Optimal Design of a Solar Car Electrical System

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Abstract. This paper introduces the optimal electrical system design for a solar car, which complies with the regulations of World Solar Challenge 2013. The optimal design principles of high efficiency, light weight and high reliability were proposed. The solar energy collection system, energy storage system, drive system and electronic control system were all designed under the guidance of the principles. The structure and working principle of the solar car electrical system are also introduced. The experimental results show that the design goals have been achieved, and the performance of the system has also been verified.

Introduction

The development of automotive industry over the past century has greatly promoted the development of human society. However, the highly developed automotive industry and the widely use of automobiles have arose consequences such as oil depletion, global warming and atmospheric pollution. In recent years, electric vehicles (EV) and hybrid electric vehicles (HEV), which could reduce carbon emission and the dependence to fossil fuel energy, are developing rapidly, becoming the new opportunity for traditional automobile industry.

Solar-powered car is an exploration for the future clean energy vehicles. It is powered by inexhaustible solar energy, which is converted to electrical power and used to drive motors, without any emission produced in the whole working process. Solar car is an ideal type of clean energy vehicle. Solar car is a multi-disciplinary subject that covers aerospace, bicycle, alternative energy and automotive industries. The related techniques have made considerable progress since the first solar car was unveiled by General Motors in 1987. However, problems such as low photoelectric conversion efficiency, high price, and limited range still need to be solved. Most of current researches on solar car topic focus on the vehicle system matching and optimization, energy management strategy, high efficiency drive system, lightweight and low drag car body, etc. Within the field of electrical system design of solar cars, Martin A. Green discussed the solar cells and array technology used by the leading cars in 1996 [1]. Louis McCarthy described the monitoring in UMR's solar car [2]. Yuki Suita proposed a MPPT control algorithm and compared two types of motors [3]. O. Ustun introduced the design of Istanbul Technical University solar race cars [4]. Douglas R Carroll's book also discussed the electrical system of a solar car in details [5].

Electrical system is the core of a solar car as it is electric vehicle. A well designed electrical system will greatly improve the dynamic performance, efficiency and range of the solar car. In this paper, an optimal solar car electrical system design solution is introduced, which complies with the regulations of World Solar Challenge 2013.

Design Principles

World Solar Challenge (WSC) was first held in 1989, and held every two years in Australia now [1,6]. The objective of the competition is to promote research on solar-powered cars. The race attracts teams from universities and enterprises all over the world.

The basic rules of the race is to construct a solar-powered car and drive it across Australia from Darwin to Adelaide in 50 hours, which covers 3021Km, thus the average speed must be higher than

60Km/h. The area of the solar panel is limited to $6m^2$ and the mass of the batteries is limited to 21Kg. Charging the batteries from any external sources are not allowed during the race [7].

The regulations of WSC make stringent requirements for solar cars from all aspects. The design of a solar car is severely limited by the amount of energy input into the car. In order to meet the requirements and finish the race, the following design principles should be implemented in the whole design process.

High efficiency

The key issue of solar cars is limited energy. A solar panel with an area of 6 m^2 generates approximately 1250W on a clear day with the sun directly overhead. That is only about one fiftieth the power of an ordinary car. While under this drive power, the solar car needs to reach an average speed above 60Km/h. Therefore, the energy conversion and utilization must be efficient, including the sunlight to electrical power conversion, the electrical power flow and storage and the electrical power to mechanical energy conversion.

Light weight

The driving resistances of a solar car are mainly rolling resistance and wind resistance. The resistance should be minimized to save energy. Besides lightweight and low drag car body, lightweight design of the electrical system is an effective way to lose the weight of the car, thus reduce the rolling resistance.

High reliability

Solar cars are complex mechatronic systems, and may operate in high temperature, vibrational and dusty environments. In order to ensure the long-term working stability of the solar car, measures such as simplify the solution, use sophisticated technology and make redundancy of the key components should be taken in the design.

In fact, the above principles are not only for the design of the solar race cars, but also general solutions for all kinds of solar cars, which share the common shortcoming with the race ones.

Electrical system design

From the perspective of function, a solar car electrical system should contain the following sub-systems, solar collection system, energy storage system, drive system, electronic control system and accessories.

Solar energy collection system design

The solar energy collection system consists of a solar panel array and several maximum power point trackers (MPPT). The solar panels convert the sunlight to electrical power with the highest efficiency of 22.5%.

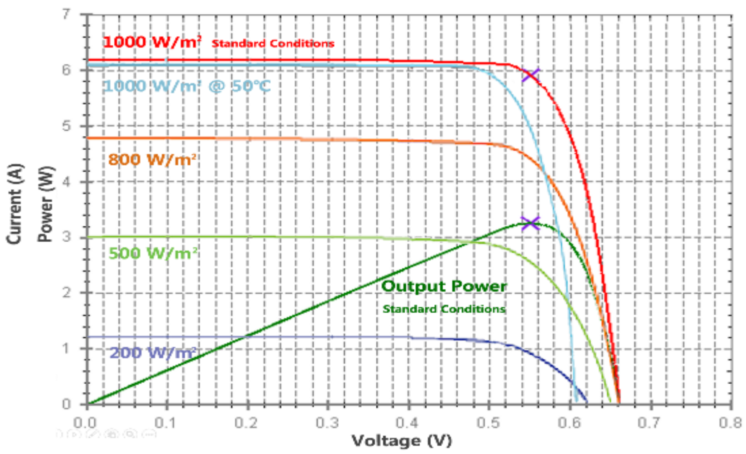

Fig. 1. Output characteristics of one piece of solar cell

In the design of this paper, limited to the area of $6m^2$, 386 pieces of photovoltaic cells are placed on the upper shell of the car. The total output power is 1240W under standard test conditions. The output characteristics of a single piece of solar photovoltaic cell is shown in Fig. 1. The open circuit voltage is 0.66V and the short circuit current is 5.84A. The marked point is the maximum power point, on which the cell output power is 3.22W. The cell could be regard as a current source as Eq. 1,

$$I = I_{ph} - I_0 \left\{ exp\left[\frac{q(V+R_sI)}{nKT}\right] - 1 \right\} - \frac{V+R_sI}{R_{sh}} \quad (1)$$

Where I_{ph} is the solar cell current, I_0 is the repercussions saturation current, V is the cell output voltage, q is the electron charge, n is the diode factor, K is the Boltzmann constant, T is the surface temperature, R_s is the series resistance and R_{sh} is the shunt resistance.

In order to maximum the output power of all the cells, MPPTs should be implemented to regulate the output voltage of the cells. Meanwhile, the MPPTs could boost the output voltage of the cells to the battery voltage of the car, thus charge the battery and supply the drive system directly. As all the photovoltaic cells are mounted together in the same surface of the upper shell, their maximum power points are generally close. However, considering the shell curvature and the possible shadow, the maximum points may be different sometimes. As a result, all the cells are dived into four sections based on their locations on the shell, as shown in Fig. 2 (panel A is section 1, panel B, C, D and E form section 2, panel F, G and J form section 3, panel H and I form section 4). Cells are series connected to form a panel. Panels in one section are series connected and output to a MPPT. The maximum power point voltage of each section is between 30V and 60V to match the MPPT input voltage range. All the panels form the whole array, and the four MPPTs are connected to the DC bus in parallel.

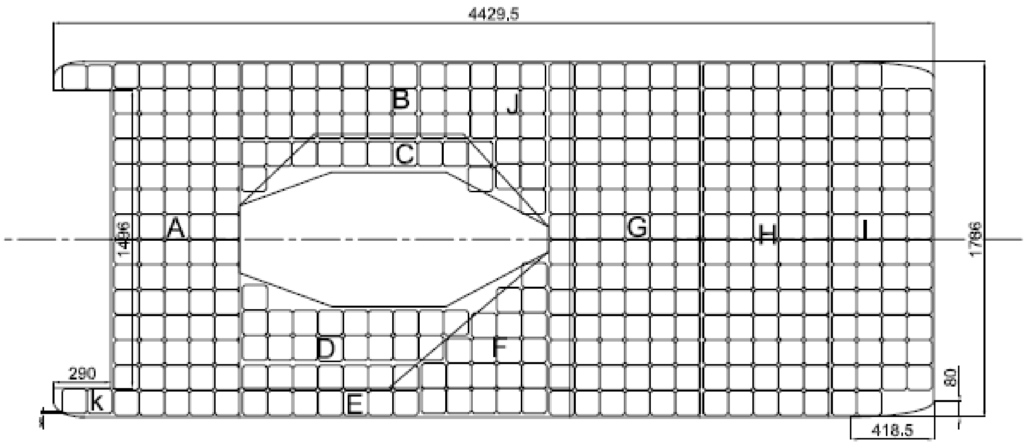

Fig. 2. Solar panel array on the upper shell

Energy storage system design

The energy storage system consists of battery pack and battery management system (BMS). The battery could storage energy when the solar power is sufficient, discharge to release energy when needed, and maintain the DC bus voltage at the same time. In the design of this paper, 18650 type lithium-ion cells which have high energy density and high charge-discharge efficiency are selected. Limited to the mass of 21Kg in the regulation, 432 pieces of battery cells are used, with a total capacity of approximately 5.1Kwh. The package of the cells depends mainly on the voltage of the battery pack, which is an important parameter of the electrical system. High battery voltage will decrease current under the same power thus lose wire weight and reduce heat. But the operating voltage range of the MPPTs and motors should also be considered. As a consequence, the rated voltage of the battery pack in this design is 96V, and the cells are packed in 27 series and 16 parallels.

For reliability and safety reasons, a battery management system should be utilized to manage the battery pack. The BMS monitors the voltage and temperature of each cell, and the current of the whole pack, thus estimate of state of charge (SOC) and state of health (SOH) of the battery. The BMS also protects the battery from over-charging, over-discharging, over-temperature and over-current by disconnecting the battery from the system.

The energy storage system also includes a separate 14.4V battery pack, and a 96V to 12V DC/DC converter as its charger. The pack and its charger are connected to the 96V pack and supply all the 12V devices in the electrical system.

Drive system design

The drive system consists of motors and motor controllers. The system converts the electrical power to mechanical energy and drive the car. The dynamic performance and the drive efficiency depend on the operating characteristics of the drive system.

The permanent magnet synchronous motors (PMSM), which has high efficiency, high power density and wide constant-power range, are the best choice of solar car drive motors. Particularly, the disc PMSM could be mounted in the wheel as hub motors to simplify the transmission. In this way, not only the transmission are simplified to improve the drive efficiency, but the frontal area of the car are reduced to lower wind resistance as well. Considering the car stability when regenerative braking and the reliability result from repeatability, two motors are separately installed in the two rear wheels.

The relationship between the power reaching the road, *P*, and the car velocity, *V*, applies for cars travelling at constant speed on a surface of slop α with no wind could be derived as Eq. 2,

$$P = C_{rr}\left(1 + \frac{V}{161}\right)mg + \frac{1}{2}\rho A C_d V^2 + mg sin(\tan^{-1}\alpha)V \quad (2)$$

Where C_{rr} is the rolling resistance coefficient, mg is the weight of the car, ρ is the air density, *A* is the frontal area of the car and C_d is the aerodynamic drag coefficient. In the design calculation, parameters are from the design goals of the solar car, in which the weight is 250Kg, the rolling resistance is 0.006 and the drag area is 0.15 m^2. The slope of the road is 3 degrees maximum according to the road profile. As a result, the car would consume about 1Kw at 60Km/h, 2.5Kw at 90Km/h on a flat surface. The consumption would increase sharply to 5.2Kw when cruising at 60Km/h on the slope of 3 degrees.

From the dynamics calculation above, the optimized design specifications of the motor should be 1Kw rated power, 2.5Kw peak power, 800rpm rated speed, 1200rpm maximum speed, 12Nm rated torque and 30Nm peak torque. Based on the above values, the motor design is conducted in the Maxwell electromagnetic simulation software. The design result is shown in Fig. 3. It is a disc PMSM with 16 pole pairs, and weighted 9.0Kg. Measures such as thick magnet, optimal pole-slot combination, thin air gap and concentrated winding are taken to improve the motor efficiency.

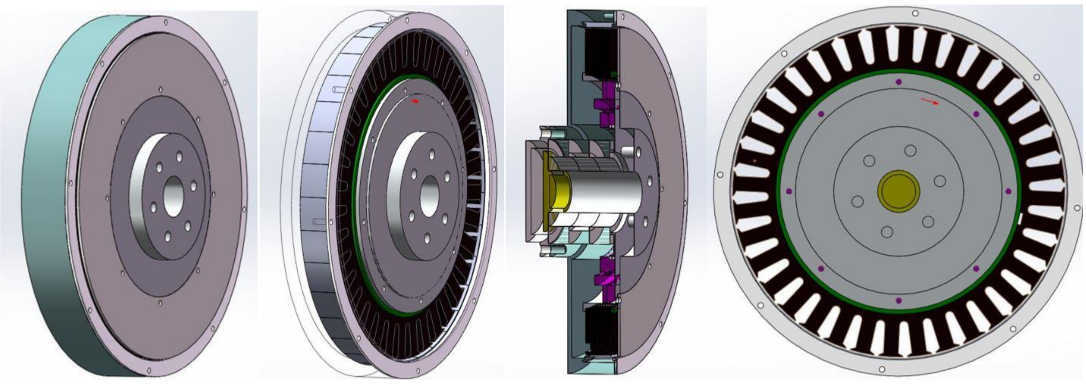
Fig. 3. Design of a disc PMSM

Motor controllers are also designed and the MOSFET are used as power switches, which are controlled by pulse width modulation (PWM). The speed-torque-efficiency characteristics of the motor-controller system are shown in Fig. 4. The system operates in the constant torque region when the speed is lower than 600rpm, and operates in the constant power region when the speed is higher than 600rpm. The system efficiency is high than 90% in the region where the speed is higher than 500rpm and torque is higher than 10Nm, which covers most of the operating conditions of the car during the race.

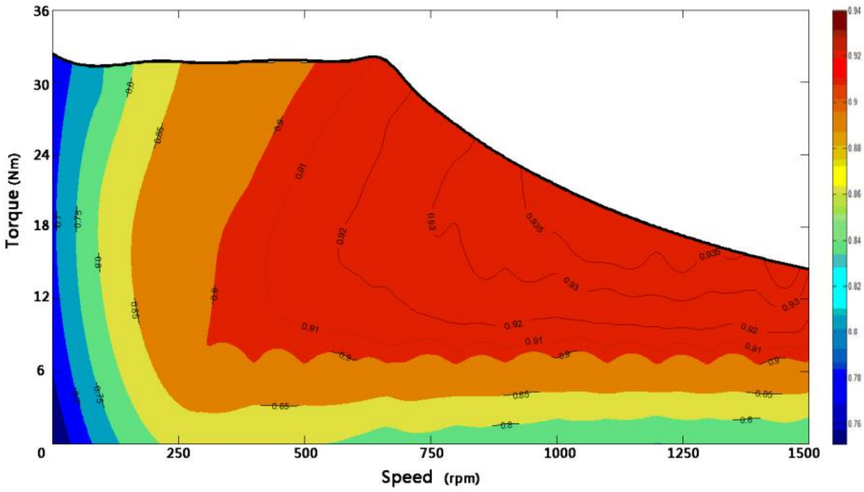

Fig. 4. Speed-torque-efficiency characteristics of the drive system

Electronic control system design

The electronic control system consists of the vehicle control unit, dashboard and operation panel. The system interacts with the driver, controls the whole electrical system and monitors the status of the car. The vehicle control unit is an industrial computer with high reliability. The program on its operating system platform realizes the functions of communication, data processing, and vehicle control and fault diagnosis. For communication, the industrial 485 bus is deployed to communicate with the AD and DI collection modules while the CAN bus is used to communicate with other devices on the car and TCP/IP protocol for the communication with the escort car via WIFI. Through communication, the vehicle control unit could capture the driver's operating intentions and the working status of the car, process the data and control the whole car, whilst it could also send the status information to the rear supply car for calculating the energy management strategy. The dashboard panel could display the speed, the SOC of the battery, the status of car lights and other information for driving through a LED screen. Operation panel could be integrated on the steering wheel which included the switches of devices, the buttons of car lights and cruising. By manipulating the buttons on the panel, the driver could control the whole electrical system.

System structure and working principle

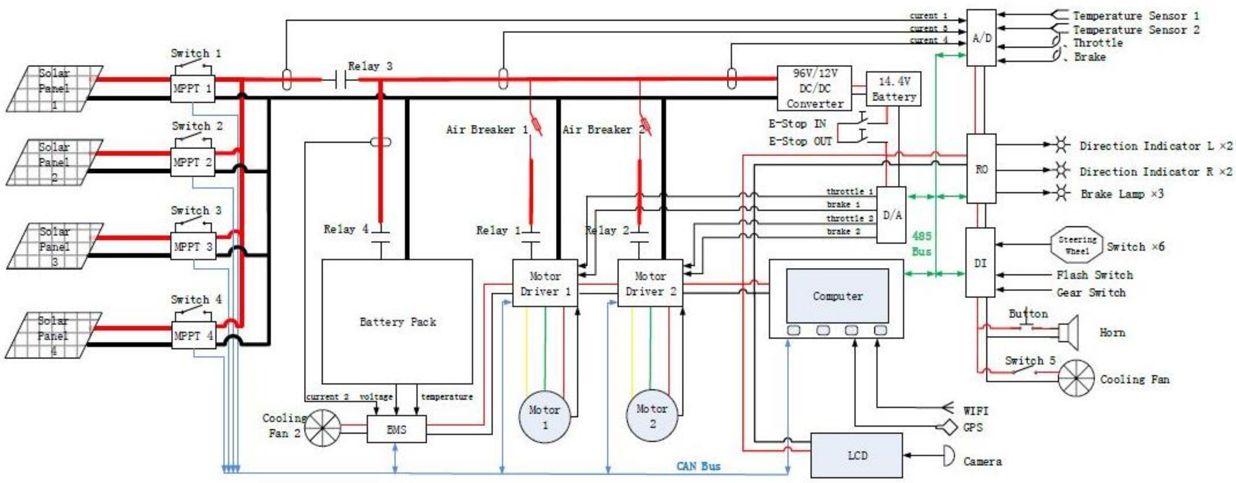

Fig. 5. Electrical system diagram

The diagram of the electrical system is shown in Fig. 5. The solar energy collection system, energy storage system and driving system are connected with each other by the DC bus and separately connect to relay, pre-charged resistances and diodes in series to control the on-off status of the high voltage, pre-charge the devices and prevent the electrical surge between each other. Electronic control system monitors the status of the car and the driver's manipulation by sensors and communicate with other devices via CAN bus. The switches on the operation panel could control all relays directly.

When driving the solar car, the driver could manipulate the relays through the switches of MPPTs, battery pack and motor controllers to control the related high voltage devices. The driver could also use steering wheel to control the direction. The driving mode could be divided into normal mode and cruising mode. Under normal mode, the driver could control the driving power and the speed directly by the throttle and brake panel, while under cruising mode, he could set a cruising speed to alleviate the driving fatigue and avoid the energy loss caused by speed fluctuation.

The energy flow modes of the solar car can be classified as follows, when the solar energy is sufficient enough, the energy flow from solar array to the battery and the diving system at the same time. When the driving power need is greater than the solar power, the energy from solar array and battery flow together to the driving system. When there is no sunlight, the solar array does not work, the battery supply the driving system alone. Since the three power sub-system are connected to the DC bus in parallel, the energy flows and distributes naturally without control. The only thing need to attention is that the driver should adjust the driving speed according to the sunlight condition and battery SOC to protect the battery from over-charged or over-discharged.

Experiment

Taking the practical conditions into consideration, the components of the electrical system were constructed and installed on the car based on the system design introduced in Chapter 3. Fig. 6 shows the appearance of the car. The solar array was stamped on the upper shell of the car while the MPPTs, battery pack and BMS were fixed separately in the reserved space of the anti-roll cage. The vehicle control unit, dashboard and operation panel were mounted in the cockpit. When designing the layout and wiring, a lot of factors were considered such as the insolation of the 96V power and 12V power, the anti-collision of battery pack, the sharing cooling wind tunnel of power devices, the length of wires and the protection of the driver from high voltage power. The parameters of the car and the comparison with an ordinary car are shown in Table 1.

Fig. 6. Appearance of the constructed solar car

Table 1. Parameters of the solar car and an ordinary car

	Mass (Kg)	Power at 80Km/h (Kw)	Peak Power (Kw)	Size (m)	Occupants (person)	3000Km fuel cost ($)
Solar car	270	2	5	$4.5\times1.8\times1.0$	1	0
Ordinary car	1100	18	80	$4.5\times1.7\times1.4$	4	300

● Solar energy charging Experiment

In a clear day, when the solar car is stationary, the charging experiment was conducted from 2 p.m. to 4 p.m. The output power of the array and the changes of the battery SOC are shown in Fig. 7. The maximum charging power is 1Kw and the minimum is 200W with an average power of 760W. The variation of the power was influenced by the sunlight intensity, angle variation, cloud shadow and temperature.

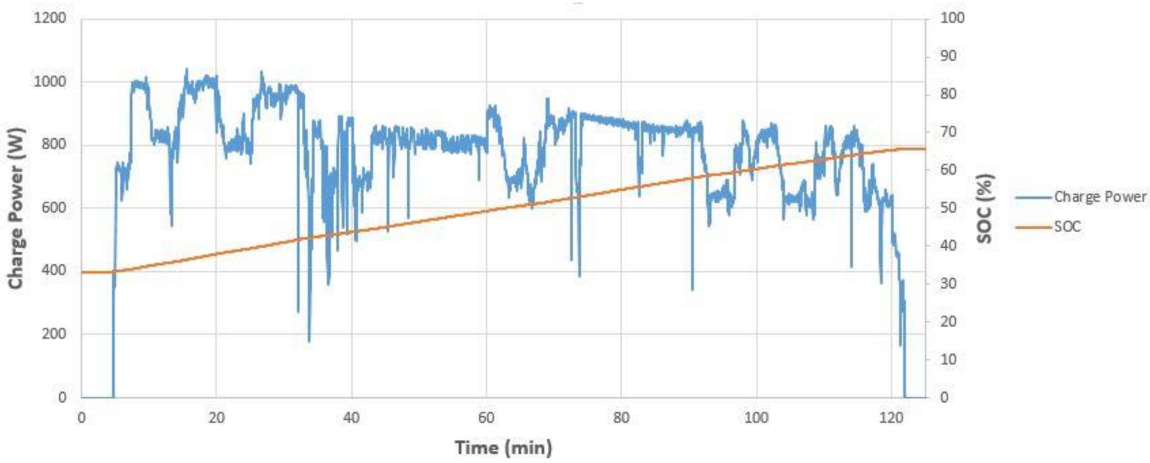

Fig. 7. Solar energy charging result

● The driving performance test

The driving performance test was conducted on flat and hard road. The driving power of the solar car under different cruising speed were tested and the result are shown in Fig. 8. The maximum speed is around 105 km/h. To meet the requirements of the minimum average speed 60 km/h, the driving power is around 1.2 Kw, which means all the power of battery pack alone could only support driving for 250 Km. With the increasing of the speed, the ascend trend of the driving power is close to exponential increase.

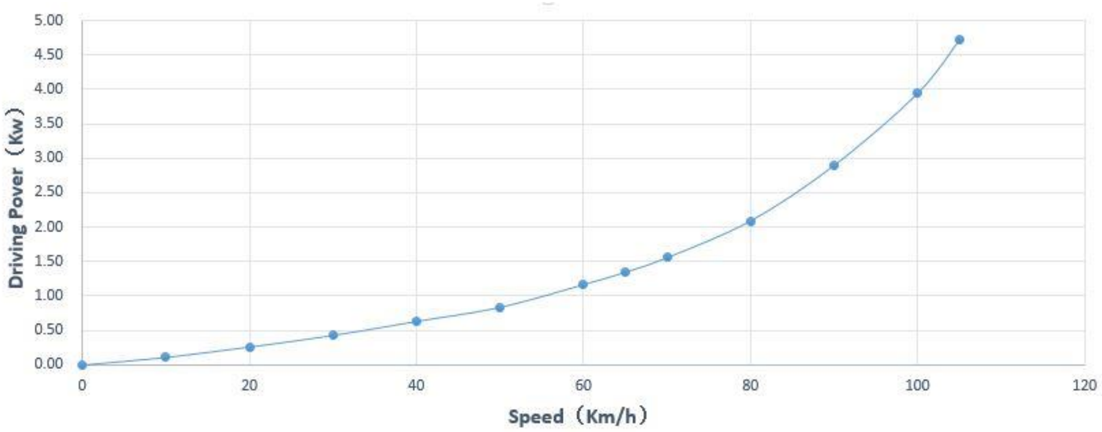

Fig. 8. Driving performance test result

● System test

We drive the solar car for 30 minutes whilst we tested the speed, driving power, solar energy charging power, SOC of battery and some other parameters. The relationship of the driving power and the speed is shown in Fig. 9. The system energy was distributed among the different modes introduced in the system working principle above. In most cases when driving, the driving power are larger than the intake solar power. The battery and solar array supply the driving power together.

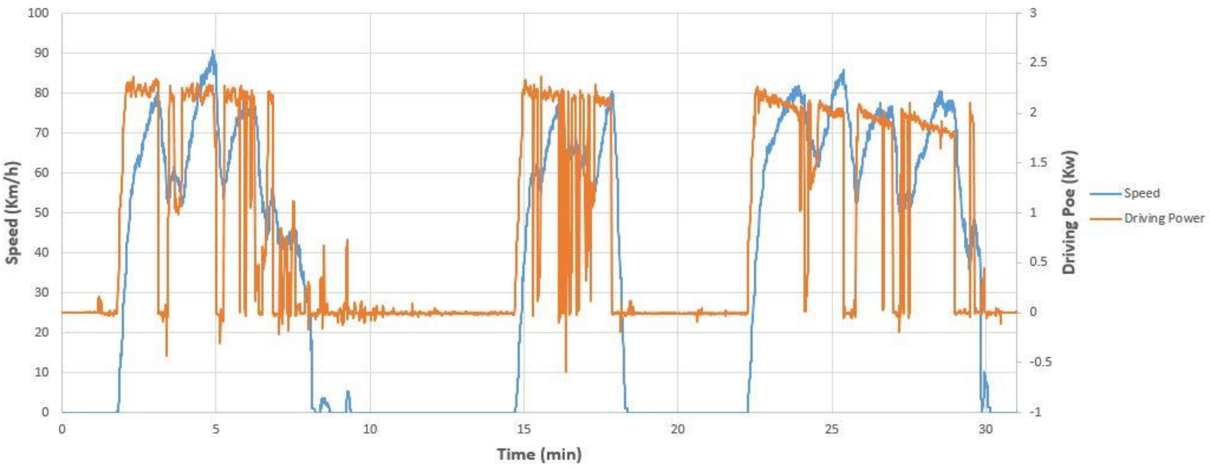

Fig. 9. System test result

Conclusion

A solar car electrical system with 6 m^2 solar array, 5.1Kwh lithium-ion battery and two 1Kw PMSMs is designed in this paper. It will attend the WSC in October 2013 and challenge the 3021Km journey.

The conclusions of the design are listed as follows.

- All the functional sub systems are designed under the guidance of the optimal design principles, which are high efficiency, light weight and high reliability. The experimental results have showed the performance is acceptable.
- The collection, storage and drive systems of the car match with each other well and the energy flows naturally within the three systems without control. Meanwhile, the whole electrical system also match the car well. The car operates efficiently under most conditions.
- The solar car achieves a maximum speed of 105Km/h, and it consumes 1.2Kw power at a cruising speed of 60 Km/h, which should have met the requirements of the race. However, it still need to be verified by the WSC and to improve to catch up with the leading cars.
- The design has to compromise the performance to some extent sometimes because of safety, complexity, cost or other reasons. In fact, optimal design is to find a restricted optimum which maximizes the utilization of the existing techniques and objective conditions.

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