

Design and Implementation of a Simulation Tool for Solar Powered Electric Vehicle

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Abstract—Electric cars are becoming alternatives to combustion cars especially the “solar cars” which are becoming great interest for researchers. This paper is about mathematical modeling of different components of a solar powered electric car, using Simulink/MATLAB, to evaluate the characteristics of various components of the solar car and also the overall performance. The basic car components that are modelled are: solar panel, battery, traction motor, charge controller and speed controller. The models of all the system components are integrated together to represent a complete dynamic model of a solar car, which is tested for different environmental conditions.

Key words— Solar car, Simulink/MATLAB, Mathematical modeling

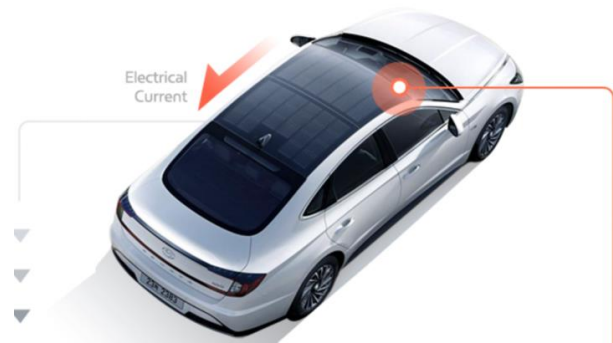


Figure 1 Hybrid Hyundai Sonata [8]

I. INTRODUCTION

The transportation is increasing every day with the increase in population which is leading to the emissions in the environment causing air pollution [1]. Also, the fuels are limited and their costs are ever increasing. It is important to now switch to some renewable and clean source of energy [2] [3].

Solar energy is a renewable source of energy which is environment friendly, never ending and free of cost. The continuous improvement in the solar energy field and increasing efficiency of solar cells has made the solar energy more attractive and fastest growing renewable energy [4].

The work on the solar car project has been started from many decades. However, the serious work in this field has begun from 1987, after the first world solar challenge (WSC), which was held in Australia for the purpose to enhance the interest of the researchers in the field of development of solar powered vehicles [5]. Since 1987, up till now, many solar cars have been invented by universities as a competition such as Shell Eco-Marathon. [6]

Commercially, Ford and Mazda have worked upon hybrid solar vehicle in which solar panel support headlights, indoor lightning and audio etc [6]. Hybrid Electric Vehicles (HEVs) are the step in the advancement towards Pure Electric Vehicles (PEVs) [7].

Also, with the addition of solar panels on the roof of the electric cars, the annual KMs of the car such as Hyundai can be increased by 1300Kms which turns out to be 4Km/day approximately [8].

However, there are still many limitations in the technology, especially in the field of energy management. The primary flaw with EVs is their autonomy. To extend driving range and reduce charging time, weight, and cost, scientists are continuously working on smarter battery technologies. These elements will ultimately define the future of Solar Electric Vehicles [9].

The work on the mathematical modeling of a complete solar car which gives a dynamic tool to the researchers to test their models according to the temperature, motor capacity, speed, weather conditions etc. somehow still lacks [10]. This paper is about developing electrical model for the solar car using Simulink to evaluate the characteristics of its various components with the capability to determine its overall performance.

The solar car components of the project include, PV module, battery, traction motor, charge controller and speed controller [11]. The block diagram in Figure 2 describing it briefly.

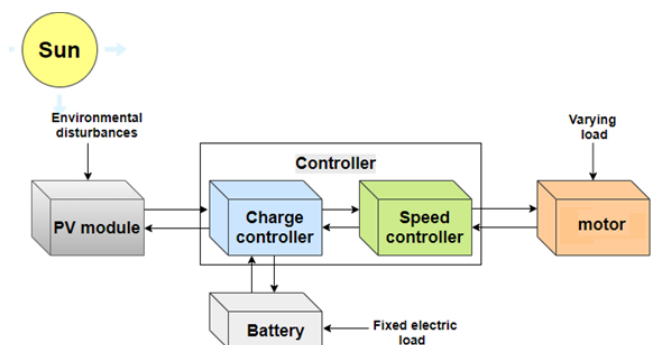


Figure 2 Block Diagram of Solar Car Model

1. PV Module

It is the solar panel, which is to convert the solar energy to electrical energy and give power to the car.

2. Battery

It is to store the electrical energy coming from the solar panel for the continuous input to the motor when required.

i. Electric Load

It is attached with the battery and includes the lightning load of car.

3. Traction motor

Traction motor is to convert the electrical energy to mechanical energy. It is connected with the wheels of the car to move it.

i. Varying Load

It is the mechanical load of the car on the motor.

4. Charge Controller

It is used with the battery to avoid over charging and over discharging of the battery.

5. Speed Controller

It is incorporated with the motor for the stable and required output speed.

II. SOLAR PANEL

Solar panel is to convert the sunlight directly into electrical energy which is stored by the battery and used to move the car [12].

A. Solar Cell and Solar Panel Equivalent Circuit

The solar cell acts as a current source in the presence of sunlight, while it is not an active device in the absence of sunlight and acts as a diode. Therefore, the ideal solar cell equivalent circuit is a current source connected in parallel with the diode. As, no solar cell is ideal therefore; resistances are connected in shunt (R_{sh}) and series (R_s), which represent internal resistance of cell. For simplification of analysis the R_{sh} and R_s are neglected as value of R_{sh} is very high and R_s is very low. **Figure 3** represents the equivalent solar cell model [13].

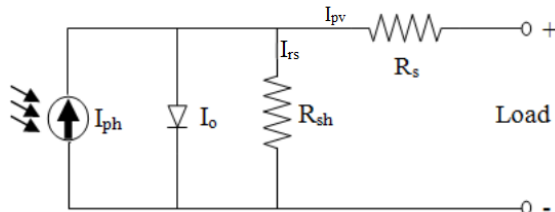


Figure 3 Equivalent Circuit of Solar Cell [13]

Solar panel has solar cells mounted in series and parallel. The equivalent circuit of solar panel is shown in **Figure 4**.

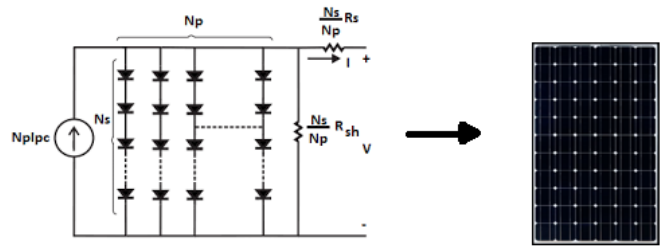


Figure 4 Equivalent Circuit of Solar Panel

1) Computation of Photovoltaic Current, I_{pv}

Photovoltaic current is computed by following the below steps:

The data provided by the manufacturer under standard test conditions is:

Maximum Power of Module, P_{max}

Short Circuit Current, I_{sc}

Open Circuit Voltage, V_{oc}

No of cells in series, N_s

No of cells in parallel, N_p

Calculation:

1. Photocurrent, I_{ph}

$$I_{ph} = [I_{scr} + K_i (T - T_r)] * \frac{G}{G_{ref}} \quad (1)$$

2. Reverse Saturation Current, I_{rs}

$$I_{rs} = I_{scr} \left[\exp \left(\frac{q \cdot V_{oc}}{N_s k A T} \right) - 1 \right] \quad (2)$$

3. Saturation Current, I_s

$$I_s = I_{rs} \left[\frac{T}{T_r} \right]^3 \exp \left[\frac{q E_g}{A k} * \left(\frac{1}{T_r} - \frac{1}{T} \right) \right] \quad (3)$$

4. Output Current, I_{pv}

$$I_{pv} = N_p * I_{ph} - N_p * I_s \left[\exp \left\{ \frac{q V_{pv} + I_{pv} * R_s}{N_s k A T} \right\} - 1 \right] \quad (4)$$

The parameters of equations 1-4 are given in the Table 1 [13].

Table 1 Current Equations Parameters

Symbol	Explanation	Value	Unit
G	Irradiance intensity	Input	W/m ²
G _{ref}	Reference Irradiance Intensity	1000	W/m ²
T	Temperature of module		K

T_r	Reference Temperature	$25^\circ\text{C} \approx 298\text{K}$	K
K_i	Current Temperature Coefficient		
Q	Electronic charge	1.6×10^{-19}	C
K	Boltzmann constant	1.38×10^{-23}	J/K
A	Ideality factor	1 (for ideal case)	
E_g	Energy band gap	1.16 (for silicon)	eV

2) *I-V and P-V Characteristics of a Solar Cell:*

Solar cell current vs. voltage I-V and power vs. voltage PV characteristic curves show the solar energy conversion ability and efficiency of a solar cell which helps in determining the device's output performance and solar efficiency.

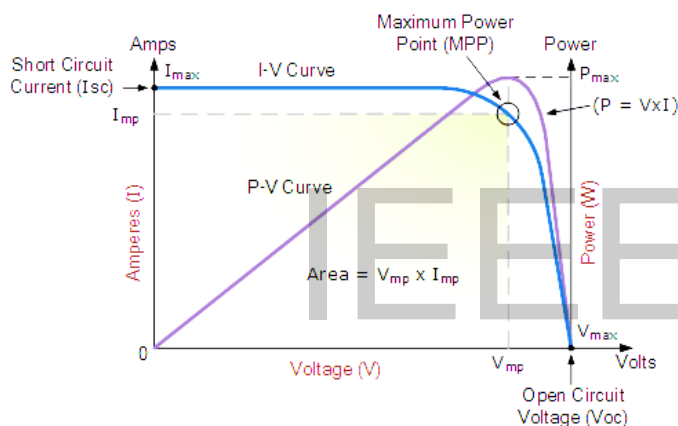


Figure 5 IV and PV Characteristics Curve of Solar Cell [14]

Figure 5 shows the IV and PV characteristics of a solar cell operating under normal conditions. There is a combination of I_{mp} and V_{mp} at which power reaches at its maximum point called P_{max} .

B. PV Module Simulink Model

The ideal operation of a solar cell is defined at its maximum power point. With the help of current equations, the Simulink model of PV module obtained, its masked model and masked parameters are shown by Figure 6 [15].

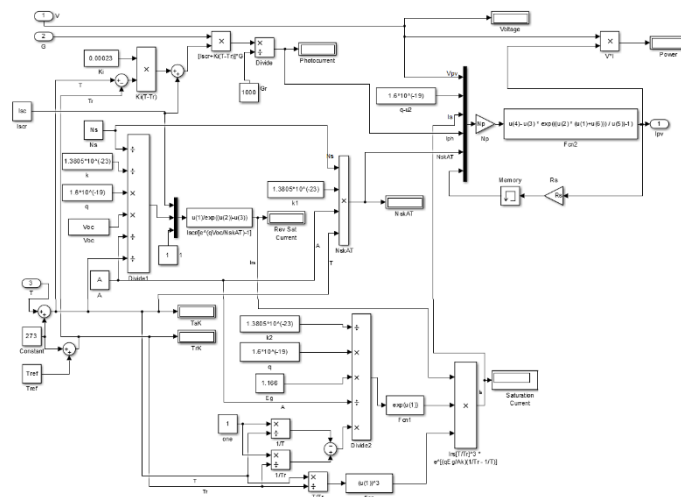


Figure 6 PV Module Simulink Model

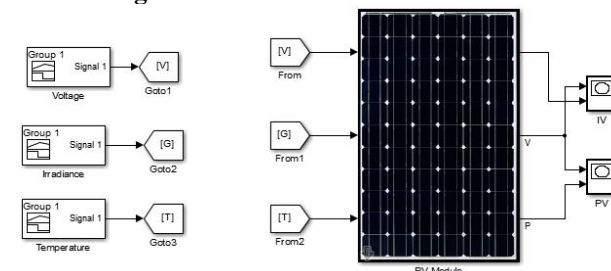


Figure 7 PV Module Masked Model

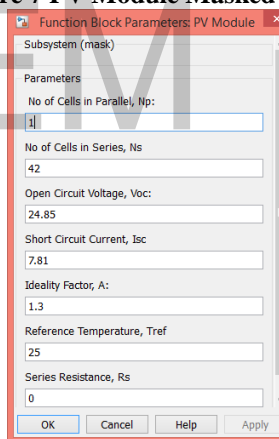


Figure 8 Masked Parameters

C. Model Testing

The model is simulated under different conditions of temperature and irradiance and the effect on IV and PV characteristics is observed. While changing the temperature, irradiance is kept constant and vice versa.

1) *Effect of Changing Irradiance*

Irradiance is varied and its effect on current, voltage and ultimately on power is observed by IV and PV characteristic curves.

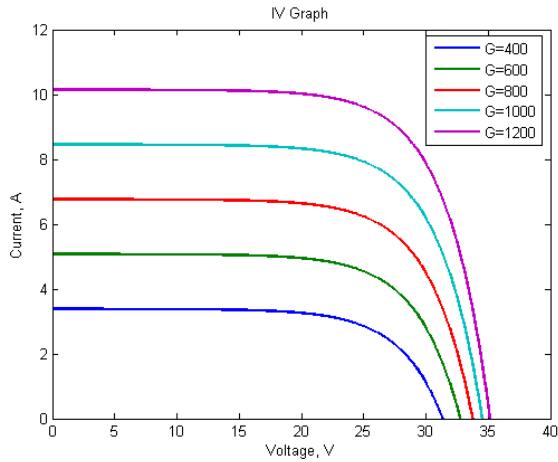


Figure 9 Characteristics under Changing Irradiance

It is obvious from the graph that with increase in irradiance, V_{oc} and I_{sc} are increasing.

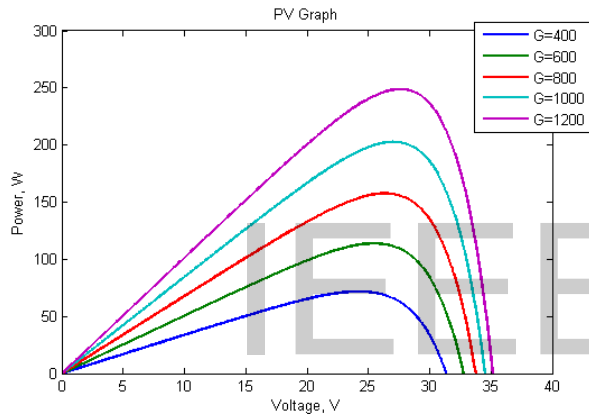


Figure 10 PV Characteristics under Changing Irradiance

Figure 10 shows that V_{oc} and P_{max} is increasing with irradiance, which means that more the sun shine more is the power produced by the cell.

2) *Effect of Changing Temperature*

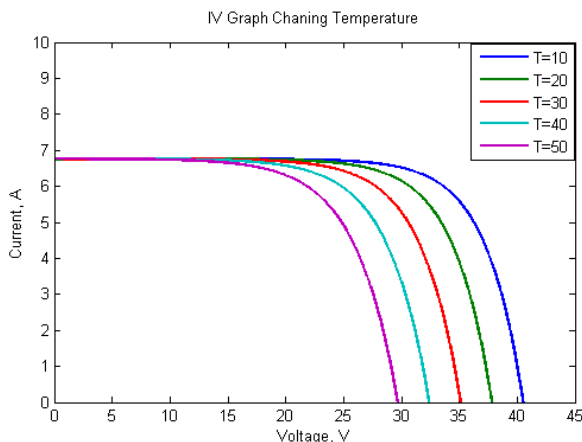


Figure 11 IV Characteristics under Changing Temperature

Current is not significantly affected by increase in temperature, but voltage decreases as temperature increases as clear from graph in Figure 11.

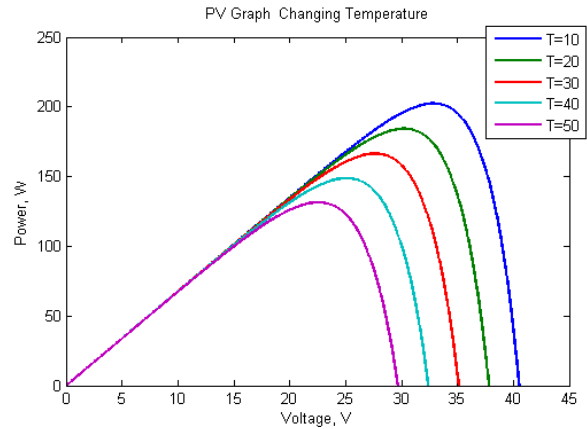


Figure 12 PV Characteristics under Changing Temperature

From the above graph in **Figure 12**, it can be seen that maximum value of power is obtained at minimum temperature. The results from changing irradiance and temperature conclude that solar cell works better in cold sunny environment.

D. Shading Effect on PV Cells

In an ideal case, all the PV cells of each PV module installed in a solar car are in the sun with no shade and if there is a shadow of clouds, trees, buildings, tunnels etc. that are hindering the solar rays, it is uniform for all the solar cells. But, practically, it is not the same scenario. The effectiveness of the solar rays striking the solar panel on the roof will not be the same as the panel attached vertically with the doors or somewhere else. Similarly, there can be shade on some part of the car while other is exposed to sunlight [16]. As all the PV modules are connected in series, so the overall performance would be greatly affected by these situations [17]. Practically, to bring each of the solar panel current output on the same level, separate controllers are attached with them so that the total output current is not decreased.

The PV module which is modeled here is assumed to be on the roof with all the solar cells exposed to direct sunlight.

III. BATTERY

Battery is used to store the converted solar to electrical energy by the solar panel to obtain the continuous output.

The type of secondary or rechargeable battery used here is lead acid battery. It is an old type of re-chargeable battery invented in 1859 which has low energy to volume and energy to weight ratio [18]. Its maintenance rate is high; also it is heavier than lithium ion battery but because of its low cost and ability to provide high current it is being used here.

A. Equivalent Circuit Models

Some of the battery models are:

1) *Simple Battery Model*

It is the most simple type of model of an ideal battery in which a source voltage, V_{source} is connected in series with an internal resistance, R_i and there is an output or terminal voltage V_t shown in Figure 12 [19].

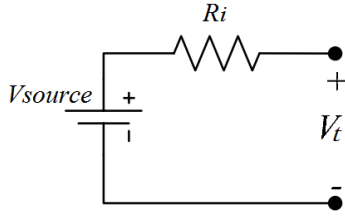


Figure 12 Simple Battery Model

It is very simple model but not dealing with the detail of varying parameters like SoC, change of internal resistance with SoC etc. Therefore, it is not an appropriate model.

2) *Thevenin Battery Model*

It is another commonly used battery model. It consists of ideal, no load battery voltage source V_{source} , internal resistance R_i , capacitance of the parallel plates C_o , and overvoltage resistance R_o .

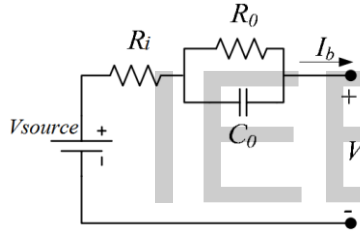


Figure 13 Thevenin Battery Model

The main drawback of Thevenin model is that it assumes all the parameters to be constant, whereas practically they are functions of battery conditions.

3) *Third Order Model*

The equivalent model selected for the car model is third order model because it is handling the system parameters more accurately and not assuming them as constants but they are the function of battery conditions including its SoC, temperature etc.

Third order battery model consists of a voltage source with EMF, E_m , and a parallel R_1 and C_1 branch (for internal impedance) in series with the internal resistance R_2 . There is another branch called as parasitic branch in the model to calculate the energy losses [20].

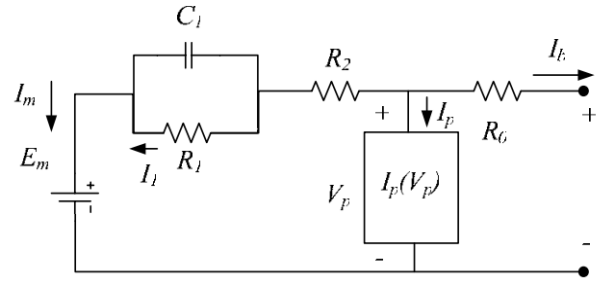


Figure 13 Third Order Battery Model

1. Main Branch Voltage, E_m :

$$E_m = E_{m0} - K_e(273^\circ + \theta)(1 - SOC) \quad (5)$$

Parameter	Unit	Description
E_m	Volt, V	Open Circuit Voltage (OCV)
E_{m0}	Volt, V	Open Circuit Voltage (OCV) at full Charge
K_e	Volt/Celsius, $V/^\circ C$	Constant
θ	Celsius, $^\circ C$	Electrolyte Temperature
SoC		State of Charge

2. Terminal Resistance, R_o

$$R_o = R_{o0}[1 + A_o(1 - SOC)] \quad (6)$$

Parameter	Unit	Description
R_{o0}	Ohms, Ω	Terminal Resistance at SoC=1
A_o		Constant

3. Main Branch Resistance, R_1

$$R_1 = -R_{10} \ln(DOC) \quad (7)$$

Parameter	Unit	Description
R_{10}	Ohms, Ω	Constant
DOC		Depth of Charge

4. Main Branch Capacitance, C_1

$$C_1 = \tau_1 / R_1 \quad (8)$$

Parameter	Unit	Description
R_1	Ohms, Ω	Main Branch Resistance
τ_1	Sec	Main Branch Time Constant

5. Main Branch Resistance, R_2

$$R_2 = R_{20} \frac{[\exp A_{21}(1-SOC)]}{1+\exp A_{22} I_m/I^*} \quad (9)$$

Parameter	Unit	Description
R_{20}	Ohms, Ω	Main Branch Resistance
A_{21}		Constant
A_{22}		Constant
I_m	Ampere, A	Main Branch Current
I^*	Ampere, A	Nominal Battery Current

6. Parasitic Branch Current, I_p

$$I_p = V_{PN} G_{po} \exp \left[\frac{\left(\frac{V_{PN}}{\tau_p} \right)}{V_{PO}} \right] + A_p \left(1 - \frac{\theta}{\theta_f} \right) \quad (10)$$

Parameter	Unit	Description
V_{PN}	Volt, V	Voltage at Parasitic Branch
V_{PO}	Volt, V	Constant
G_{PO}		Constant
τ_p	Second (sec)	Parasitic Branch Time Constant
A_p		Constant
θ_f		Electrolyte Freezing Temperature

7. Extracted Charge, Q_e

$$Q_e(t) = Q_{e(Init)} + \int_0^t -I_m * \tau d\tau \quad (11)$$

Parameter	Unit	Description
$Q_{e(Init)}$	Ampere-sec	Initial Extracted Charge
τ		Integration Time Variable

8. Estimated Average Current, I_{av}

$$I_{av} = \frac{I_m}{(\tau_1 s + 1)} \quad (12)$$

9. Total Capacity, $C(I, \theta)$

$$C(I, \theta) = \frac{(K_c C_o * K_t)}{1 + (K_c - 1)(I/I^*)^\delta}, K_t = LUT(\theta) \quad (13)$$

Parameter	Unit	Description
K_c	Ohms, Ω	Constant
K_t	Sec	Temperature Dependent
C_o^*		Constant
δ		Constant

10. State of Charge, SoC

$$SoC = 1 - \left(\frac{Q_e}{C(I, \theta)} \right) \quad (14)$$

11. Depth of Charge, DoC

$$DoC = 1 - \left(\frac{Q_e}{C(I, \theta)} \right) \quad (15)$$

12. Electrolyte Temperature, $\theta(t)$

$$\theta(t) = \theta_{init} + \int_0^t \frac{P_s \frac{\theta - \theta_a}{R_\theta}}{C_\theta} d\tau \quad (16)$$

Parameter	Unit	Description
θ_{init}	$^{\circ}C$	Battery Initial Temperature
θ_a	$^{\circ}C$	Ambient Temperature
P_s	Watt	Power Loss in R_0, R_2
R_θ	$^{\circ}C/Watt$	Thermal Resistance
C_θ	Joule/ $^{\circ}C$	Thermal Capacitance

B. Battery Simulink Model

The third order model of the battery is modeled in Simulink which is shown in figure below.

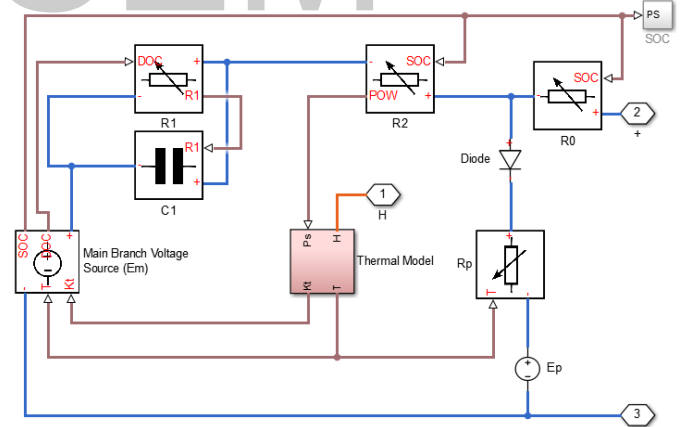


Figure 14 Third Order Battery Model

This is the model for 2V lead acid battery, the requirement is 12V. Therefore, 6 batteries are connected in series.

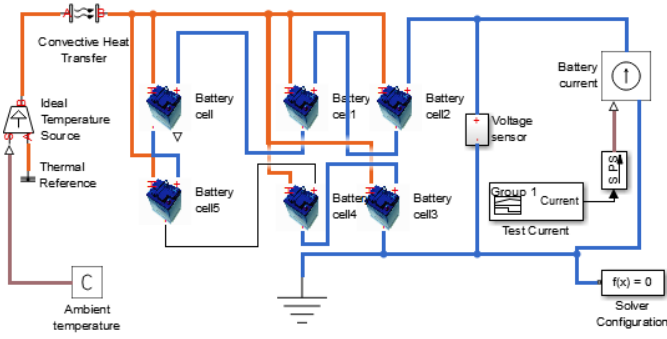


Figure 15 12V Battery Model

Battery model results are given by the Figure 15.

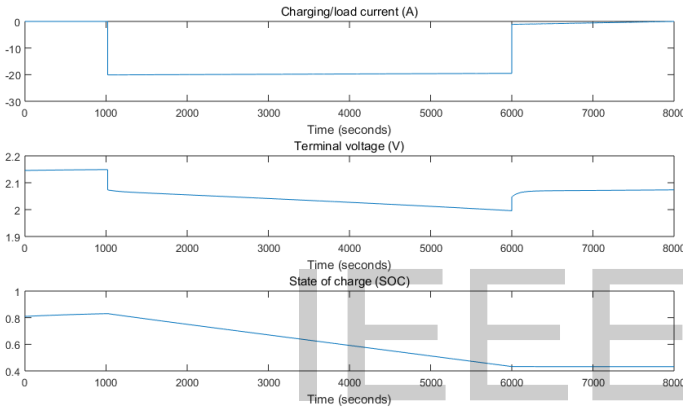


Figure 15 Lead Acid Battery Model Results

1) Parameters of Battery Model

Battery parameters of the equivalent model are important to get the correct results. Third order model depends upon many parameters. The values of these parameters given in the Table 3 are used in Simulink to get the closest possible results.

Table 3 Value of Parameters of Battery Model

Parameter	Value
K_E	0.00061 V/°C
A_0	-0.61
G_{PO}	$2 \cdot 10^{-3}$ sec
τ_P	3sec
τ_1	102sec
V_{PO}	0.12
A_p	2.1 Amps
E_{mo}	2.18V

R_{00}	0.0041Ω
R_{10}	0.00011Ω
R_{20}	0.11
A_{20}	-8.75
A	0.7
K_c	1.2
θ_f	-40°C

C. Merged Model with PV Module

Battery model is being merged with the PV Module to observe its behavior. The output of the PV module is input to the battery.

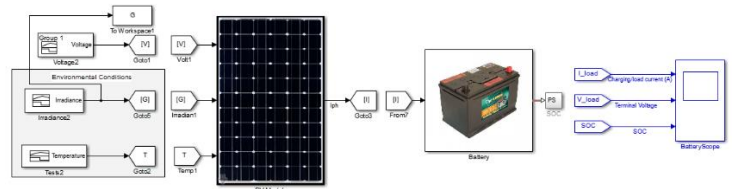


Figure 17 Battery Model Merged with PV Module

As the current from the solar panel is in one direction only, which represents the charging of the battery. So, for the discharging, current must be in opposite direction. For that purpose, negative cycle is introduced manually as clear from the graph in the Figure 18.

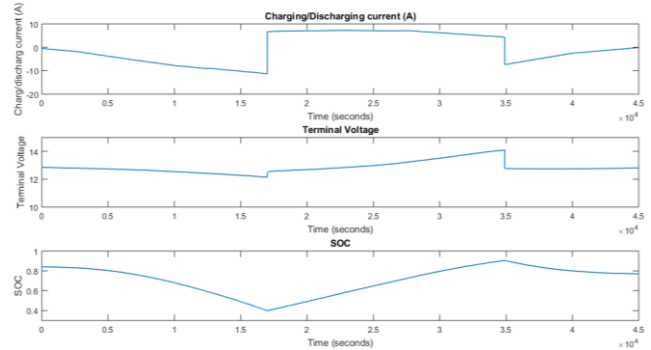


Figure 18 Battery Results with PV Module

Initially, battery is being charged with SoC = 0.82. Now the discharging current cycle is started (battery discharging). After 4.5h (17000sec), the discharging cycle has ended. Then after the charging of next 5h, the battery is near full charged, because of high current. Then again, battery is discharged for the next 2.5h. This is how the state of charge of the battery is behaving for the 12h of the day.

A charge controller is required to avoid the battery overcharging and discharging which is coming later [21].

IV. TRACTION MOTOR

Traction motor is an electric motor which is used for the propulsion of vehicles that include electric vehicles (EVs), electric trains, elevators etc.

DC series motor is an old type of traction motor which is used in the vehicles because of its ability to provide high surge current, high starting torque and easy speed control. It is also used in small sized applications because of its wide range of functionality [22].

Brushed DC series motor is selected as a traction motor for the modeling because of the following reasons:

- ✓ Simple circuit, operation and modeling
- ✓ High starting torque with less power
- ✓ Easy speed and direction control
- ✓ Cost efficient and reliable

A. Electrical Model

The equivalent circuit of the motor is shown in the Figure. From the current equations of the circuit the modeling of the motor is done in Simulink [23].

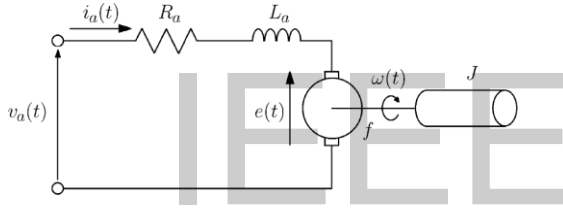


Figure 19 Equivalent Circuit of Motor

The motor equations which are used to create Simulink model of the motor are given by Equation 17 and Equation 18.

$$\frac{di_a}{dt} = \frac{1}{L_a} (V_a - i_a R_a - K_{af} i_a \frac{d\theta}{dt}) \quad (17)$$

$$\frac{d^2\theta}{dt^2} = \frac{1}{J} [K_{af} i_a^2 - B \left(\frac{d\theta}{dt}\right) - T_L] \quad (18)$$

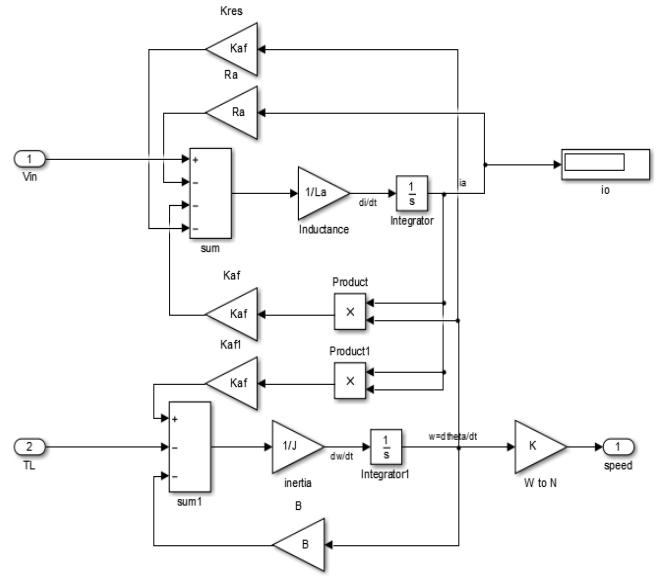


Figure 16 Motor Simulink Model

B. Motor Output

The following results are obtained at different loads.

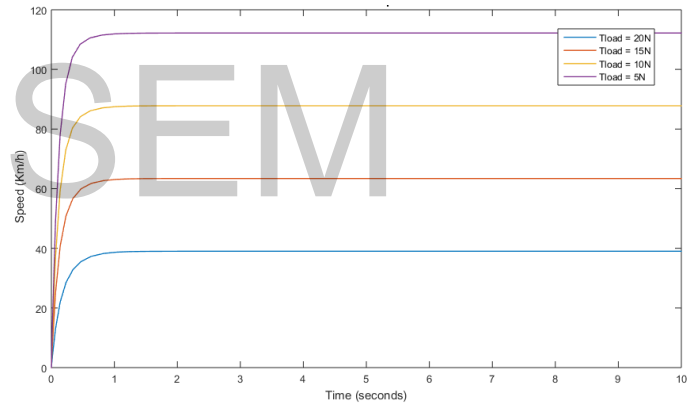


Figure 17 Motor Output

It shows that the speed is varying significantly with the load which is not desirable. Therefore, there must be some controller to maintain the motor speed with changing load (mechanical load that depends upon number of passengers, road quality, etc.)

V. CONTROLLERS

The two controllers that are used in this car project are:

A. Charge Controller

It is incorporated with battery in order to prevent battery from overcharging and over discharging. It is necessary to protect the battery and improve its lifetime.

Fuzzy logic is used to implement this charge controller in the Simulink and practically microcontroller can be used with the desired set points of battery SoC.

Table 4 Input Output Relationship of Controller

SoC	Pout	Iout
SoC < 0.25	0	Iin
SoC > 0.5	Pin	--
SoC > 0.95	Pin	0
SoC < 0.8	--	Iin

With the help of above table, the controller modelled in the Simulink can be seen in Figure.

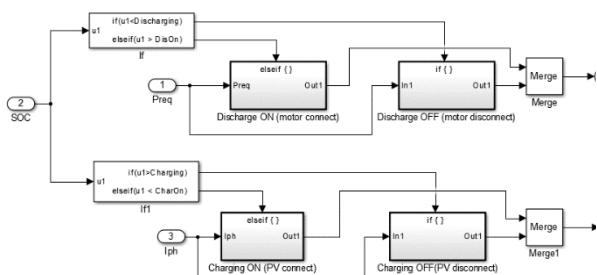


Figure 18 Charge Controller Simulink Model

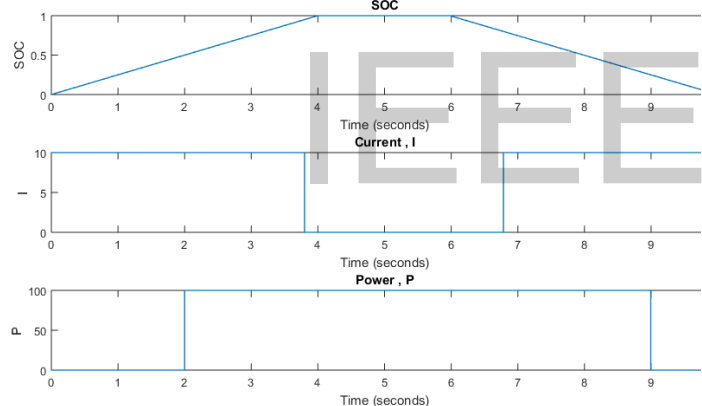


Figure 19 Charge Controller Output

The controller is working fine according to the given set points. It is disconnecting the panel from the battery for when SoC > 0.95 (95%) and reconnecting when SoC < 0.8 (80%) to make sure that battery is not overcharged.

Similarly, load is connected to battery only when SoC > 0.5 (50%) and disconnected when is less than 0.25 (25%) so that battery is not over discharged.

B. Speed Controller

Speed controller is used with the motor to achieve desired results. The required results from the step response are:

- ✓ Minimum/no overshoot
- ✓ Minimum settling time
- ✓ Minimum/zero steady state error

- ✓ Less/no speed variation with load or other disturbances.

The controller used is basically PID controller with the parameters tuned to achieve the best possible response [24]. The PID controller is selected for following reasons:

- ✓ Simple design
- ✓ Easy construction
- ✓ Good closed loop response.

For the PID controller parameters tuning, PID tuning command is used in Simulink/MATLAB which helps in finding the parameter values to achieve the desired response.

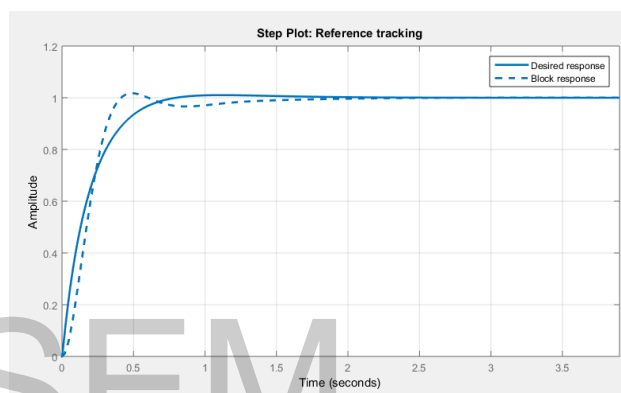


Figure 20 PID Tuning

The desired response is set by the user and PID tuner sets the values of its parameters accordingly [25]. The values set by the tuner are given by the Figure 22.

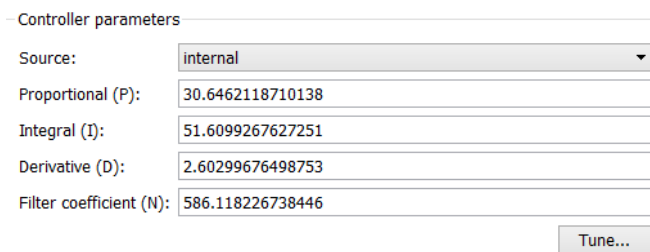


Figure 21 PID Controller Parameters

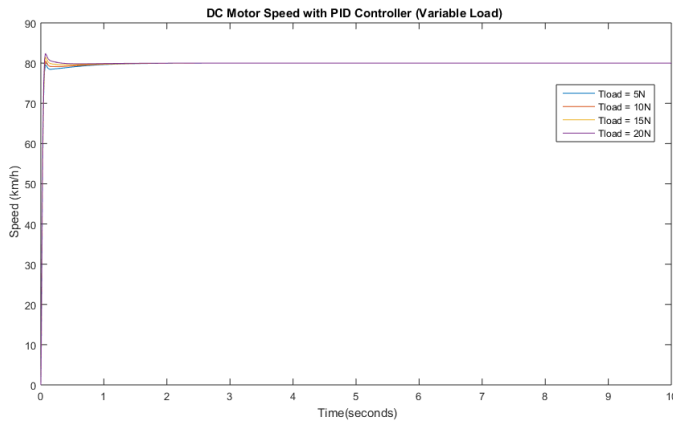


Figure 22 PID Controller with Motor

PID controller is handling the variable load and maintaining its desired speed with varying load.

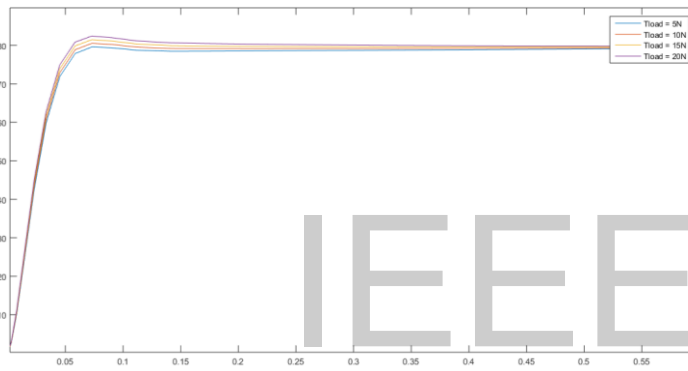


Figure 23 Zoom in Motor Output with Controller

It is clear that with PID controller motor is achieving its reference or desired speed in less than 1sec and also the speed is not varying with load and the error is tolerable.

VI. THE SOLAR CAR

All the components that are modelled are combined together for the complete solar car. The Simulink model of the solar car looks like Figure 24.

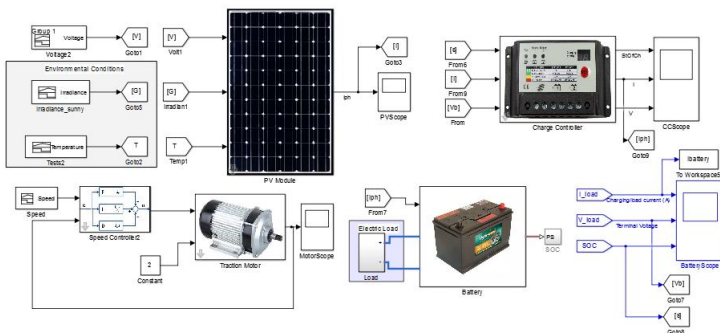


Figure 24 Solar Car Simulink Model

A. Solar Car Simulink Results

The overall performance of solar car is tested under three environmental conditions; sunny day, partially cloudy day and mostly cloudy day. The irradiance graph is varied according to the weather condition and hence the effect on the PV current and ultimately on car performance is observed.

1) Sunny Day:

a) Irradiance:

The graph of irradiance on a sunny day looks like similar to the Figure 25. It is minimum at the start and end of the day and maximum peak is at the mid-day [26].

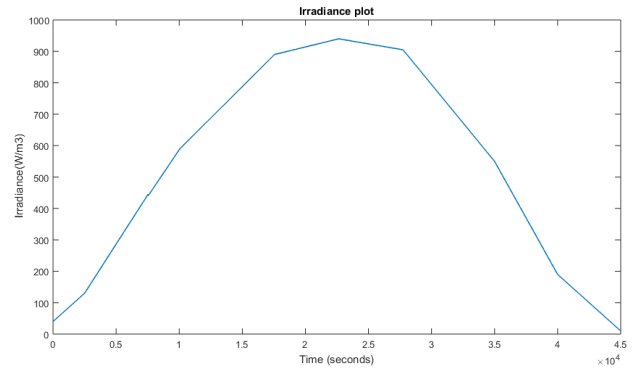


Figure 25 Irradiance (Sunny Day)

b) Photovoltaic Current:

This is the current produced by the solar panel as a result of solar irradiance. It highly depends upon the amount of solar radiations striking the solar panel.

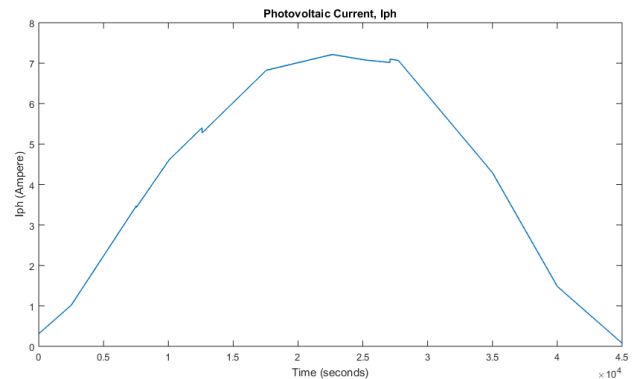


Figure 26 PV Current (Sunny Day)

c) Charge Controller:

To avoid battery overcharging and discharging, it is incorporated with battery as discussed earlier.

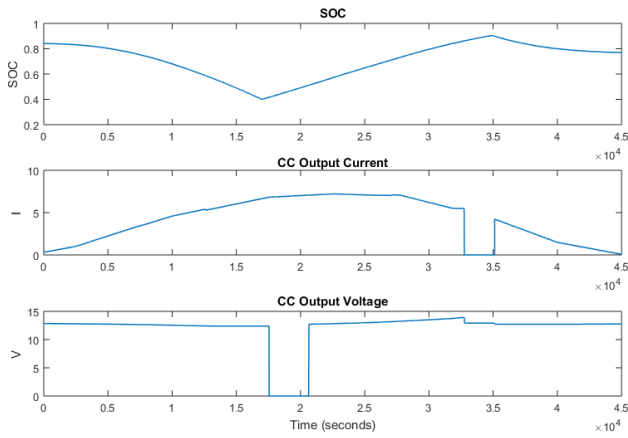


Figure 27 Controller Output

For the pre-set points by the user, the charge controller is stopping the panel current for the duration (3.25×10^4 to 3.5×10^4) to prevent overcharging and similarly the output voltage to the motor is set to 0V when the battery's SoC is low.

d) Battery:

There is an electric load attached with the battery and SoC of battery is compared with and without the electric load.

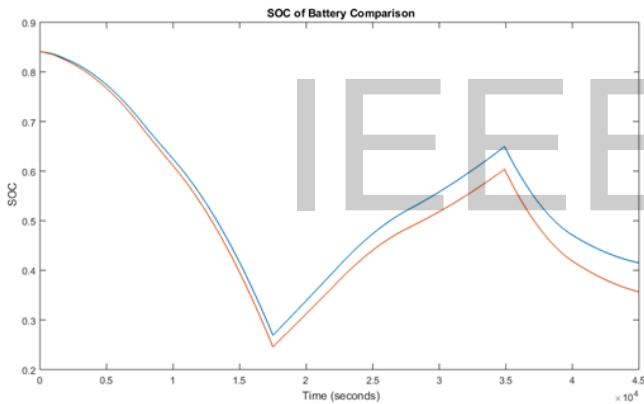


Figure 28 Battery SoC with and without Electric Load

With the electric load, battery is charging slowly and discharging faster as it can be seen from the above graph. All the coming battery results are including the electric load.

Also, the battery results are compared with and without the charge controller to see how the charge controller is working.

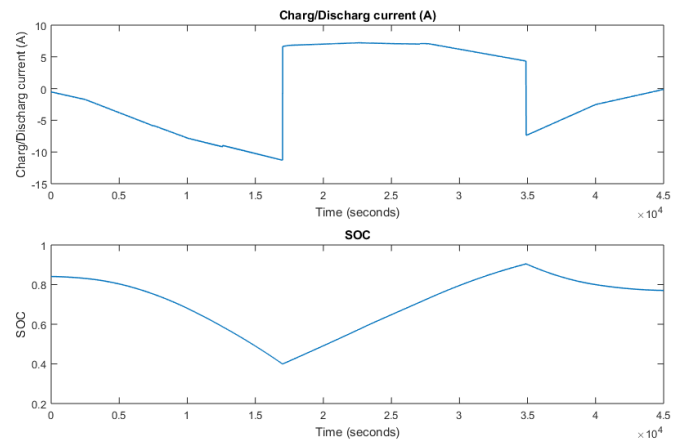


Figure 29 Battery Result without Charge Controller

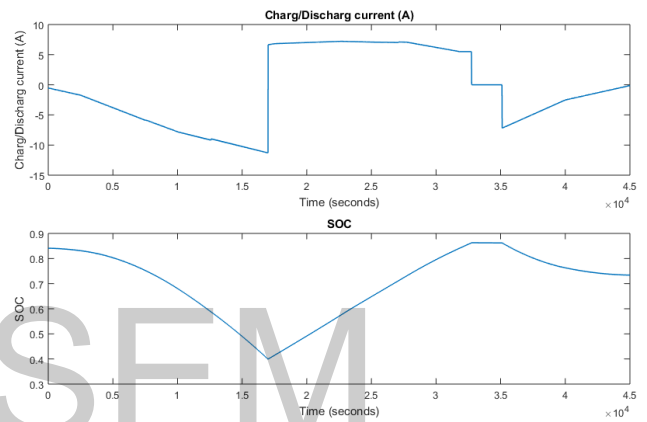


Figure 30 Battery Result with Charge Controller

With charge controller the charging current has some limitations which is helping to stop the overcharging.

e) Traction Motor:

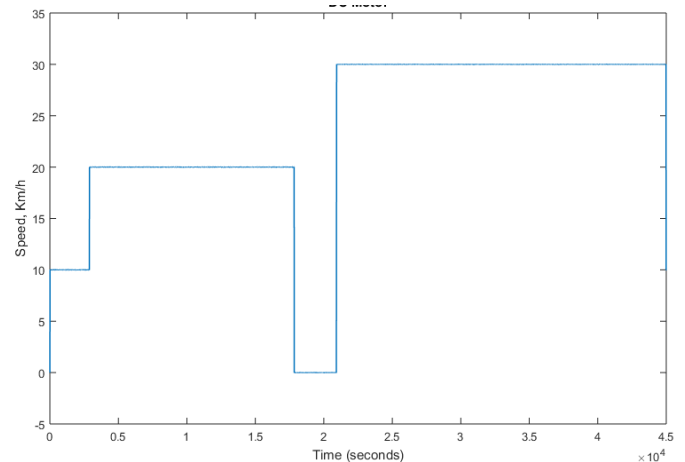


Figure 31 Motor Output

Traction motor is following the reference speed and 0km/h when the battery is low controlled by the charge controller. Practically, there would be another backup and battery and charge controller will switch the battery when SOC of the working battery becomes low.

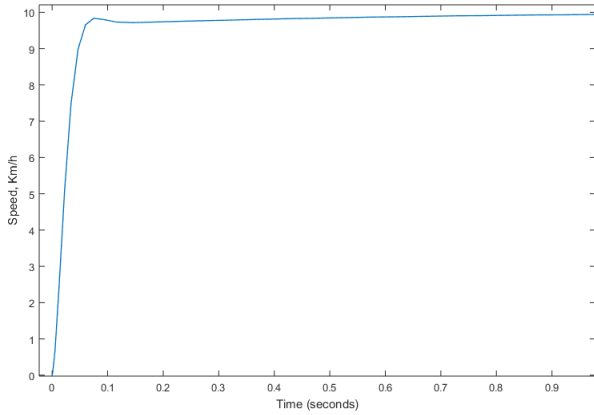


Figure 32 Zoom in Results

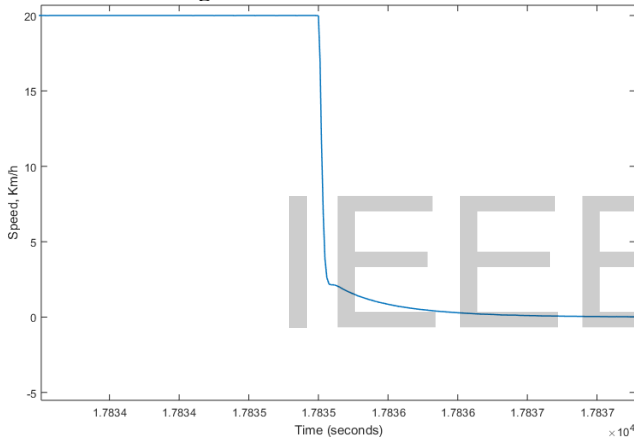


Figure 33 Traction Motor Results (zoom in)

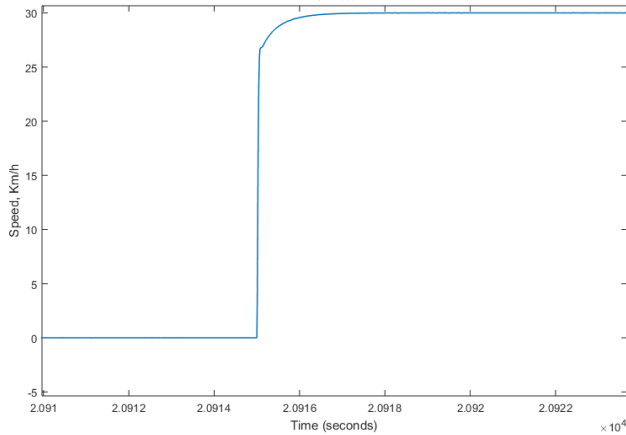


Figure 34 Traction Motor Results (zoom in)

2) *Partially Cloudy Day*

a) *Irradiance*

The irradiance is highly affected by the clouds [27]. The estimated graph of the irradiance in a cloudy day is shown by the **Figure 35**.

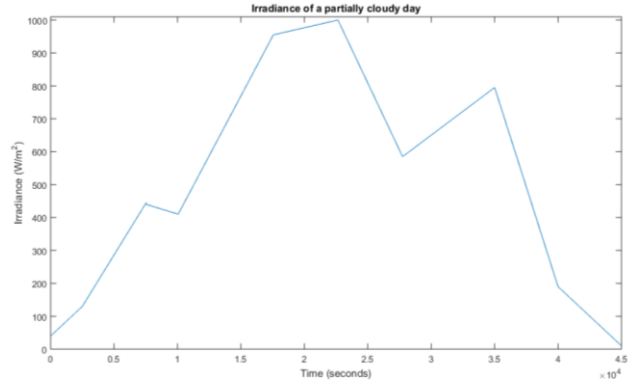


Figure 35 Irradiance (Partially Cloudy Day)

b) *PV Current*

The PV current being dependent upon the solar radiations incident on the solar panel is now reduced to some extent as compared to the sunny day.

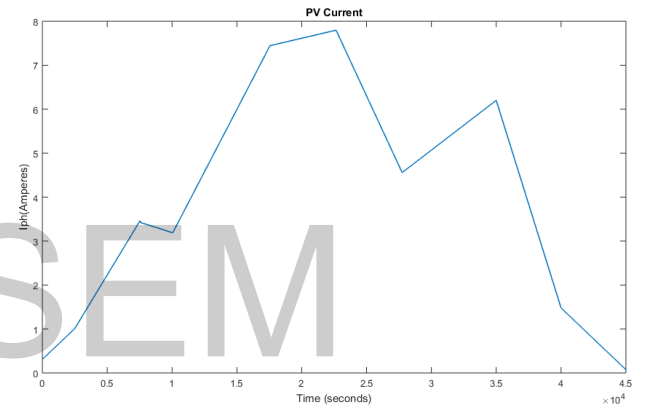


Figure 36 PV Current

c) *Charge Controller*

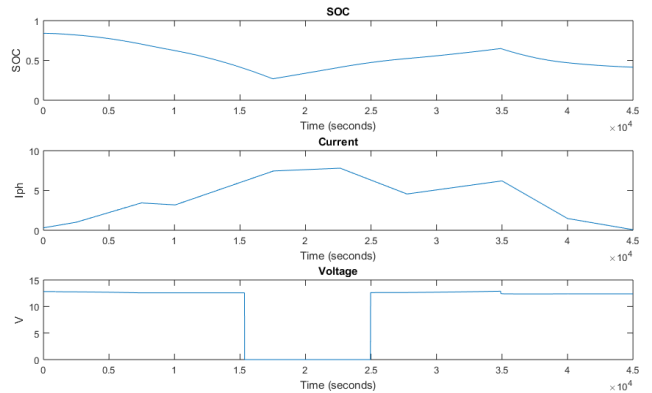


Figure 37 Charge Controller Output

The charge controller need not to stop the PV current as the battery is not overcharging here. The output voltage is set to zero for the time when battery is draining too much to stop the battery over discharging. The voltage level is also reduced.

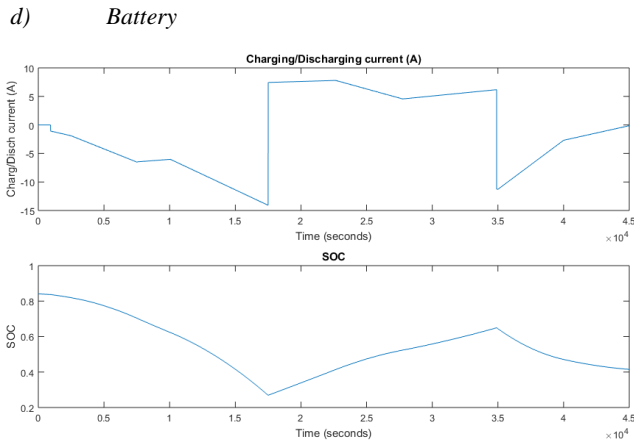


Figure 38 Battery Output

Figure 39 is representing battery current and SoC. The battery is not reaching state of charge level which was the case of sunny day. It means that now more time is required to fully charge the battery.

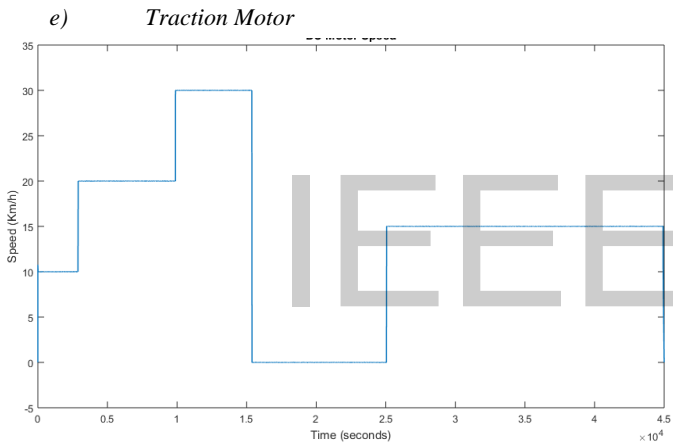


Figure 39 Traction Motor Results

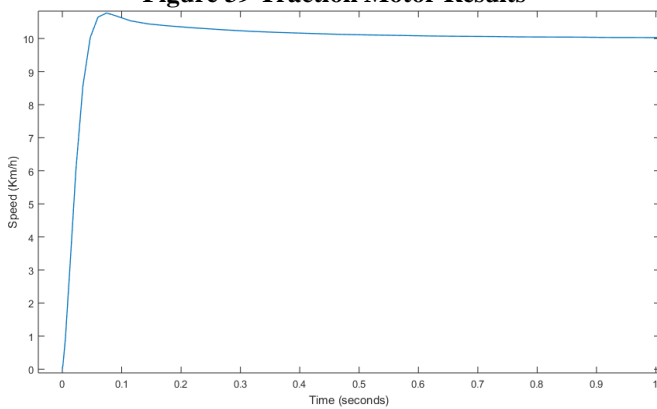


Figure 40 Traction Motor Zoom in Results

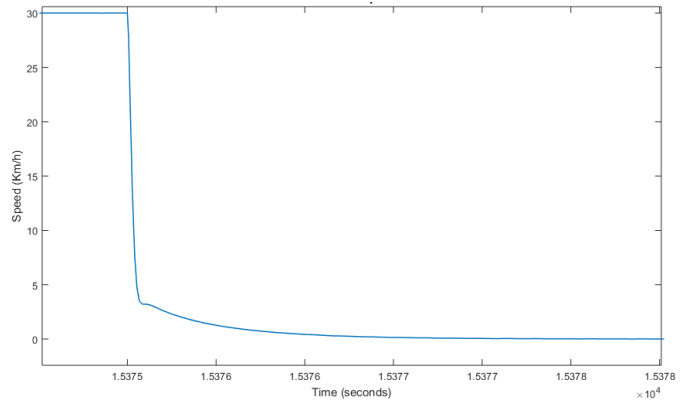


Figure 41 Traction Motor Zoom in Results

3) *Mostly Cloudy Day*



Figure 43 Irradiance

Figure 43 is the estimation of irradiance of a day with the clouds hiding the sun most of the time. Therefore, hindering the solar radiations.

4) *PV Current*

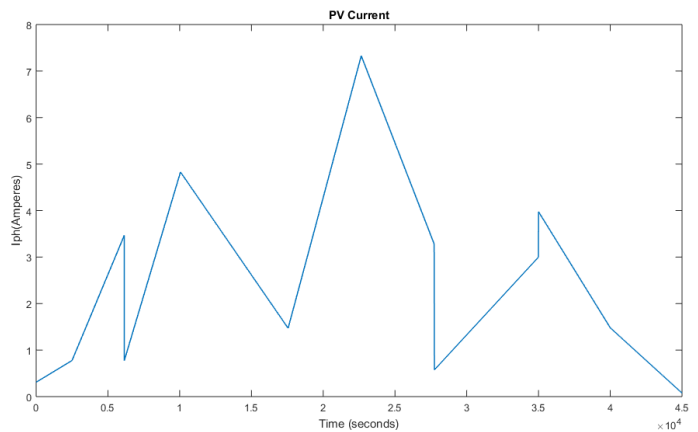


Figure 44 PV Current

The decrease in irradiance is affecting the current of the solar panel as clear from the graph in **Figure 44**.

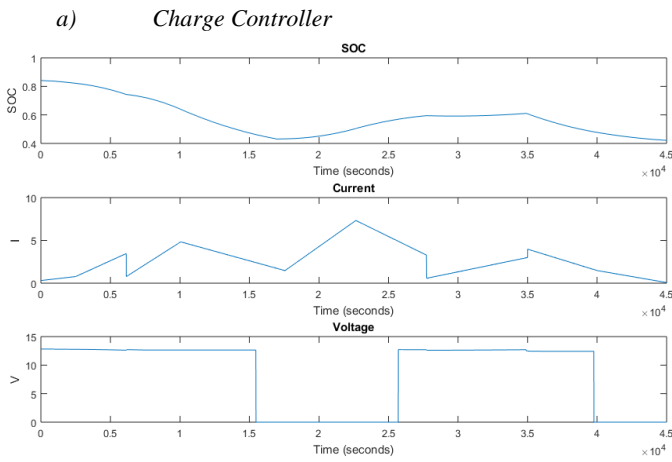


Figure 45 Charge Controller Output

The battery is not being charged enough because of low charging current, therefore, there is no need of stopping the PV current. The output voltage is also reduced and also it is zero for longer time span as compared to sunny and partially cloudy day. Therefore, the motor performance is being affected.

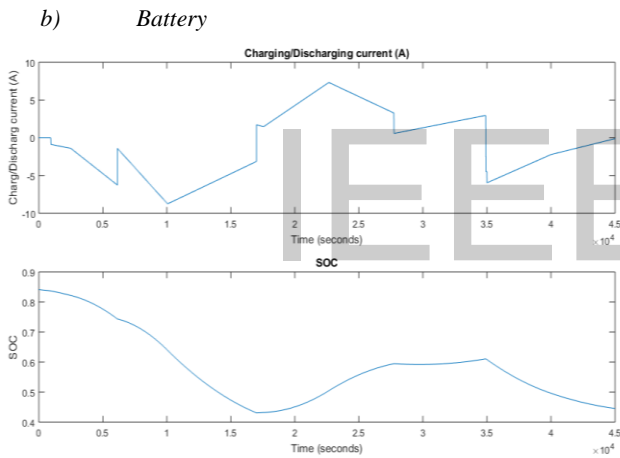


Figure 46 Battery Output

There is not enough charging current to charge the battery once it has drained.

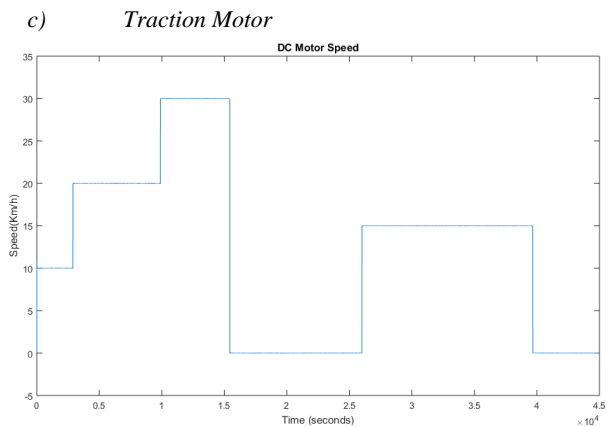


Figure 47 Traction Motor Results

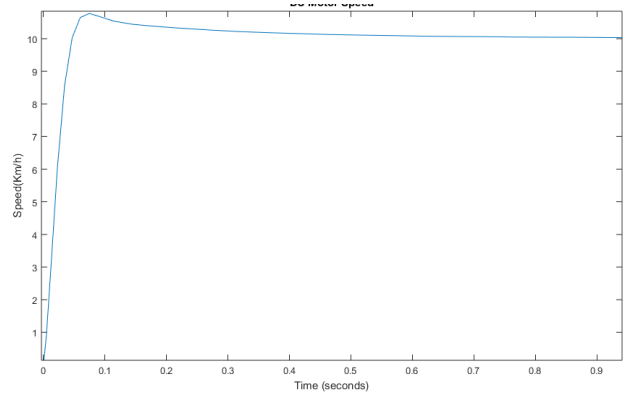


Figure 48 Traction Motor Results (zoom in)

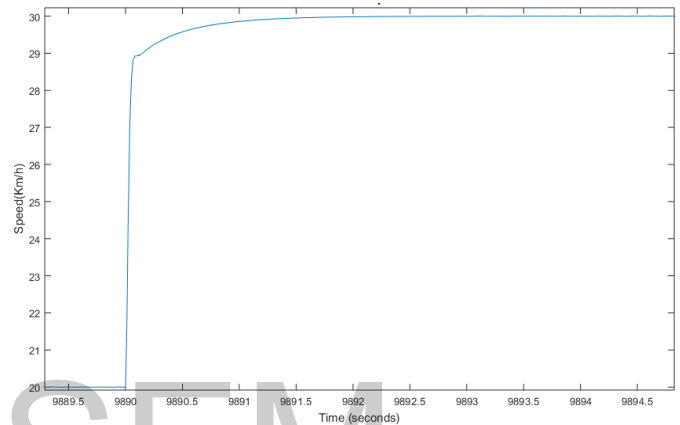


Figure 49 Traction Motor Results (zoom in)

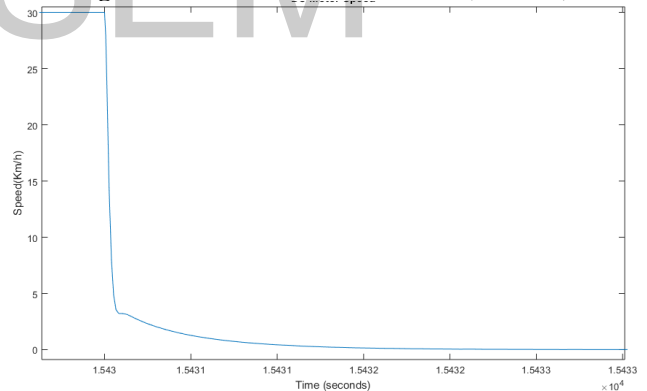


Figure 50 Traction Motor Results (zoom in)

The zoom in results are to see the transitions in the motor speed clearly.

These are the results for the analysis purpose. Practically, there must be a backup battery to cope up with these kind of situations and provide continuous output.

VII. CONCLUSION AND FUTURE WORK

In this paper, the mathematical modeling of different components of solar car is done using Simulink/MATLAB. All the components are separately modelled and verified. Finally, they're combined together to make a solar car and the model is tested under different environmental conditions and its behavior is observed.

There's a lot of room for the improvement in this model which includes: modeling of voltage regulator with the PV module for the constant current supply for battery, a backup system in case of bad weather conditions or night travelling. Lead acid battery can be replaced with Li-ion battery which is more efficient. Brushed DC motor can be replaced by brushless DC motor because of its low maintenance cost, less noise and high efficiency. Also, variable loads are also not entertained in this model which can be considered in the future modeling.

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