



New Design and Implementation of a Solar Car of the American University of Ras Al Khaimah: Electrical Vision

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ABSTRACT

This paper explains a full design and implementation process of a feasible solar car as an effective alternative to the gasoline powered car. A solar car is independent of fossil fuels, and would entirely eliminate emissions. Comparing to the previous manufactured solar cars which were characterized by expensive, one seat driver and unfeasible, the presented solution in this study develops a commercially feasible version of a solar car. The structure's mass and passengers' mass are considered to calculate the required electrical power for the car to be able to reach the target speed at 100 km/h. A three photovoltaic panels of 320 W are parallel connected as a photovoltaic array to charge a lithium ion battery bank of 48 V and 200 Ah during the day hours. The testing of the implemented car guarantees the successful and flexible design and promises an effective commercial prototype of solar car. The presented work is done in the American University of Ras Al Khaimah.

KEYWORDS

Solar photovoltaic panel, Battery charger, Battery bank, Speed controllers, Brushless motor.

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INTRODUCTION

The concerns of the environmental and the economic issues which are represented by the global warming and the negative consequences of fossil fuels dependency that are leading to increase the focusing on the effective alternatives of green renewable energy. In terms of transportation, the Hybrid Electric Vehicle (HEV) and the related researches took more focusing. In the same point of fact, many research studies and proposals have been presented.

In Khan and Kar [1], the technologies of implementing the hybrid vehicle have been reviewed in terms of the sustainable trend, the system efficiency, and reducing the dependency on fossil fuel. Different types of partly and fully electric power dependency vehicles have been explained in the study of Khan and Kar [1]. A detailed design HEV has been presented in Nicolae *et al.* [2], an induction motor and a three phase Voltage Source Inverter (VSI) with battery bank design steps have been explained, in addition to the concerning aspects of involving VSI in the system.

Different HEV module configurations have been simulated and presented in Simic and Bauml [3], and different operation strategies of the energy sources for the power supplying to the HEV under the study have also been explained, with supporting by smart library.

A power management system for HEV applications has been proposed in Amador *et al.* [4] using supercapacitors for energy saving. The proposal also included switching-mode power supply with step up transformer in single phase system. Whereas the work of Panday and Bansal [5] regarding the HEV, has been developed a modified estimation method of charging state through an efficient energy managing. Based on global strategy of Fuzzy Logic Control, many topologies of HEV, and operating modes have been explained in Ahmed and Cui [6]. The HEV under the study adopted a machine type of the Permanent Magnet-Dual Mechanical Ports which considered as Electrical Variable Transmission and considered the vehicle specifications of the Prius HEV. The conclusion of Ahmed and Cui [6] work is that the Toyota Hybrid System (THS) transmission particularly the Prius Series-Parallel Hybrid Electric Vehicle (SPHEV) can be successfully replaced by the proposed HEV system based on the Permanent Magnet Electric Variable Transmission (PM-EVT) machines.

Renewable energy sources, particularly solar energy have been adopted in many studies to deliver clean and cheap energy, this energy can be converted to an electrical power using the photovoltaic (PV) panel [7]. Many applications of several kilowatts range PV systems have been proposed in as a stand-alone systems to mitigate the load over the grid electrical power in indirect way in reducing the usage of the fossil fuel [8]. The panel can deliver the desired power level in PV systems, as low level or high level PV supply with a specific voltage and current levels by connecting the PV cells serial and/or parallel [9].

In terms of HEV, the output power of the PV panel can be used to charge the battery bank of the electric vehicle (EV) instead of the alternating grid supply. In other words, the battery bank can be charged by the additional renewable supply in the same EV [10]. Solar vehicle is a valuable HEV because it can replace the traditional fossil fuel vehicle.

International Rectifier Company has had a first attempt to manufacture a solar car which is a modified module of the Baker electric car 1912, the attempt was installing individual solar cells around 10,640 on the car's rooftop [11]. Other attempts have been introduced for more effective solar vehicles, University of Michigan solar HEV [12], Sunstang solar HEV [13], Prince Mohammad bin Fahd University solar HEV [14], and University of Adelaide solar HEV [15].

In addition, there are many research studies have been focused of improving the performance of the HEV powered by solar energy through different considerations,

different renewable energy sources have been reviewed in Zhang *et al.* [16], then, a hybrid thermoelectric-photovoltaic energy source has been presented for HEV applications, and the successfully investigated.

An ultra-capacitor with a battery bank have been proposed as a hybrid energy storage system for HEV application in Zhang *et al.* [17]. A new design of motor running by battery beside the internal combustion engine of fossil fuels has been presented through Rajkumar *et al.* [18]. A small scale of HEV in terms of power, speed, and dimensions powered by solar energy has been presented in Sankar and Seyezhai [19]. The study designed, implemented the HEV involving the PV panel, the battery and the charger, the converter, the inverter, in addition to direct current moto. MATLAB/SIMULINK modelling, simulation and implementing steps have been developed and investigated. Whereas the study [20] of has been proposed other HEV powered by solar energy of average speed of 40 km/h.

Different aspects in designing and implementing a small size solar vehicle have been presented in Spina *et al.* [21], an experimental solar vehicle named Pampa Solar has been manufactured, and successfully tested.

The above mention studies are common in the limitations in terms of maximum speed, no more than one passenger, and missing of the analysis of power requirements with respect to the specifications of mechanical structure shape, dimensions, and total mass.

Based on the mentioned demerits of the previous studies, this paper presents a new design and implementation steps of a new module of HEV powered by solar energy. The presented solar car considered increasing the maximum speed limit, able to carry more than one passenger, and flexible in design modifying.

PREVIOUS ATTEMPTS OF SOLAR ELECTRIC VEHICLE

Four different modules of solar HEV will be shown in this section, these attempts have been done by different universities and research institutions. Many advantages and disadvantages are carried out with these attempts.

University of Michigan Solar Hybrid Electric Vehicle

This car has been powered by 6 m² of PV panels in order to provide 1.5 kW power, this harvested power charges a 5 kWh lithium-ion battery. The solar panels are fixed on the car's roof as shown in Figure 1a, Aurum could reach a speed of 65 to 70 km/h [12].

Sunstang Solar Hybrid Electric Vehicle Project

This solar car has been focused on having a chassis of a high strength tabulated aluminium frame as shown in Figure 1b. The car driving has been done by an in-wheel brushless Direct Current (DC) electric motor. A battery bank of the lithium cells was providing a normal 120 V at 30 Ah current delivering rate [13].

Prince Mohammad bin Fahd University, Saudi Arabia

The material of this solar car's frame and base has been constructed by the Aluminium (6061-T6) as shown in Figure 1c. The PV panels' type is mono crystalline, the panels have been used for charging the battery 48 V and 100 Ah [14].

University of Adelaide, Australia

The body of this solar HEV has been manufactured by carbon and glass-fibre. Silicon-based solar cells array of 6 m² has been fixed on the car topside as shown in Figure 1d. The solar panels have been designed to charge a battery of lithium-ion Panasonic cells. A high efficiency in-wheel electric motor has been selected for car running [15].

All of the mentioned above modules of solar HEV in Figure 1, the solar cars are suffering from a low efficiency of PV panels due to adopting a flexible type to be used for power supplying, and the limitation of one passengers.

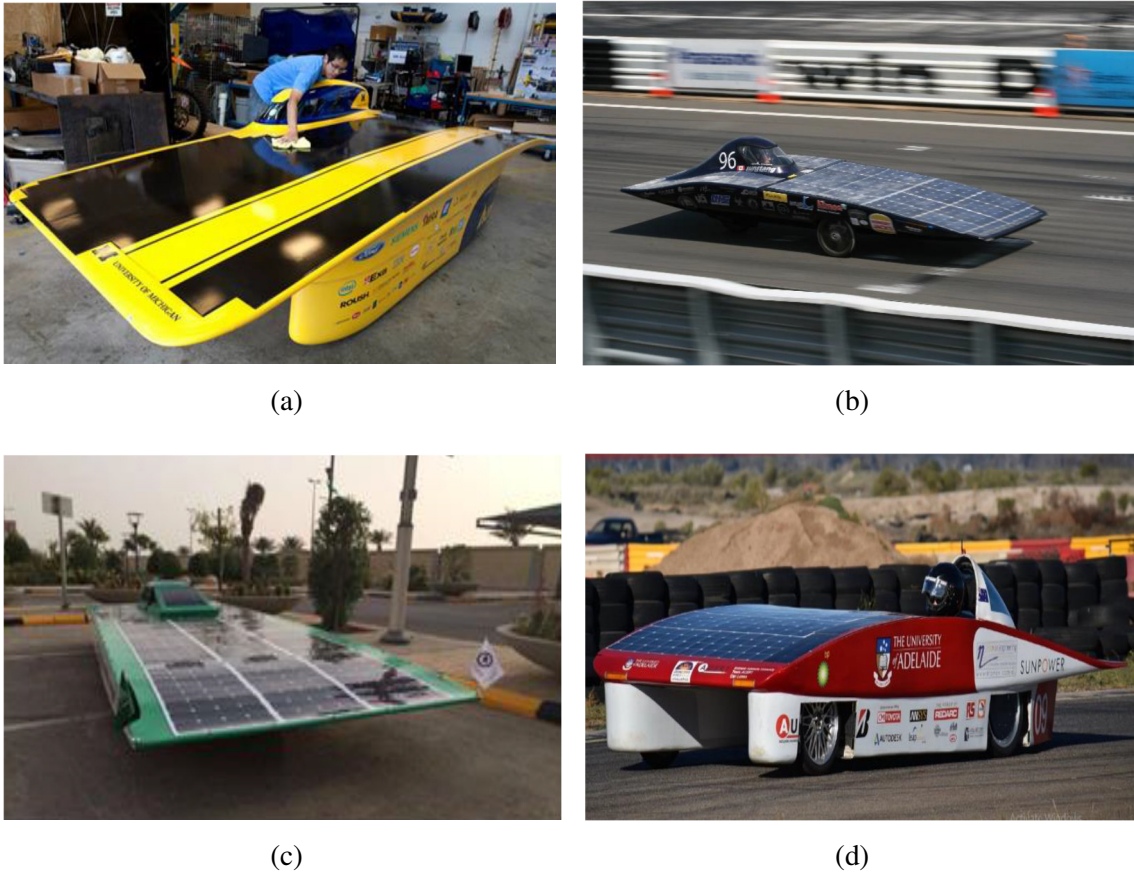


Figure 1. The previous modules of the solar HEV: University of Michigan solar HEV [12] (a); Sunstang solar HEV project [13] (b); Prince Mohammad bin Fahd University solar HEV [14] (c) and University of Adelaide solar HEV [15] (d)

PROPOSED SOLAR HYBRID ELECTRIC VEHICLE

Based on the mentioned demerits of the proposed solar HEVs, this study presents a new design and implementation steps of a solar HEV which have been done in American University of Ras Al Khaimah. The proposed design focuses on increasing the number of passengers from one to two, with considering the effect of total vehicle and passengers' mass on the power requirements.

Power calculation

By considering the mechanical structure design (shape and mass) in order to have a maximum speed limit of 100 km/h through reducing the aerodynamic effect, and other related mechanical parameters as shown in Table 1, the required electrical power can be calculated. Table 2 shows the range of the required power for different vehicle speeds using eqs. (1-3) [22], Figure 2 draws the power trend with respect to vehicle speed.

$$P = (F_r + F_D)V_m \quad (1)$$

$$P = (C_{rr} m g + 0.5 \rho C_D A V_m^2)V_m \quad (2)$$

$$P = (24.525 + F_D) V_m \quad (3)$$

where P [W] is the required power for car moving, F_r [N] is the force of rolling resistance, F_D [N] is the car drag force in, V_m [m/s] is the speed of the car, C_{rr} is the rolling coefficient, m [kg] is the total mass of car including 2 passengers. The gravitational acceleration [m/s²] is represented by g , ρ [kg/m³] is the air density, C_D is the drag coefficient, and finally, A [m²] is the frontal area of the car.

Table 1. The list of the desired mechanical parameters

Parameter	Value
Total mass (m) [kg]	500
Velocity (V_m) [km/h]	100
Rolling coefficient (C_{rr})	0.005
Earth gravity (g) [m/s ²]	9.81
Air density (ρ) [kg/m ³]	1.2
Drag coefficient (C_D)	0.4
Frontal area (A) [m ²]	2

Table 2. The required power for different speeds of the solar car

Solar HEV speed [km/h]	Solar HEV speed (V_m) [m/s]	Drag force (F_D) [N]	Suitable power (P) [kW]
10	2.778	3.704	0.078
20	5.556	14.817	0.219
30	8.333	33.331	0.482
40	11.111	59.258	0.931
50	13.889	92.594	1.627
60	16.667	133.339	2.631
70	19.444	181.473	4.005
80	22.222	237.032	5.812
90	25.000	300.000	8.113
100	27.778	370.376	10.970

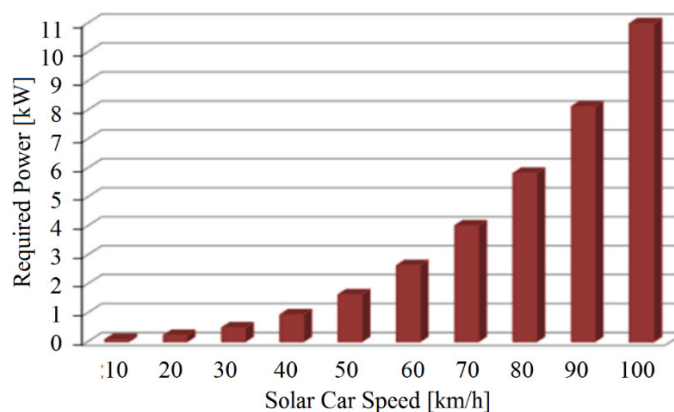


Figure 2. The trend of the required power with respect to vehicle speed

System block diagram

This study presents a new design of the solar HEV which is shown in Figure 3, the design is considered by explained power requirements. The design includes PV array which serves as a renewable DC source, battery charger which is involved for battery charging function, battery bank for solar energy saving and serves as a stable supply for the two speed drives. The two rear wheels motor drives supply the rear motors separately

for vehicle motion. The design facilitates the connecting and wiring steps of the involved electrical devices to be able to connect in the engineering’s workshop of the school of engineering of the university.

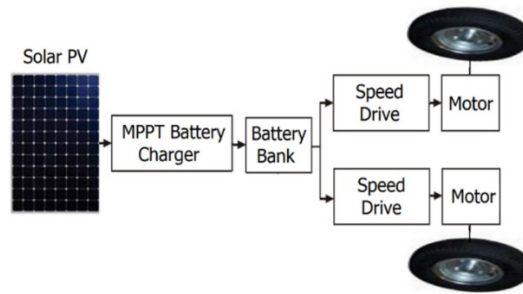


Figure 3. Block diagram of the proposed design of the solar HEV

Solar panel function is converting the incident solar energy into a certain quantity of the electrical power [23]. The solar PV array involves 3 panel module SPR-E19-320W of 19% efficiency. Table 3 shows the selected PV panel specifications [24]. The dimensions of the selected PV panels are matched with the vehicle’s dimensions.

Table 3. The specifications of the selected solar panel module SPR-E19-320W

Parameter	Value
Dimensions [mm]	1,559 × 1,046 × 46
Weight [kg]	18.6
Peak power [W]	320
Efficiency [%]	19.6
Rated voltage (V_{mpp}) [V]	54.7
Rated current (I_{mpp}) [A]	5.86
Open circuit voltage [V]	64.8
Short circuit current [A]	6.24

One PV panel module SPR-E19-320W is tested outdoors in front of the material lab in the university, Figure 4 shows the PV panel performance during a day timing from 8:00 AM to 5:00 PM. The test is done by connecting a resistive load of 11 Ω, and by recording the load current and voltage, then the load power is calculated by multiplying the instantaneous records of the load current and the load voltage. It is noticeable that the high power levels are shown between 10:00 AM and 2:30 PM.

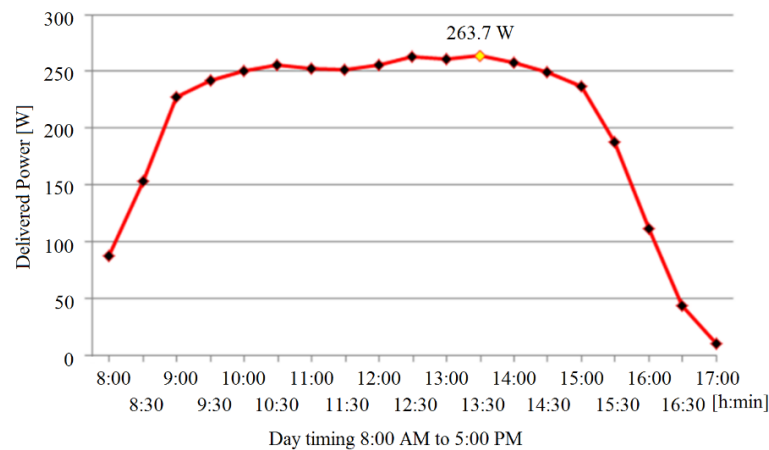


Figure 4. PV panel performance during day timing

The solar charge controller is an important device in the solar PV system applications, this device controls the charging current drawn from the solar panel/array/matrix to the batteries. The charge controller protects the battery from the overvoltage and/or reverse current flow. Solar cars typically use Maximum Power Point Trackers (MPPTs), but due to the market limitations, the type of the selected battery charge controller is from the category of Pulse Width Modulator (PWM) battery charger of rated voltage 48 V, and maximum charging current of 45 A. Figure 5a shows the physical view of the selected battery charge controller.

Since the rate of power generation from the solar PV panels less than the rated power of the HEV motors, battery bank is necessary to deliver the required power for vehicle motion, saving the solar energy as an electrical energy, and to deliver a stable direct current link supply voltage. The designed battery bank involves four individual rechargeable lithium ion batteries, each of 12 V/200 Ah. The four batteries are connected serially as shown in Figure 5b to deliver 48 V with current delivering ability of 200 Ah.

Pulse width modulation technique based drive has been adopted in this study to drive and control the car' motors speed [25]. In the proposed design, there are 2 drives which are individually controlling the load powers by controlling the duty cycle of the gate drive PWM pulses, the two drives are working through decentralized principle [26], to have the desired dimming of the load power based on the selected speed. The selected type of the speed drive is APT96600, 96 V sinusoidal brushless motor controller. The selected drive is able to work on an input voltage range of 42 to 120 V, with a maximum current limit of 600 A. The drive is a programmable device, so all of its parameters are setting by connecting the drive to the computer through RS232 serial cable. Figure 5c shows top view of the speed drive.

As seen earlier, the required power reaches to 11 kW to achieve the target speed of 100 km/h, so, in order to guarantee reaching to the desired speed, two gearless brushless DC hub motors with power of 6 kW are selected to have total power of 12 kW of rated power greater than the acceptable required power. The system voltage is designed to be 48 V that to be matched with the earlier stages of the main block diagram. Figure 5d shows one of the selected motors, with the brake disc installed.



(a)



(b)



(c)



(d)

Figure 5. Physical views of the selected electrical parts in the solar HEV: battery charger (a); battery bank (b); motor speed drive (c) and motor 6 kW (d)

Figure 6 shows the electrical parts included in the designed and implemented solar car.

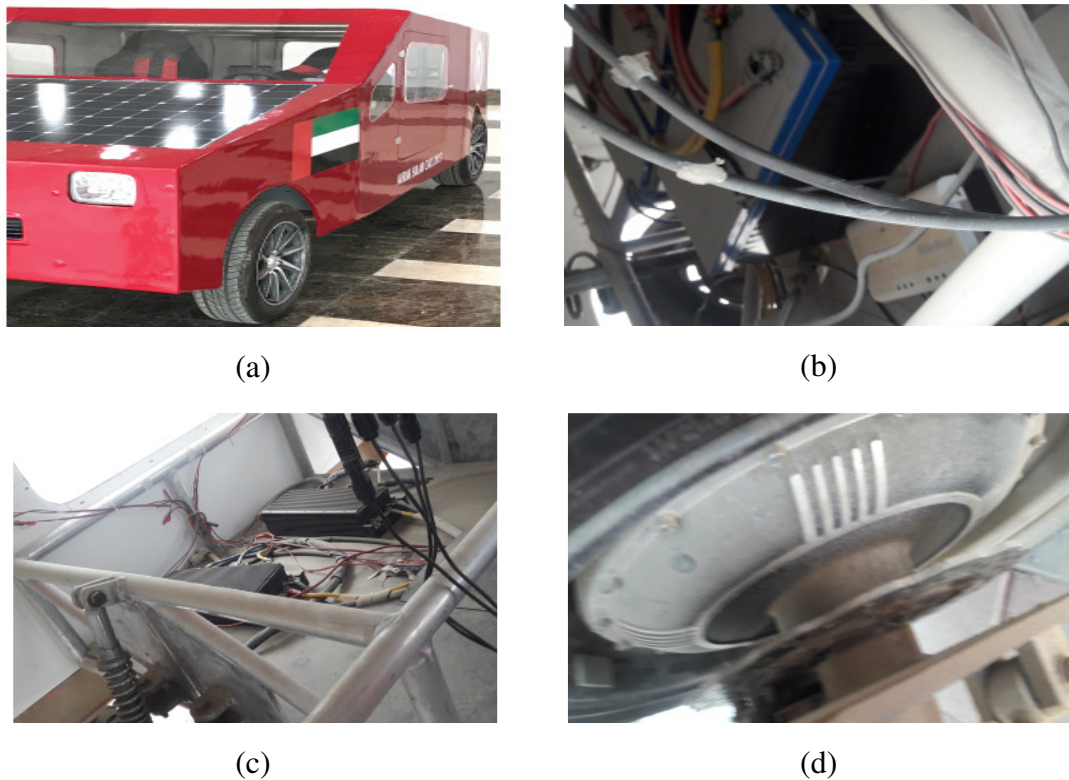


Figure 6. Physical views of the implemented solar car which are including the electrical parts: PV array on top of the car (a); battery charger and battery bank (b); motor speed drive (c) and in wheel motor 6 kW (d)

The involved accessories in the implemented car are represented by a set of front lights, back lights, two sides lights, in addition to a set of relays. It is deserve to explain that the function of the relays set is controlling the light lamps, and the speed drives' selectors. All the mentioned accessories are from the category of the direct current DC loads which are working on 12 and 24 V. In order to avoid the fluctuation of the supplied DC link voltage, a DC-DC converters of 12 and 24 V are inserted in the electrical system. The implemented system also includes a set of high current fuses and a set of circuit breakers in order to protect the system against the over current and to facilitate the system operation.

DRIVING AND CHARGING DURATIONS

This section explains the detailed calculations, firstly for the drive time of the designed and implemented solar HEV, and secondly, for the required charging time of the system's battery bank.

Drive time

To determine the drive time, firstly, it is needed to determine the motor rated current from eq. (4):

$$P = I \times V \quad (4)$$

where P [W] is the power, I [A] is the current, and V [V] is the voltage, $I = P/V = 12,000/48 = 250$ A.

$$\text{Drive time} = \text{Battery capacity} / I_{\text{Motor}} \quad (5)$$

where drive time = 200 Ah/250 A = 0.8 h = 48 min.

Battery charging time

The charging time depends on the capacity of the battery bank and the level of the provided current by the panels:

$$\text{Charging time} = \text{Battery capacity} / I_{\text{Charge}} \quad (6)$$

The quantity of the harvested power from the PV array = $3 \times 320 \text{ W} = 960 \text{ W}$. Maximum I_{Charge} which can be delivered by PV array = $P/V = 960/48 = 20 \text{ A}$. So, the charging time = 200 Ah/20 A = 10 hours.

From the above equations, the battery bank takes around 10 hours for full charge.

ASPECTS OF PERFORMANCE IMPROVEMENT

The presented design is characterized by the flexibility in terms of the design modifying leading to the system's performance enhancement. From this point of view, this section focuses on increasing the harvested power from solar energy by replacing the selected PV panels by other type of higher power such as SL360TU-36MD of peak power 360 W, and study the positive effects of this replacement on the charging time length.

The harvested quantity of rated power from solar array = $3 \times 360 \text{ W} = 1,080 \text{ W}$. Maximum I_{Charge} that can be delivered from solar array = $P/V = 1,080/48 = 22.5 \text{ A}$. So, charging time = 200 Ah/22.5 A = 8.9 hours.

It is clearly noticeable that the reduction of the charging time by around 11% of the battery bank.

Based on the above analysis, to enhance the level of the harvested power from solar energy, either select a higher power PV panel or increase the number of the PV panels by fixing additional flexible type PV panels on the car sides.

In terms of increase the maximum limit of the car speed, the motor type is needed to be reconsidered with respect to speed capability.

On the other hand, to improve the car performance, the car's structure mass can be reduced, either by modifying the structure shape or by selecting a lighter metal in order to have a reduction in the power requirement.

In addition, MPPT functioning of the battery bank charge controller will increase the level of the harvesting power and consequently will contribute positively in system enhancement. The MPPT capability and the system losses analysis are subjected as a future works of this study.

All the above mentioned improving aspects (in case adopted) definitely will enhance the car performance in terms of battery bank charging time, driving time, and maximum speed limit.

Here, it deserves to mention that for system improving, additional parameters are needed to be considered, such as, physical dimensions, and PV panel specifications.

CONCLUSION AND FUTURE WORKS

AURAK solar car is presented in this paper as a hybrid electric vehicles powered by solar energy. Firstly, the required electrical power with respect to the maximum limit of vehicle' speed is calculated, the speed calculation is considered the mechanical design of the car structure and the allowable mass limit. Secondly, the implementation steps of the solar HEV is done based on a new electrical system design. Solar energy is adopted as an

important renewable energy source to charge the designed battery bank through PWM battery charge controller. Then, the manufactured solar car is tested and driven successfully inside AURAK University. The driving indicated the integration and the matching among the vehicle's parts and promising for high performance prototype. The future work sides for performance improving can be represented by selecting more efficient PV panel with adopting MPPT, selecting thinner wheels to reduce the friction effects, as well as reduce the car's structure mass. All the mentioned future sides if considered, the system performance definitely will be improved in terms of reduction the charging time of the battery bank, and increasing the driving time of the car.

NOMENCLATURE

A	frontal area	$[m^2]$
C_D	drag coefficient	$[-]$
C_{rr}	rolling coefficient	$[-]$
F_D	drag force	$[N]$
F_r	rolling resistance force	$[N]$
g	earth gravity	$[m/s^2]$
I	current	$[A]$
m	mass	$[kg]$
P	required power	$[W]$
V	voltage	$[V]$
V_m	maximum velocity	$[km/h]$

Greek letters

ρ	air density	$[kg/m^3]$
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