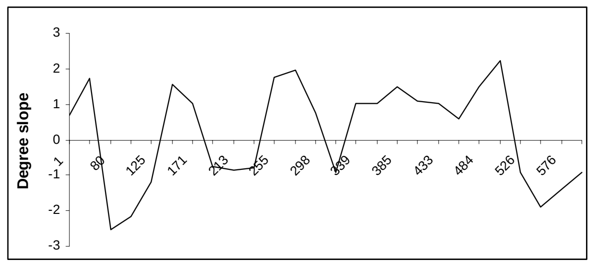

Figure-12(d). The road slope in degree.

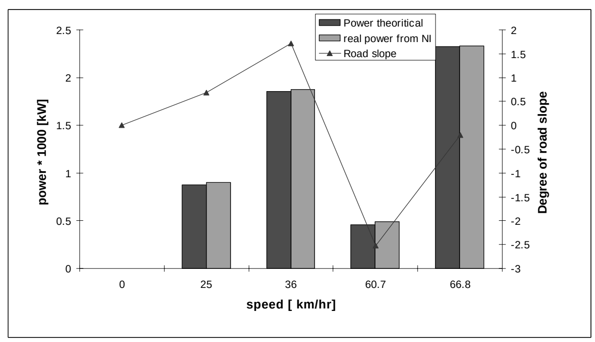

Figure-13. Data plot from telemetry and theoretical calculated power at various speeds until the maximum speed.

Figure-13 shows the comparison between theoretically calculated power and power calculated based on data from telemetry.

The theoretical power is calculated based on velocity (from Figure-12(a)) and slope (from Figure-12 (d)) in ideal condition such as zero head-wind velocity, and no pervious momentum. The actual power is calculated from Figure-12(b) and Figure-12(c). However, there is a slight difference in the theoretically calculated power at 25, 36, and 60.7 km/h with no difference at maximum speed of 66.8 km/h.

There was power consumption difference at 25 km/h as in Figure-7 and Figure-13 because the consumption in Figure-7 was calculated without the losses due to vehicle acceleration. However in Figure-13 the power consumption was slightly higher since the calculated power had included the acceleration and deceleration due to slope of the road.

The power consumption of the solar vehicle is 2.32kW when traveling at the maximum speed. The maximum power that can be supplied by array is 2.688 kW. Therefore the array can produce enough power to drive the vehicle.

CONCLUSIONS

The characteristics of a 4.75 kW permanent magnet motor are presented and discussed for the application on the solar vehicle by calculating the driving force, power consumption and road test. As a result, it was found out that there is enough drive force from the motor to drive the vehicle and also enough power from array. This PM motor is applicable for the solar vehicle.

Technical Specifications

Type : Single seat
Top Speed : 70 km/h
Source of Energy : Battery and Sun

Integrated power system

Motor : PMG 132 (DC motor) power rating 2.2 kW to 7.2 kW
Controller : Alltrax AXE7245 Pmax 21kW
MPPT charger : Outback MX80
Power Pack : 48 Volt, 105AH Trojan Deep Cycle battery

Instrumentation

DAQ : NI-cRIO 9014
Telemetry system: XStream Radio Freq Module
Current Transducer : DHR 100 C10 LEM
NI Card : 9233+/- 5V, 50 ks/s per channel
NI Card : 9211 +/- 0.08V, 14s/s
NI Card : 9221 +/- 60V, 800 ks/s
NI card : 9215 +/- 10V, 100 ks/s

Dimensions

Length : 4620 mm
Width : 1395 mm
Height : 1375 mm
Weight : 370 kg

ACKNOWLEDGEMENTS

This study is supported by IPPP-UM (PS091/2008C) and also by National Instruments Malaysia. The authors would like to acknowledge their advice and support.

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