Design of Solar Powered BLDC Motor Driven Electric Vehicle

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Abstract-Any equipment without power is an idle bunch of components.It is very prominent with those dependable upon the non-renewable sources.It's a pro-active approach to shift our source of energy to renewable source.This paper details the study of designing a Solar Powered BLDC Motor Driven Electric Vehicle which is one of the solutions for the oncoming crisis.The approach of selecting the appropriate components for this application is studied and each of them are simulated and subjected to various tests in real time environment.The integrated system consisting of the solar module, charge controllers, batteries, boost converter and BLDC motor, henceforth developed into the Solar Powered Electric Vehicle.

Keywords-Solar Vehicle, Photovoltaic, Renewable energy, BLDC motor

1. Introduction

This paper discusses about the usage of solar energy to power up the vehicle.In order to achieve the required voltage, the Photo Voltaic (PV) Module may be connected either in parallel or series, but it's costlier.Thus to make it cost effective; power converters and batteries are been used.The electrical charge is consolidated from the PV panel and directed to the output terminals to produce low voltage (Direct Current). The charge controllers direct this power acquired from the solar panel to the batteries.According to the state of the battery, the charging is done, so as to avoid overcharging and deep discharge.The voltage is then boosted up using the boost power converter, ultimately running the BLDC motor which is used as the drive motor for our vehicle application.In the course work, the characteristic features of the components; solar panel, charge controller, battery, power converter and BLDC motor required for the vehicle application were studied in real time and also were modelled individually using MATLAB/SIMULINK and the complete hardware integration of the system is tested to meet up the application's requirement.

2. Acquiring Power from the Sun

The first part of this paper deals about how to acquire the power from the sun, and there on to recharge the battery.The second part deals with using the power from battery in running and controlling the motor and recharging the battery simultaneously.The rating of the components required for this work is completely based on the motor which is to be used for the application.We are using the 500Watts (48V, 10.5A) BLDC motor for our application.According to the rating of the motor the other hardware components are selected.In order to drive the BLDC motor through the batteries, we would require four batteries of rating 12V/42Ah connected in series; which increase the cost of the vehicle expected to design.In order to avoid this, the boost power converter is used; which can boost to the required rated voltage with half the number of batteries actually required.In this work, two Amaron Quanta 12V/42Ah batteries are connected in series and then it's boosted to the rated voltage (48V).

After selecting the batteries, the solar controller and the solar panels are to be selected.A single battery's voltage is 12V; we must look for solar panels which could deliver the required charging voltage of 12±2V individually so as to charge the batteries.The Tata BP Solar 40W and 35W solar panels are used for this work.The complete flow of the work is represented in the schematic diagram in Fig 1.Once the components for the work are finalized, the corresponding simulation studies and the hardware testing are done.

2.1. Current Voltage relationship of solar module

The solar module consists of a set of solar cells connected in parallel and series to meet up the power requirement.Initially a solar cell is simulated using M-file in MATLAB [1], and thereon it's done for the whole module (40W solar panel is considered) using the current-voltage relationship equation given below.The simulated result is shown in Fig 2(a), with the Open circuit voltage (Voc) about 43V and the Short circuit current (Isc) around 4.8A.The solar module has an adverse effect on Temperature and Irradiance.As the module temperature (TaC) increases, the module voltage drastically decreases and the module current decreases gradually.Likewise, when the Irradiance (G) increases, the module current increases drastically while the module voltage increases very gradually [2].The simulated outputs for the effects of Temperature and Irradiance for the 40W solar module are shown in Fig 2(b) and 2(c) respectively.

$$I = I_{sc} - I_o\left[e^{q\left(\frac{V+I.R_s}{nkT}\right)} - 1\right] - \left(\frac{V+I.R_s}{R_p}\right) \qquad (1)$$

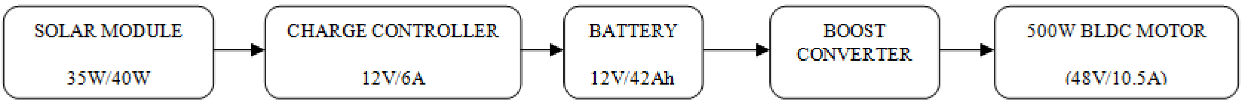

Fig 1. Schematic approach of the whole system

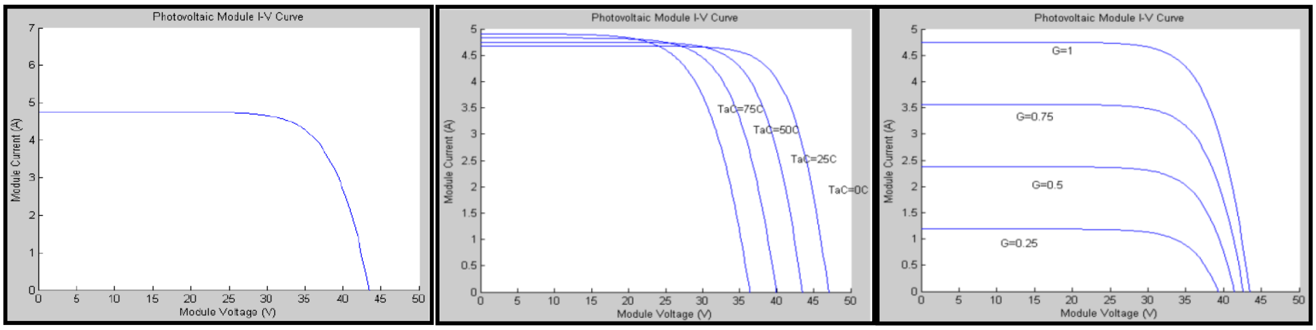

Fig 2. a) IV curve of the 40W solar module b) Effect of Temperature c) Effect of Irradiance

Where *I* is the cell current,

V - Cell voltage

Q - Electron charge (1.602e-19)

K - Boltsmann's constant (1.381e-23)

T - Temperature in Kelvin

I_o - Reverse saturation current of the diode

N - Diode ideality factor and takes the value between one and two.

The solar modules (35W solar module is considered for the below discussion) were also tested in real conditions with a resistor connected in parallel with the module [2].For different resistance values (used rheostat to vary the resistance) the voltage and the current were observed and tabulated in Table 1.Using these values, the graph (refer Fig 3) was plotted; which approximately matched with the simulated result and also with the manufacturers graph.

The 40W and 35W solar modules can be connected in parallel or series according to the requirement of the application.The observation tabulated in Table 2 emphasizes that to increase the output voltage using two or more solar modules; they must be connected serially.On the other hand, to increase the current rating, it must be connected in parallel.Depending upon the need of the application, the appropriate connections can be made.A combination of serial and parallel connection is also possible to meet the need.

Table 1. Solar Module Testing Observation

Resistance(Ω)	Module Voltage(*V*)	Module Current(*A*)
0	0	1.6 (I_{sc})
9.33	14	1.5
10.90	15.27	1.4
14.05	16.87	1.2
17.38	17.38	1
22.25	17.8	0.8
25.78	18.05	0.7
36.95	18.48	0.5
46.52	18.61	0.4
62.5	18.75	0.3
95	19	0.2
Infinity	19.4 (V_{oc})	0

Table 2. Solar Module connected in Parallel and Series

Type Of Connection	Open Circuit Voltage (V_{oc})	Short Circuit Current (I_{sc})
Series	37.5	1.6
Parallel	19.6	4.3

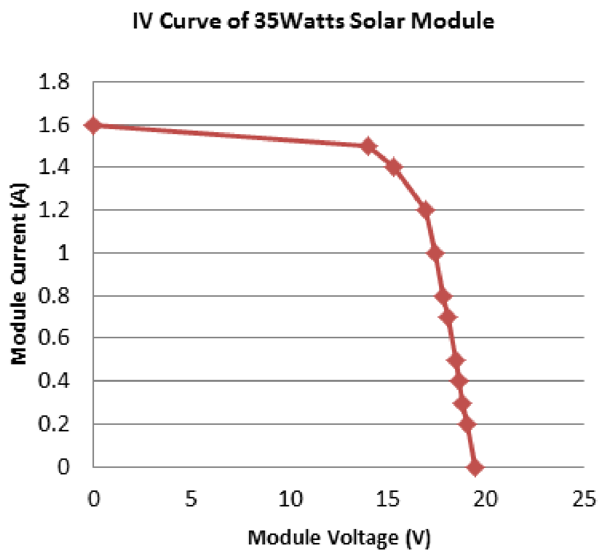

Fig 3. IV curve plotted with the observation done on a partly cloudy weather condition

2.2. Charging the Batteries through the Charge Controllers

Charge Controller limits the rate at which electric current is added to or drawn from the electric batteries.The prime purpose of using the Charge Controller is to prevent against overcharging and deep discharging of a battery.For the 12V/42Ah battery, 12V/6A solar charge controller is an ideal choice.According to the rating of the battery and solar module the selection of the charge controller is done.Two charge controllers are connected between the solar modules (35W and 40W) and the batteries individually.As the next step, the battery is studied and simulated.The battery is modeled using a simple controlled voltage source in series with a constant resistance [3], as shown in Fig 4.This model assumes the same characteristics for the charge and discharge cycles.The open voltage is calculated with non-linear equation based on the actual State of Charge (SOC) of the battery.

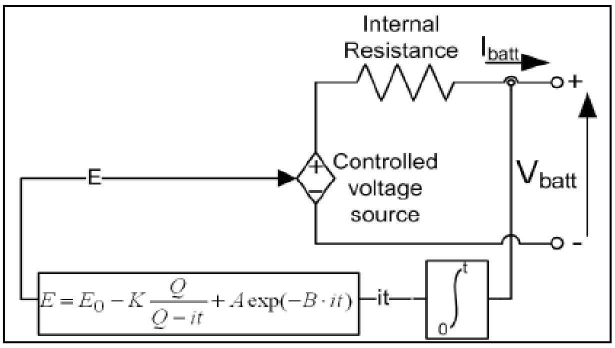

Fig 4. Non-Linear battery model

The simulation of the battery is done using MATLAB/Simulink.The controlled voltage source is described in equation (2).

$$E = E_o K \frac{Q}{Q-it} Aexp(-B.it) \qquad (2)$$

E = no-load voltage (V)
E_o = battery constant voltage (V)
K = polarization voltage (V)
Q = battery capacity (Ah)
$\int i_{dt}$ = actual battery charge (Ah)
A = exponential zone amplitude (V)
B = exponential zone time constant inverse (Ah)-1
V_{bat} = battery voltage (V)
R = internal resistance (Ω)
i = battery current (A)

The simulated output in Fig 5 shows the discharge characteristics over a period of time.It's been observed that according to the load, the discharge of the battery varies.The 12V/42Ah battery can supply the specified 12V for 42hours, if the demanded ampere rating is one, which means it will take 42hours for the battery to discharge.While on the other hand, the same battery can deliver 42 ampere for an hour and get deeply discharged.Thus it depends upon the requirement of the current rating of the application, that the batteries are chosen.

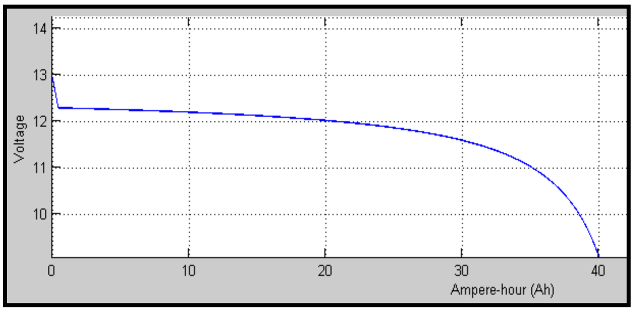

Fig 5. Discharge curve of the 12V/42Ah battery

This brings to the completion of the first phase; acquiring the energy from the sun.The solar energy is tapped from the solar modules and then through the charge controller the batteries are charged.Fig 6 depicts the first phase of the work.

Fig 6. Acquiring power from sun

3. Power from the Batteries to Motor

In the next phase of the work, the power which is stored in the batteries is used in driving the BLDC motor.In this phase the detail study of motor is done and simulated.The specification of the BLDC motor is given in Table 3.From the specification it's well understood that the required voltage to run the motor is 48V, while the rated voltage of a single battery is 12V.Thus to achieve the rated voltage of the motor; we are in need of four batteries which when connected in series can satisfy the requirement. In order to make it cost effective, two batteries are connected serially, giving 24V as the output voltage.This 24V from the serially connected batteries are then boosted to 48V using the boost converter.

Table 3. Specification of the BLDC Motor

Power	500Watts
Rated Voltage	48V
Rated Current	10.5A
Rated Speed	3500rpm
Rated Torque	198 oz-in
No load Current	1.6A

Direct Current (DC) converters can be used as switching-mode regulators to convert a DC voltage, normally unregulated, to a regulated DC output voltage.The regulation is normally achieved by PWM at a fixed frequency and the switching device is normally BJT, MOSFET or IGBT [4, 5].The electrical circuit of the boost converter is shown in Fig 7.The input voltage 24V is been given as the input for the boost converter, which is boosted up to 48V.The simulated output (MATLAB/SimuLink) of the boost converter is shown in Fig 8.

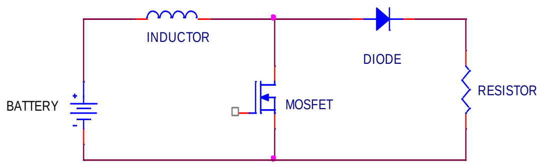

Fig 7. Boost converter circuit

The hardware designing part of the boost converter involves a lot of precision in choosing the inductor (sometimes it's designed by oneself).The input voltage given to the boost converter varies from 21V to 25.5V, while the output of the converter is fixed 48V.The switching frequency used for the boost converter is 20 KHz. The design specification for the boost converter is given in Table 4.

Table 4. Design Specification of Boost Converter

Input Voltage *(V_{in})*	21V-25.5V (min. and max voltage of the battery)
Output Voltage *(V_o)*	48V
Switching frequency *(f_s)*	20KHz
Duty Cycle *(D)*	0.51

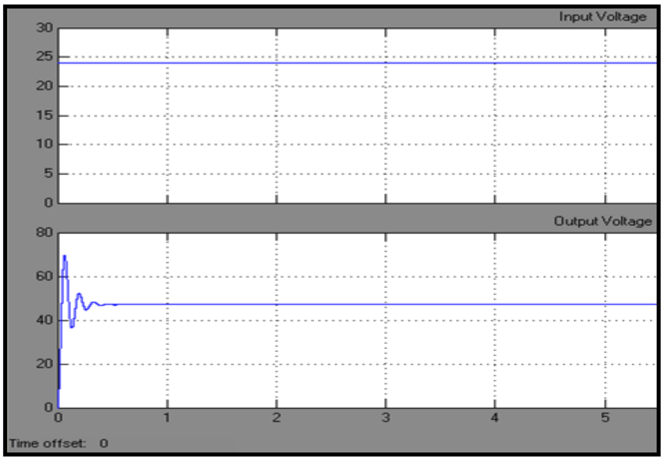

Fig 8. Input and Output voltage of the boost converter

The switching diode used in the boost converter must withstand a reverse voltage equal to the circuit output voltage and must conduct the peak output current.A suitable diode must have a minimum reverse breakdown voltage greater than the circuit output voltage.Schottky barrier diodes are often used.The current supplied to the output RC circuit is discontinuous.Thus a larger filter capacitor is required to limit the output voltage ripple.The filter capacitor must provide the output DC current to the load when the diode is off.

The ripple current charges the capacitor during each switching cycle [6].The open circuit voltage of the battery is 25.5V and the output voltage is 48V.The diode factor is taken as 0.8, the switching and mosfet parameters are taken as 0.3. The value of inductor (L) is been calculated using equation (3),

$$L = \frac{V_o \delta_{Tmin}(1-\delta_{Tmin})}{\Delta I_L f} = 52.3\mu H \approx 54\mu \quad (3)$$

In a boost converter the output voltage is greater than the input voltage.The boost converter required for the Solar Powered BLDC Driven Electric Vehicle needs 24V (from batteries connected in series) to 48V (required rated voltage of BLDC motor).Fig 9 shows the designed boost converter for the vehicle application.

Fig 9. Hardware design of the boost converter

4. Driving the Motor

The Brushless DC (BLDC) motor is used as the drive motor for the vehicle.It's a permanent magnet square wave motor.BLDC motor uses feedback directly of the rotor angular position so that the input armature current can be switched among the motor phases in exact synchronization with the rotor motion.The specification of the BLDC motor is given in Table 3.The reason for opting for the BLDC motor is because of its efficiency, noiseless operation, dynamic response and high torque to weight ratio.

The simulation results (as shown in Fig 10 and Fig 11) of the BLDC motor shows that initially motor goes to its rated speed and settles at t=4 sec. Corresponding electro torque also changes.Results are presented under the operating condition for the same in closed loop condition, for which the reference speed is set 150 rad/sec, load torque of 0.5Nm is applied at t=10sec.

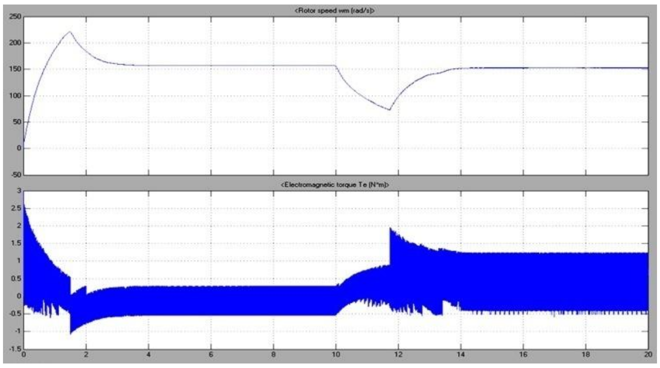

Fig. 10. Speed variation of motor and electromagnetic torque waveforms for a step change in load of 0.5Nm at t=10sec for closed loop

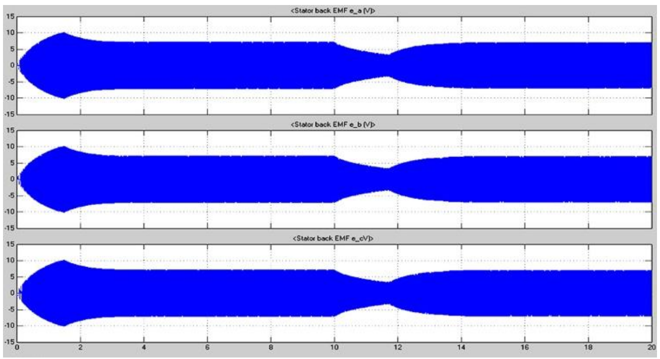

Fig. 11. Back EMF waveforms for a step change in Load of 0.5Nm at t=10

The BLDC motor is coupled with the DC generator (7.5A, 75V) to perform the load test in open loop condition.In the No-Load and Loaded condition, the starting current is been taken into consideration.Some of the observation of the BLDC motor in various loaded conditions is tabulated in Table 6.From the table, it's observed that as the load current is been increased, the current drawn by the motor increases. While the speed of the motor starts decreasing, when the load is been increased [8].

Table 6. Motor Reading at various Load Conditions

DC Generator		BLDC Motor	
Voltage (V)	Load Current (A)	Line Current (A)	Speed (rpm)
6.4	0.3	1.4	1000
5.75	1	1.61	991
5	2	1.89	976.5
4	2.5	2.25	959.75
3	3.2	2.7	942.5
2	4	3.2	925.5
0.5	5.5	3.9	897.5
0.07	5.7	4.05	891.25

The load test directly reflects to the speed of the vehicle with respect to the load.For a vehicle, irrespective of the driver; the wind force, friction, incline or decline movement, and the weight of vehicle (for a solar powered vehicle; the solar modules, batteries, controllers and motor) are the parameters that affect the speed of the motor, thereby affecting the speed of the vehicle [7].The permanent magnet creates rotor flux and stator creates electromagnetic poles.The rotor is attracted by the energized stator phase generating a rotation.BLDC motor requires an inverter and a position detector to perform commutation. BLDC motor is electronically controlled and requires rotor position information for proper commutations of current.

At various speed conditions, the input current for the converter from the battery were noted.The starting current of the motor was observed to be 1.7Amps in no-load condition.From the observations at various speeds tabulated in Table 7 we can see that as the speed of the motor is been increased, the current drawn from the battery also increases.It's observed that the motor draws 1.1Amps of current from the battery, which means; theoretically the battery can supply the motor for approximately 38hours.

In the next step of the work, the 500Watts BLDC motor is been run using the batteries whose (connected in series and thereby supplying 24V) output voltage is been boosted up to 48V using the boost converter, while the batteries are been charged by the solar modules concurrently.

Table 7. Input Current for Boost Converter from the Battery

Speed of the BLDC motor (rpm)	Input current of boost converter (A)
1000	0.9
2000	1.1
2500	1.4
3000	1.7
3500	1.9
4000	2.2

The setup is shown in Fig 12.Individually, the solar modules could supply only 12V and 1.5A at nominal conditions.These modules which when connected in series or parallel could not supply sufficient power to drive the BLDC motor of rating 48V/10.5A.Thus to meet this demand, two batteries of 12V/42Ah were connected in series to provide of 24V/42Ah, which was then boosted to the rated voltage of 48V.

Fig. 12. BLDC motor powered by the batteries with the boost converter

5. Integration of the System

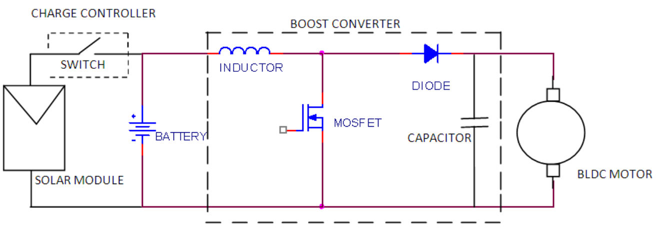

Fig. 13. Integration of the entire system

The complete integrated setup consists of the solar panel, solar charge controller, batteries, boost converter and finally the BLDC motor.The schematic diagram of the complete setup is shown as in Fig 13.Its observed that the input voltage of the boost converter from the batteries keeps decreasing since the battery discharges with respect to time (refer Fig 14), on the other hand the batteries are also been recharged using the soloar modules.The rate of discharge depends upon the load.From Table 8 we can observe the whole flow of the system.Its observed that the solar module charges the batteries, from the batteries which is connected in series, the 24V is been boosted to 48V to meet the required voltage of the BLDC motor.It is noticed that the 0.9A current values is halved to 0.45A when it throughs the boost conveter.And finally the motor current keeps increasing as the speed of the motor is increased.

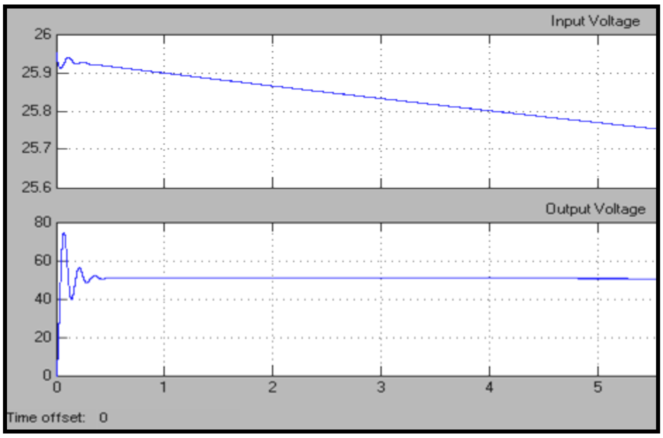

Fig. 14. Simulation output of the integrated system

6. Solar Powered Vehicle Prototype

The integration of the whole system evolves as the Solar Powered BLDC Motor Driven Electric Vehicle.The prototype of the vehicle (as shown in Fig 15) was designed with just forward and backward movement which was able to achieve a speed of 23Kmph.The rear axle of the vehicle is connected to the driving shaft of the BLDC motor through the fly wheel.With the change in motor, which has high torque, the vehicle would be capable of been driven with heavy load.The current from the batteries flows to the controller, which controls the whole control system of the vehicle.With respect to the movement of the accelerator, the controller sends forth the current, thereby increasing or decreasing the speed of the vehicle [9].

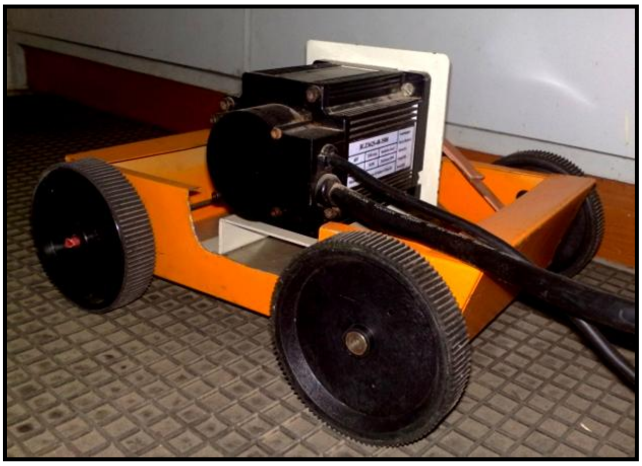

Fig. 15. Prototype of the Solar Powered Vehicle

Table 8. Integrated Setup Observations

Solar Module			Battery			Boost Converter			Motor			
V	A	W	V	A	W	V	A	W	V	A	Rpm	W
18.6	1.91	35.52	24	0.9	21.6	48	0.45	21.6	48	1.4	1000	67.20
			24	1.1	26.4	48	0.55	26.4	48	1.62	2000	77.76
			24	1.7	40.8	48	0.85	40.8	48	1.91	3000	92.16
			24	2.2	52.8	48	1.1	52.8	48	2.1	4000	100.8

7. Conclusion

The importance of making shift in the source of energy which is made cost effective was put forth, and utilization of solar power in vehicle application was implemented. The objective of selecting the appropriate components for the application was studied, and the various components for the same is subjected to various tests which was cross checked with simulation results too.The designing of the whole system depends on the application for which it shall be used, and accordingly the components are been chosen starting from the motor to the solar modules.It was observed that according to the application, the motor was chosen first.From the rating of the motor, the battery which could satisfy its starting current and full load current was been selected, and then according to the rating of the battery, the solar charge controllers and the solar modules were selected.Finally the BLDC motor mounted upon the frame realized the prototype of the vehicle which was tested at different load condition.

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