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Design and Simulation of On-board Solar PV powered Electric Vehicle integrated with Battery Energy Storage System

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Abstract: Electric Vehicles are becoming world's primary modes of transportation for minimizing operating costs, reducing reliance on fossil fuels, lowering carbon emissions, and enhancing public health and urban air quality. Electric Vehicles are facing the major problems of limited battery range, battery life, charging stations and long charging times. This research work proposes an installation of Solar PV array on EV's rooftop integrating with Battery Energy Storage System to power the drive of an Electric Vehicle to reduce the charging and discharging cycles of the battery and enhancing the battery life. The solar PV panels are fixed onto the body of vehicle so as to be exposed to the Sun light. The electric power generated by PV cells is directly fed to the DC drive during daytime while the vehicle is moving and batteries are charged during daytime while the vehicle is parked.

Keywords: Solar Photovoltaic (PV), Boost Converter (BC), Maximum Power Point Technique (MPPT), Electric Vehicle (EV), Electric Drive, Bidirectional Converter Circuit.

I. INTRODUCTION

Electric vehicles (EVs) represent a promising technology for realizing a sustainable transportation sector in the future, owing to their minimal to zero carbon emissions, reduced noise levels, high efficiency, and adaptability in electric grid operation and integration. Electric Vehicles are forms of transportation, such as cars, buses, and trucks, that operate using electric motors supplied by rechargeable batteries or alternative energy sources. There is many EV technologies associated with energy storage systems and charging mechanisms. The important component of an EV is the Charging. An average minimum time of 5 hours to get fully charged and the non-availability of charging stations at remote locations are the main disadvantages for Electric Vehicles[1].

Solar PV-Powered electric vehicles use photovoltaic (PV) panels to convert sunlight into electricity, either to directly power the motors or charge the battery. Solar panels on the vehicle's surface capture sunlight and convert it into direct current (DC) electricity. This DC electricity can power the dc motors of EV and charges the batteries associated with Electric Vehicles, which then powers the electric motors. The process of charging electric vehicles battery with solar energy is referred to as solar EV charging. Solar panels capture sunlight and convert it into electricity that can power EVs directly or by charging the batteries[1], [2].

Here, in this work the solar PV array is fixed onto the vehicle which is connected to the DC motor driving the axle of EV and storing battery at a common DC bus. The DC drive receives electrical power either from PV array or from battery depending upon their supplying capacity.

II. SOLAR-POWERED ELECTRIC VEHICLE

An electric vehicle which charges its battery directly or indirectly from the sunlight is known as a solar-powered EV. These vehicles are either charged at solar-powered charging stations or have photovoltaic solar panels integrated into their bodies. Solar- Powered Electric Vehicle which is fitted with solar panels on its rooftop and side walls as shown in the Figure 1 is referred as Integrated Solar EV and the other type is called Externally Solar Charged EV. Here, in this work the integrated solar EV on-boarded with PV panels is considered for study.

Solar panels are fitted to onto the body of electric vehicle so as to absorb the sun light during day time. The Battery Energy Storage System is fixed into the vehicle to store the energy generated by solar PV during day time while parking the vehicle and moving. The solar PV panels, Electric Drives and Batteries are interconnected for coordination and sharing of electric power during day and night times.

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Figure 1: Electric Vehicle integrated with PV array

III. LITERATURE REVIEW

Atul Sarojwal et al., (2017) aimed at designing and building a cheaper solar powered car. Following performance studies, the storage system is able to operate the solar car about 12 kilometers. The solar car's maximum speed was measured at 20 km/h. Thus, because of its less costly and nil pollution effect, solar energy vehicles are created and manufactured in this study can be utilized as green vehicles in poor nations[3].

Nirmala. M et al., (2018) deliberates about operation of the BLDC motor in closed loop control in accord with the change in solar irradiance condition and change in set speed of an electric vehicle. The advantages of BLDC motor are higher value of efficiency, power density and speed ranges, which makes selection of this motor, for various applications[4].

Harin M Mohan1et al., (2019) have explained that Solar-powered electric vehicles are safe with no volatile fuel or hot exhaust systems. They are zero emission vehicles, odorless, smokeless and noiseless. They require minimal maintenance, are more reliable with little or no moving parts and can be efficiently charged nearly anywhere. Needless to say, it is very much cost efficient The Solar Powered EV would benefit by the end users like Industries, university campus, amusement parks etc.,[5].

Julio A. Sanguesa et al., (2021) have analyzed the types of EVs, the technology used, the advantages with respect to the internal combustion engine vehicles, the evolution of sales within the last years, as well as the different charging modes and future technologies. They also detailed the main research challenges and open opportunities. Regarding EVs, batteries are a critical factor, as these will determine the vehicle's autonomy[6].

Tobias Bostrom et al., (2021) the visionary conceptual study presented here shows that it is indeed theoretically possible to power a complete country like Spain solely by the use of photovoltaics, and to balance the intermittency solely by using the battery capacity of a fully electric transport system and V2G technology. Surplus energy from PV generation is stored in electric vehicle's batteries. The same batteries power Spain's energy demand during times with low availability of solar energy[7].

Harsh Srivastava et al., (2022) have concluded that Solar battery helps in reducing the cost of electricity and at present mostly consumers have installed solar panels, as it's the part of renewable energy source and abundantly available free of cost and just by installing panels for the wattage required the electricity can be generated like 2 KW required by most residential purposes[8].

Aqib Shafiq et al., (2022) investigates the possibility of designing a solar photovoltaic-based EV charging station for security bikes located in the State of Azad Jammu and Kashmir, Pakistan. Before installing a PV charging station, the charging station's feasibility must be studied. The proposed study also analyzes the power reliability, energy cost, and CO2 emissions of a PV-powered charging station. The proposed system's outcomes are compared to grid-based charging stations. In comparison to other existing approaches, there is a significant reduction in greenhouse gas emissions, including CO2, CO, SO2, and NOX. The proposed study anticipates the economic and environmental benefits of EV charging stations powered by renewable energy resources[9].

Mandakuriti Nivas et al., (2022) have presented the usage of renewable energy resources for the reduction of the effect of greenhouse gases on the environment caused by combustion engines. PV panels are used for the generation of electricity in solar-powered electric vehicles (SPEVs). Completely depending on solar power also have some disadvantages like limited range, high initial cost. But these can be avoided by conducting further research in this area and also by using ultra-efficient solar cells which give 30-35% efficiency. SPEVs will be more functional in the future[10].

D Nageshwar Rao et al., (2023) aims to run a vehicle using solar energy. The batteries store the electric energy from the solar panel. So, the vehicle is able to run even at night by energy stored in the batteries. The android application can control the movement of the robot as per instructions given, which are displayed on LCD[11].

Deepti Singh et al., (2024) have stated that it is imperative to switch to a new source of energy, namely solar power, which would be a cheap, efficient, limitless, and, of course, environmentally friendly alternative to meet the rising fuel demands and the catastrophic environmental pollution caused by driving carbon-based vehicles. Electric cars fueled by solar energy are safe since they lack hot exhaust systems or flammable gasoline[12]. They produce no emissions and are also odorless, smokeless, and silent. Because they have fewer or no moving components, they are more reliable and can be effectively charged almost anywhere. It goes without saying that it is incredibly cost-effective. The solar-powered EV would gain support from end users, including businesses, college campuses, and theme parks. PVEV's technology contributes to the environment.

Abhishek Kumar Tripathi et al., (2025) have addressed the integration of solar PV panels into electric vehicle (EV) charging infrastructure addresses several critical needs by enhancing sustainability and reducing reliance on fossil fuels. Solar-powered charging stations provide a renewable energy source that lowers greenhouse gas emissions and alleviates range anxiety for EV users, especially in areas where traditional grid infrastructure may be lacking. Despite these benefits, there are significant challenges, including technical complexities, grid integration issues, and compatibility with existing technologies. Current methods for EV charging primarily rely on conventional grid electricity, which may not fully support sustainable urban transportation[13]. New methods, such as incorporating solar PV, are essential for improving the sustainability and efficiency of EV charging systems.

Aritra Ghosh., (2025) have summarised that integrating solar energy into BEV and FCEV infrastructure can advance sustainable mobility by reducing lifecycle emissions. While current PV efficiency, storage, and hydrogen production limitations require hybrid energy solutions, ongoing technological improvements and supportive policies can enable broader adoption. A balanced renewable energy mix, with solar as a key component, will be essential for realizing truly sustainable zero-emission transport[14].

Oluwapelumi John Oluwalana et al., (2025) have comprehensively reviewed and systematically examined the evolution and current state of solar electric vehicles and vehicle-integrated photovoltaics, revealing both significant progress and persistent challenges in this transformative field. The analysis demonstrates that although substantial advancements have been made in photovoltaic efficiency, lightweight materials, and integration techniques, several critical barriers remain before SEVs can achieve widespread adoption[15].

IV. BLOCK DIAGRAM OF PROPOSED SYSTEM

As per the block diagram shown in Figure 2, Solar PV array generates electric power during the available period of solar irradiance. The PV generated power is boosted up at the required level of voltage and it is fed to the DC bus where the electric vehicle and battery energy storage system are inter connected. The Maximum Power Point Controller generates the required Pulse Width Modulated signals to trigger the boost converter switch so as to track maximum power from solar PV array at required constant output DC voltage.

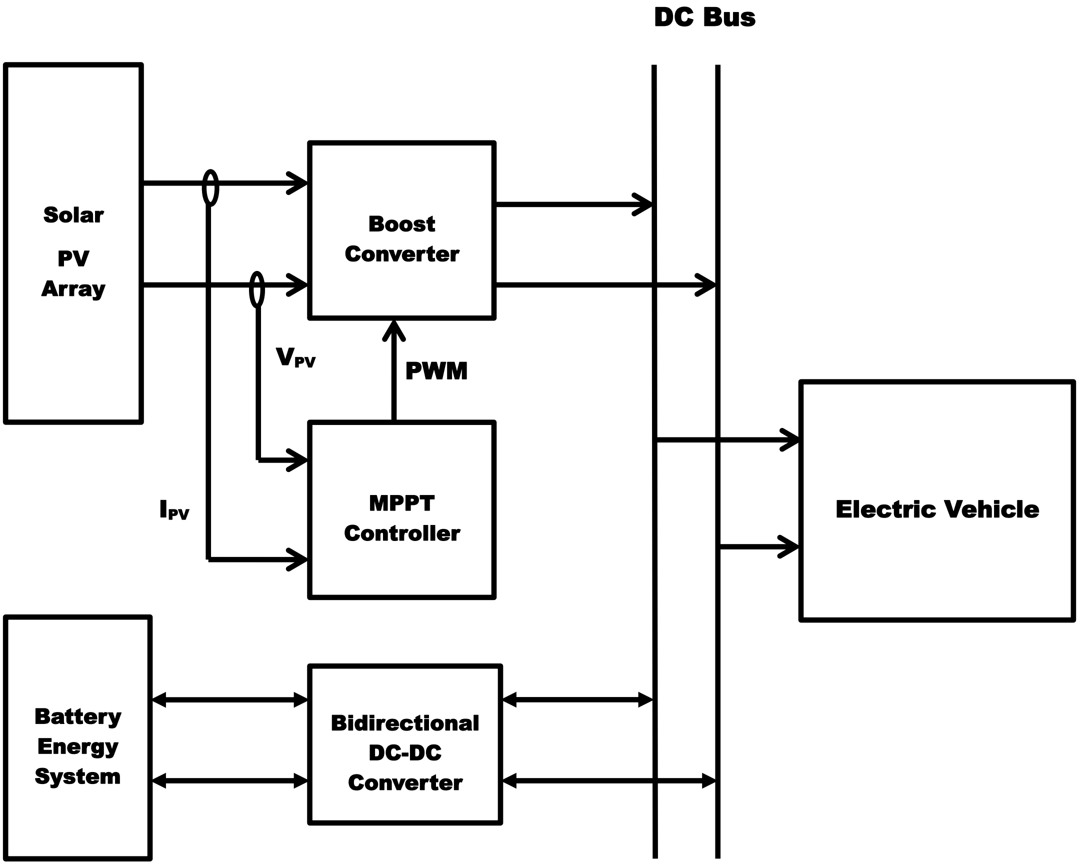

Figure 2: Block diagram of on-board solar PV powered EV integrated with battery

During the period of vehicle parking and availability of solar irradiance, the battery energy storage system receives power from DC bus via bidirectional converter and it gets charged. While the vehicle is moving and solar irradiance is available, the vehicle motor receives DC power from solar PV as long as the irradiance is available and it keeps moving. If the solar PV is not generating the required power, the remaining power is taken from BESS to compensate the power needed by the vehicle motor. During night time, when the vehicle is to be driven, the Battery Energy System provides the required amount of DC power to drive the motor fitted with the vehicle to keep the vehicle moving.

V. CONTROL SYSTEMS

(a) MPPT Controller: The MPPT controller is necessary to improve the PV system utilization and extracting maximum power generated by the solar PV array. The MPPT algorithm has been implemented by using many methods such as INC, P&O, ANN, Fuzzy Logic and PSO based approaches. For simplicity, the widely used method known as "Perturb and Observe" is applied here. This method involves measuring the PV voltage and current while perturbing the boost converter duty ratio. After then, the power change is calculated then checked according to the flow chart of Figure. The controller is adapted to generate the necessary duty ratio for the boost converter switch to achieve MPPT conditions.

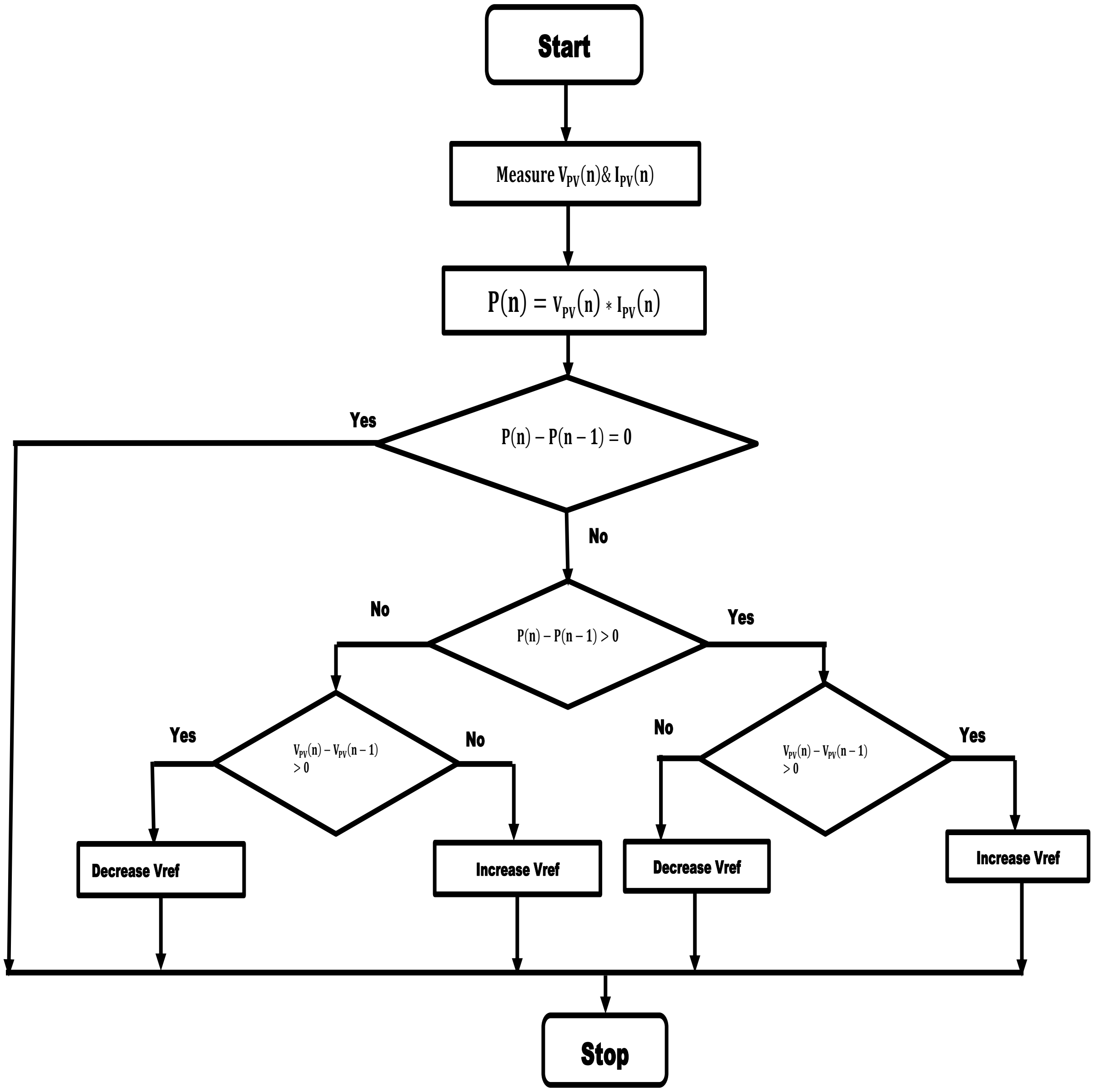

Figure 3: Flow chart of P&O MPPT algorithm

(b) Battery Storage Converter Controller: This controller's goal is to maintain a steady reference value for the DC bus voltage. The storage battery's charging and draining processes are therefore modified to fulfil this purpose. The PI controller is also modified for this converter. The converter stops charging after the batteries are fully charged, with the exception of a tiny trickle current.

VI. DESIGN PARAMETERS AND THEIR SPECIFICATIONS

(a) Design of Photovoltaic Array: To provide high power capacity in the PV system, a series and parallel combinations of PV modules are used. Here in this paper, 1Soltech (1STH-215-P) module is used. This module has the specifications as presented in table 1.

Table 1: Specifications of Solar PV Array

Measured at STC: irradiance of 1000/m² and cell temp. 25°C		
STC Power Rating	P_{MP}	215 W
Voltage at maximum power	V_{MPP}	29.0 V
Current at maximum power	I_{MPP}	7.35 A
Open Circuit Voltage	V_{OC}	36.3 V
Short Circuit Current	I_{SC}	7.84 A

(b) Modelling and Design of Solar PV Boost Converter: A boost converter is a very effective power electronics device which steps up the input voltage without using a transformer. However, during the step-up process, the system's overall power input is kept constant with its output by lowering the current. A number of components, including an inductor, power switch, diode, and filter capacitor, are involved in the energy transfer process.

Power MOSFETs make up the majority of the electronic switch however research indicates that IGBTs can also be employed for switching. Pulse width modulation techniques are typically utilized for switching in circuits with simple designs.

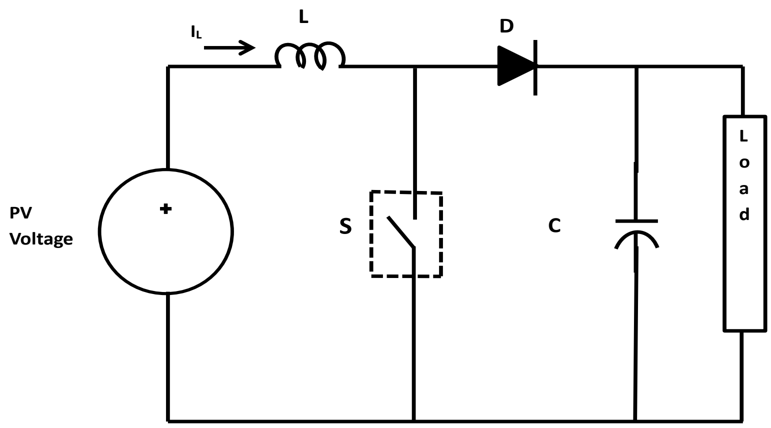

Figure 4: Circuit diagram of PV-Boost Converter

The design of boost converter inductor and capacitor are calculated by considering the behavior of inductor and capacitor during turn-on and turn-off times of the boost converter. When the switch S is closed the inductor current $\mathbf{i_L}$ starts increasing and energy is stored in it in the form of magnetic field. When the switch S is opened the inductor current $\mathbf{i_L}$ flows through diode D and the current decreases gradually. The capacitor C is charged while $\mathbf{i_L}$ flows through it during **S** is open and the capacitor discharges its stored energy making its current flowing through load during the switch **S** is closed.

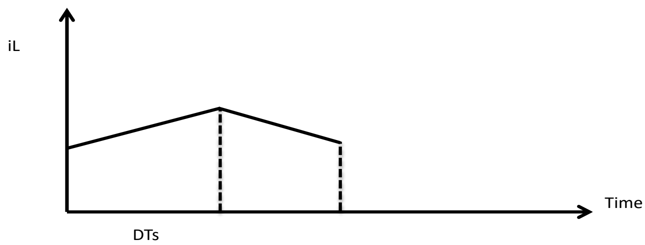

Figure 5: Graph showing the inductor current Vs time

During "Ton" time of the switch, the inductor current increases gradually as shown in the Figure 5. Hence, the slope of the curve over the time DTs will be equal to Vi/L as given below in Equation 1.

$$\frac{\Delta i_L}{DT_s} = \frac{V_i}{L} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

$where,$

$\Delta i_L = Inductor\ Ripple\ Current$
$D = Duty\ Cycle$
$V_i = Input\ Voltage$
$L = Inductance$

Hence, the Equation (1) is simplified as,

$$\Delta i_L = \left(\frac{V_i}{L}\right) DT_s \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

$The\ Equation\ (2) also\ can\ be\ re-written\ as$

$$The\ Inductance, L = \left(\frac{V_i * D}{\Delta i_L * f_s}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

$Where\ f_s = Switching\ frequency$

$$The\ Duty\ Cycle\ D = \frac{(V_o - V_i)}{V_0} \ldots\ldots\ldots\ldots\ldots.\ldots\ldots\ldots (4)$$

$$The\ Inductor\ Current\ I_L = \frac{(V_0 * I_0)}{V_i} \ldots\ldots\ldots\ldots\ldots\ldots (5)$$

The Capacitor Current graph will be as shown in Figure 6.

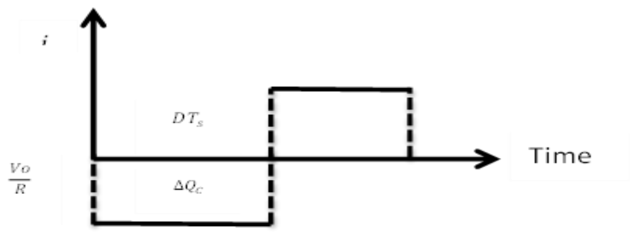

Figure 6: Graph showing capacitor current Vs time

During the switch on time (DTs), the capacitor is discharged and current flows through the capacitor in the reverse direction.

Hence, the charge can be written as depicted in Equation (6).

$$\Delta Q_c = \frac{Vo}{R} * DT_s \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

By multiplying the Equation (5) with Capacitor value (C) on both the sides, it is obtained as

$$\frac{\Delta Q_C}{C} = \frac{Vo}{CR} * DT_s \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

$$Where, \left(\frac{\Delta Q_C}{C}\right) = \Delta V_0\ and\ T_s = \frac{1}{f_s}$$

By substituting these into Equation (7), we can get the Capacitance value for the boost converter as given in Equation (8).

$$C = \frac{D}{R\left(\frac{\Delta V_0}{V_0}\right) f_s} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots .(8)$$

As per PV output and in order to achieve 415V AC in the system, boost converter is designed with the following parameters,

Input Voltage (V_{in}) = 290V

Output Voltage (V_o) = 800V

Switching Frequency (F_{SW}) = 5 KHz

Voltage Ripple=1%

Current ripple = 5%

The inductance of boost converter is calculated as, L = 2.1407mH

And the capacitance is calculated as, C = 1996µF

VII. MATLAB SIMULINK MODEL OF THE SYSTEM

The overall MATLAB Simulink model of On-board Solar PV powered Electric Vehicle integrated with Battery Energy Systems is shown in Figure 7. The solar PV array is considered with variable irradiance and constant temperature of 25°C. A resistive load is taken for representing the DC drive of electric vehicle connected between Boost Converter and DC-DC bi- directional converter of the battery.

The simulation model is executed for a period of 5 seconds and the readings of PV output voltage (V_{pv}), PV output power (P_{pv}), DC link voltage (V_{dc}), EV load current (I_{ev}), Boost Converter current (I_{boost}), Battery current ($I_{battery}$) are recorded for various values of irradiance.

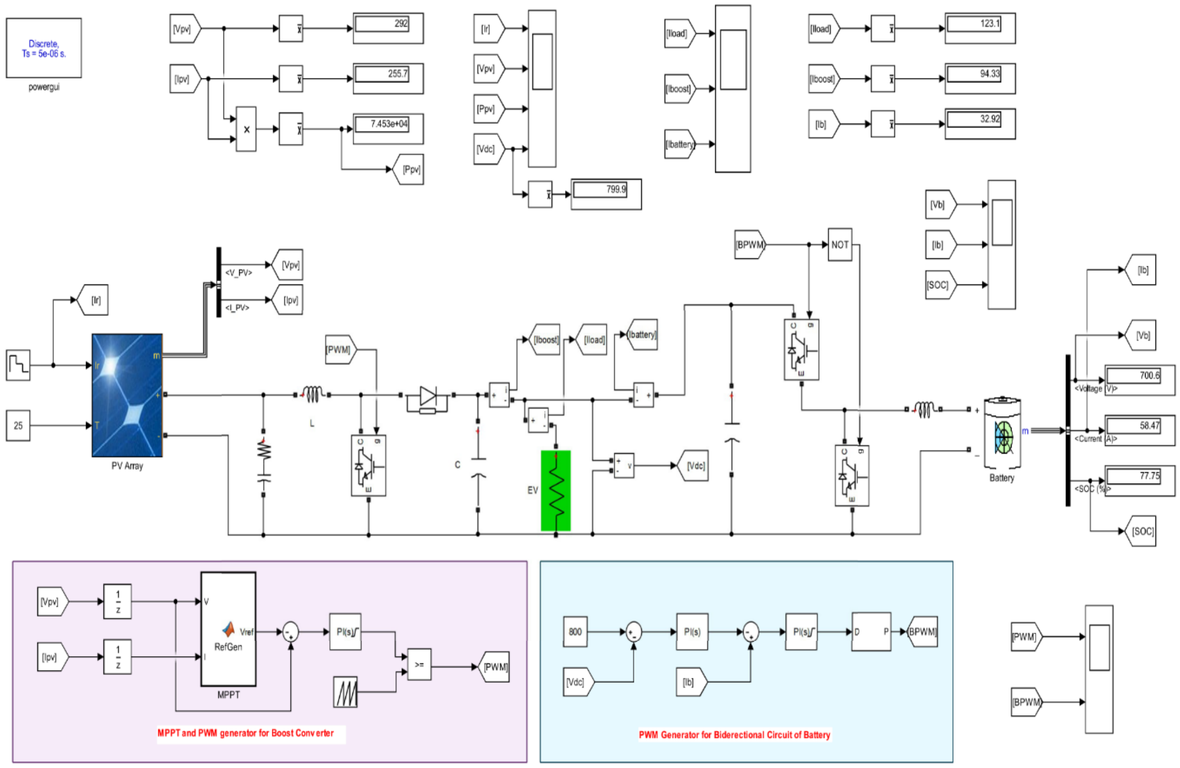

Figure 7: MATLAB Simulation circuit of PV powered EV integrated with battery

VIII. RESULTS AND ANALYSIS

The Figure 8 (a) given below shows the PWM Pulses generated by perturb and observe MPPT algorithm to be used for triggering the IGBT switch S of DC-DC boost converter and Figure 8 (b) shows the pulses generated for DC-DC directional converter for turning-on its switches.

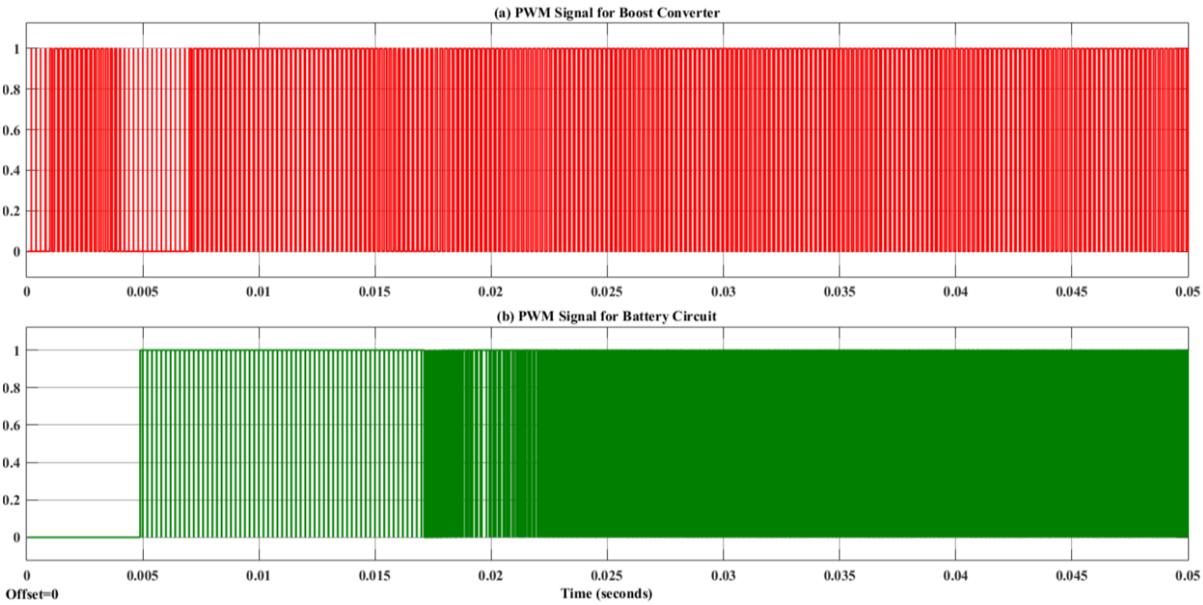

Figure 8: PWM Pulses for (a) DC-DC Boost Converter Switch (b) DC-DC Bidirectional Battery Circuit

From the results of simulation during the battery charging shown in Figure 9, at constant irradiance of 1000 W/m^2, the generated PV output voltage 290 V and power output 100kW are constant throughout the simulation period as the irradiance is constant. The DC link voltage is obtained as 800 V by PV-MPPT technique using Bost Converter.

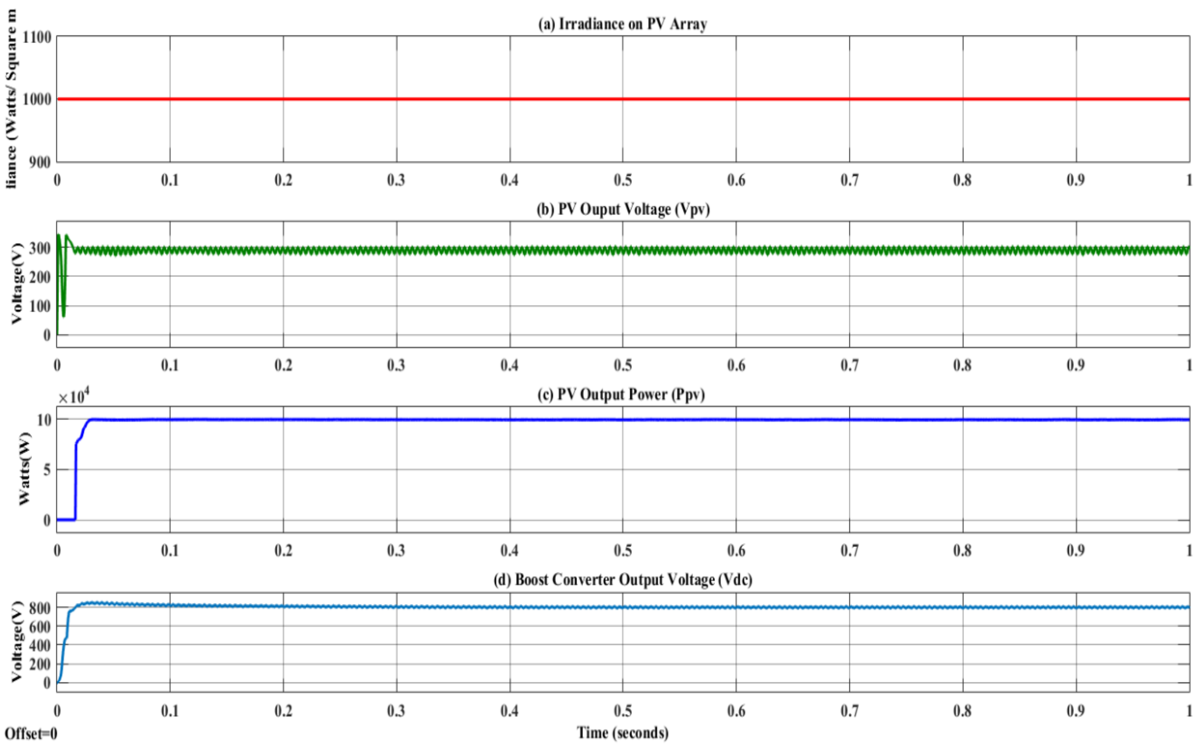

Figure 9: Simulation results of (a) Solar Irradiance (b) PV output voltage (c) PV output power (d) Boost Converter output voltage.

Figure 10 shows the charging of battery from its initial residual voltage to maximum voltage within 1 second of battery response time. The charging current is high at initial times, decreased later and continued as constant until the battery is fully charged.

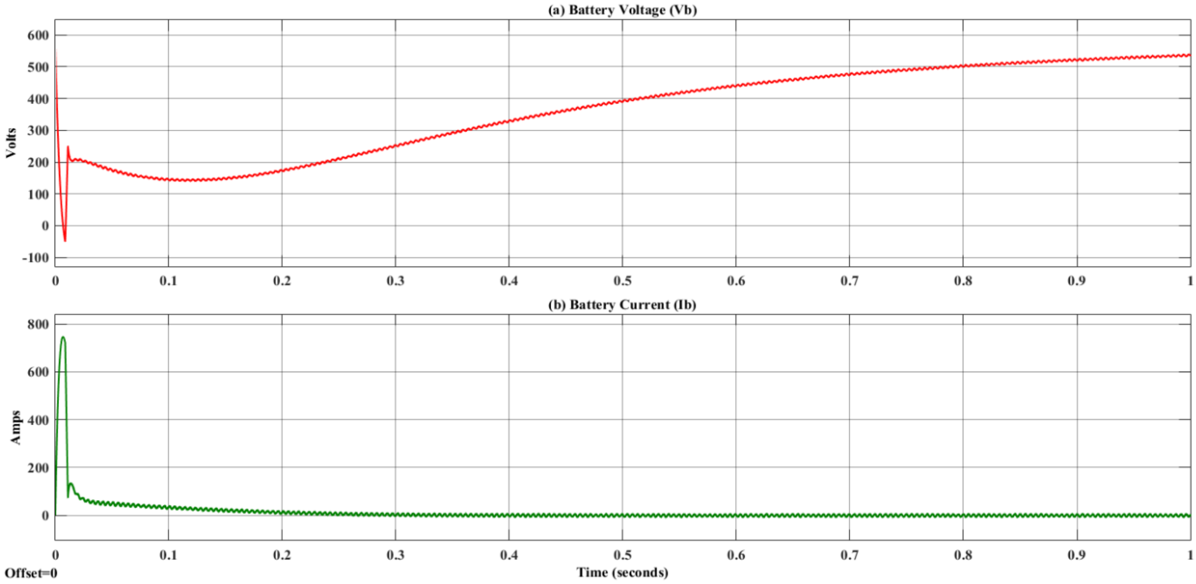

Figure 10: Simulation Results of (a) Battery voltage (b) Battery current during charging.

Figure 11 below describes the PV output voltage, PV output power, and boost converter's output voltage for variable irradiance. Figure 11(a) indicates the different irradiance values which are 1000W/m^2, 750 W/m^2, 500 W/m^2 for duration of 1 second, 2 seconds, and 3 seconds respectively. The corresponding PV output voltage is fixed at 290V throughout the execution period even the irradiance is changing shown in Figure 11(b). Figure 11(c) proves that the PV output power is varied depending upon the irradiance of solar PV array. For higher value of irradiance, the higher is the power output and for lower irradiance, the output power is low. Figure 11(d) reveals that the MPPT algorithm is generating the suitable pulses which in turn turning-on and turning off of the boost converter switch so as to get constant DC output voltage of 800V.

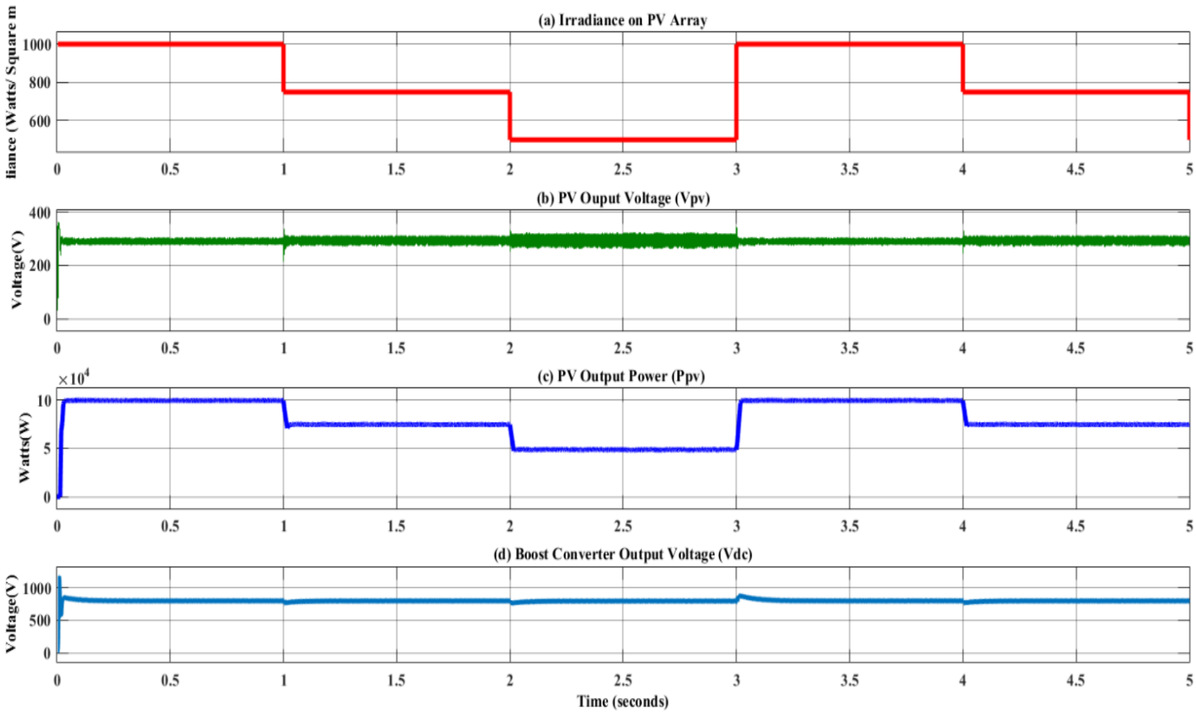

Figure 11: Simulation results of (a) Irradiance (b) PV output voltage (c) PV output power (d) Boost Converter output voltage

The Figure 12 below clarifies that the required current of electrical vehicle which is approximately 130A is taken either from solar PV array or charged battery depending on the availability of irradiance. Figure 12(a) shows the current drawn by the vehicle.

At t=0 sec the irradiance is 1000 W/m^2 and the EV current is 130A.The entire current of EV is being supplied by solar PV only as shown in Figure 12 (b) and the current taken by battery is zero which is shown in Figure 12 (c).

At t=1 second, the irradiance is reduced to 750 W/m^2 but the current required by the DC drive is fixed at 130A. As the irradiance is less, lesser current is generated by solar PV array which is not sufficient for the EV drive. In this scenario, the remaining required current is drawn by the storage battery as shown in the Figure 12 (c).

At t=2 seconds, the irradiance is further decreased to 500 W/m^2, as shown in Figures 12(a), 12(b) and 12(c) it is confirmed that the current required by the EV is constant to drive the vehicle but the current shared by solar PV is further reduced and the current sharing of stored battery is increased in the same ratio to make the total EV current 130A.

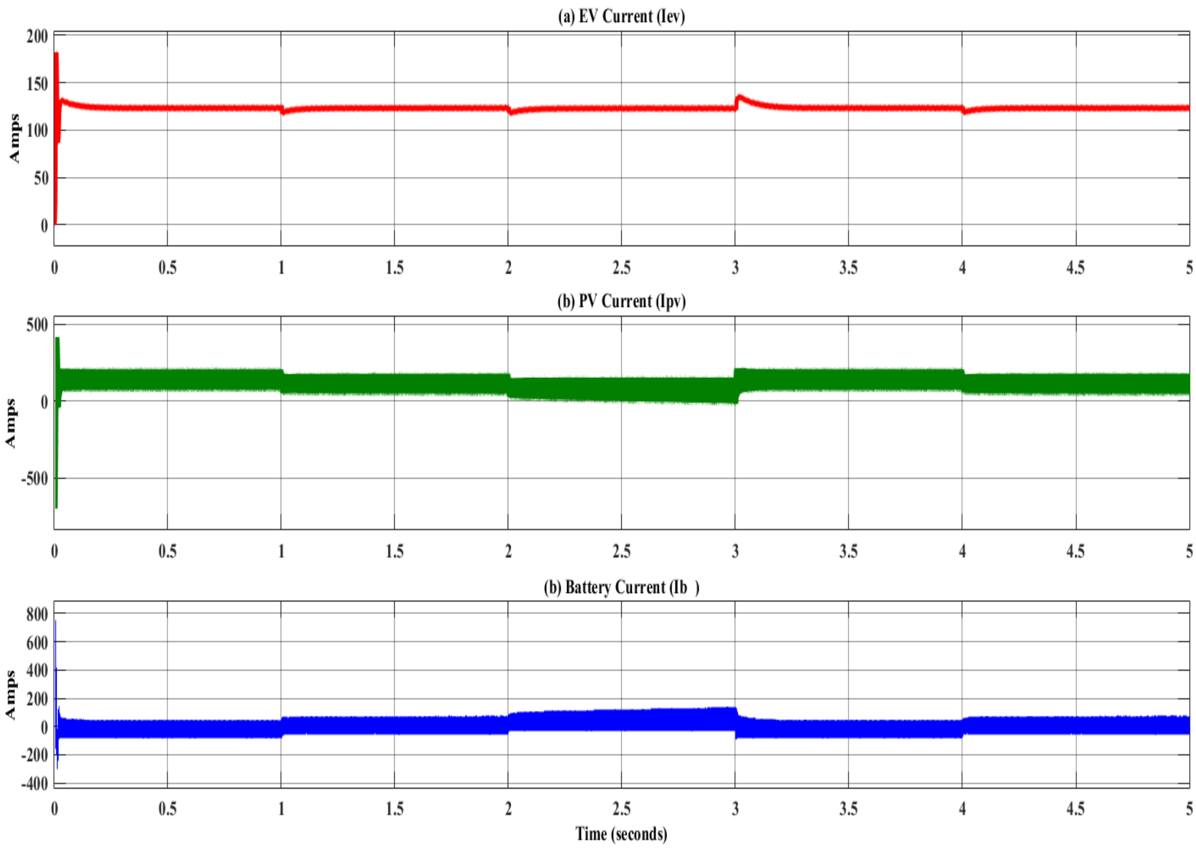

Figure 12: Simulation Results of (a) Required EV Current supplied by (b) Solar PV Current and (c) Battery Current for variable solar irradiance.

The Figure 13 indicate the battery voltage (Vb), battery current (Ib), and battery SOC corresponding to various irradiance values as discussed above. At=0 second the battery starts charging by taking current from PV as irradiance is 1000 W/m2, at t=1 second battery discharges and supplies current to EV as irradiance is reduced to 750 W/m2.

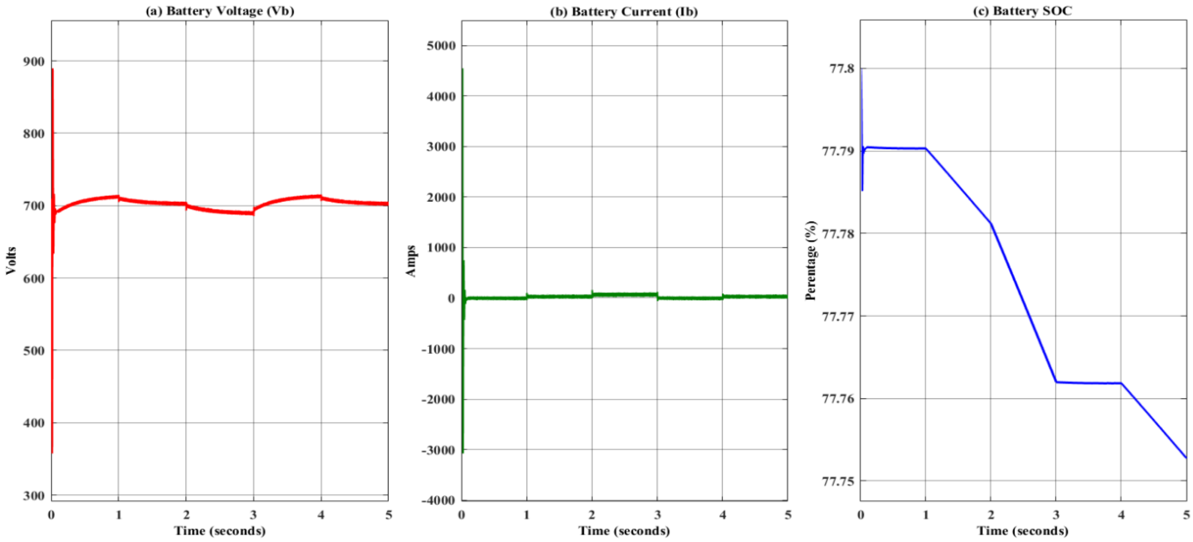

Figure 13: Battery (a) Voltage (b) Current and (c) SOC for variable irradiance values.

IX. CONCLUSION

It is understood that the solar PV array and Battery have taken care of the required EV current when the vehicle is on. As long as the sufficient solar irradiance available, the EV can be driven by solar PV current and no need to take current from the battery. Battery supports the EV during the low irradiance and the battery can be charged during parking of vehicle when solar irradiance available. which indicates that during the availability of solar irradiance.

As the power required by EV is shared by solar PV array and Battery Energy Storage System to supply power to the DC drive existing in the electric vehicle, the charging time of the battery will be reduced and life of the battery will be improved significantly. In this scenario, there is no need of charging EV at charging stations as it is a continuous process of generating PV power to supplied for EV drive and integrated battery system.

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