iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 10 **Issue:** XII **Month of publication:** December 2022

DOI: https://doi.org/10.22214/ijraset.2022.48138

www.ijraset.com

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International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 10 Issue XII Dec 2022- Available at www.ijraset.com

Grid and Solar Photovoltaic Sources Assisted Charging System for Electric Vehicles

G. Sai Kiran[1], M. Premkumar[2]
[1]PG Student, Department of Electrical and Electronics Engineering, Dayananda Sagar College of Engineering, Bengaluru, Karnataka 560078, India
[2]Associate Professor, Department of Electrical and Electronics Engineering, Dayananda Sagar College of Engineering, Bengaluru, Karnataka 560078, India

Abstract: Power generation using Photovoltaic (PV) cells is the primary source among renewable energy sources. The PV cell, which utilizes solar energy, turns solar radiation into electrical energy without adversely affecting the earth's atmosphere. The key issue regarding PV power generation is that solar irradiation varies with time on an hourly basis. To extract the high power from the PV panel during the change in environmental condition, Single-Ended Primary Inductance-Capacitor (SEPIC) based DC-DC converter, and a highly efficient Maximum Power Point Tracking (MPPT) algorithm are used. In this study, an isolated SEPIC converter is used to charge the battery of an electric vehicle via a grid or PV source. The incremental Conductance (INC) algorithm is more efficient among the MPPT methods due to the accuracy in steady state and flexibility to the environment, increasing the system's overall efficiency. Therefore, this study uses the INC method to obtain high power output during the change in environmental conditions. The converter, MPPT algorithm, and controller are developed in MATLAB/Simulink environment, and the results are verified through the simulations. The results show the applicability of the SEPIC converter with INC for electric vehicle battery charging applications.
Keywords: Electric vehicle; incremental conductance; MPPT; photovoltaic system; SEPIC converter.

I. INTRODUCTION

The environment's growing carbon effluents have shifted emphasis away from conventional vehicles and toward electric vehicles with conventional Internal Combustion Engines (ICEs) powered by gasoline, diesel, natural gas, etc. Conventional cars are a factor in the rise in harmful CO2 and NOX are air pollutant in the atmosphere. An Electric Vehicle (EV) is a fantastic substitute, given its efficiency in reducing the use of fossil fuels and managing air pollution toxicity levels. Additionally, traditional vehicles must frequently choose a trade-off between mileage and engine power. On the other hand, EVs are anticipated to deliver better power transmission without sacrificing the quality of the complete range of vehicles. The world has turned its focus to EVs, and by 2030, most nations are anticipated to market electric vehicles only. By then, India was too committed to promoting EVs. Hence, infrastructures for domestic and commercial charging stations need to be built nationwide [1].

The installation of a diesel generator and solar Photovoltaic (PV) battery system based on a charging station for electric vehicles. If the storage battery runs out and there is no solar PV generation, the charging station uses the grid and a diesel generator set to generate power [2]. Multiple-port charging has been discussed in relation to solar power for recharging electric vehicles [3]. The use of solar energy in conjunction with EV charging and the discussion of solar chargers help to reduce the reliance on fossil fuels significantly. To maximize the use of solar energy, a converter is reprocessed for voltage regulation, and Maximum Power Point Tracking (MPPT) is carried out [4]. Battery Electric Vehicle (BEV) ingests fewer moving parts than a modern ICE vehicle, resulting in less complex and low maintenance costs [5]. Additionally, a battery energy storage device is required for the PV system's reliable system behavior under changing environmental conditions. It saves additional power during peak solar irradiation and provides the energy saved during peak loads [6-7].

On the other hand, the working of PV energy conversion is based on the steps of charging the PV, as it operates with MPP, and the power generated is supplied to the load [8-9]. The maximum possible power is extracted when the load resistance is the same as the equivalent resistance of the proposed circuit according to the maximum power transfer theorem. As a result, MPPT can rectify the PV energy conversion system's nonlinearity and inject maximum power extracted from the PV source to the load using a DC-DC conversion device which is managed by adjusting the duty of the gate pulses with algorithms that are used to extract maximum power [10-13]. Due to the proper implementation of renewable energy technologies, the EV battery charging market is expanding along with daily growth in demand for renewable energy [14-15].

Battery charging using non-isolated topologies of the DC-DC converters has been observed for medium-level and high-power appliances or instruments [16]. The boost converter and interleaved boost converters are used to charge the batteries of electric vehicles with medium and lower DC-link voltages [17-19]. The dc voltage gain ratings of CUK converters and buck-boost converters are lower. To provide non-inverting and stable output, the sepic converter is used for charging the batteries. The transformerless SEPIC converter provides a higher voltage gain, though often [20]. However, there are several risks, including increased ripple current on the supply side and increased conducting losses in the power electronic switches. Thus, the Currently being investigated is a high-gain SEPIC converter. Being used, providing a constant supply of current with decreased switching losses, less ripple, improved efficiency, and zero requirements of additional pulse transformer for isolation purposes are huge benefits. How effectively a high voltage gain-based SEPIC converter works without the transformer has been experimentally analyzed thoroughly under various circumstances. The generated voltage, current, switch currents, inductor voltage, and comparison are done under different irradiations [21]. Energy storage components are essential for storing and supplying energy in times of abundance and crisis. Developing suitable battery management systems enables the State-Of-Charge (SOC) to operate in the ideal range and provide overcharging protection [22]. Without a controller, using solar panels ultimately lead to higher installation costs and equipment failure. The DC-DC Converters are an essential component of the photovoltaic power conditioning system. These are offered to control a constant output voltage under various PV cell operating circumstances. An electronic device called a DC-DC converter transforms a direct current source from one voltage level to another. The maximum power extracted from a solar photovoltaic system is determined by variables such as irradiation, temperature, and load profile. In the PV system, a variation in an MPP is observed. To achieve maximum power, the MPPT algorithm is required [23]. The DC-DC converter's operating system is very simple and clear. The inductor in the input resistance causes unexpected variations in the input current. The inductor feeds energy from the input and stores it as magnetic energy if the switch is left at its highest setting.

The energy is released if the switch is off. The dynamics of the DC-DC converters are lightly damped and nonlinear. Cont roller design is crucial for addressing the system's nonlinearity issue and achieving the desired output voltage with good dynamics. The DC-DC converter can be controlled using various control techniques, including PI controllers, fuzzy logic, and neural networks [24]. A new data-dependent, a multiple-constraint energy management strategy for hybrid electric buses (HEBs) that emphasizes awareness of degradation and thermal safety of the onboard lithium-ion battery (LIB) system [25-26].

This study used an isolated SEPIC converter to charge the electric vehicle's battery. The Incremental Conductance (INC) algorithm extracts the maximum power. The performance of the proposed strategy is tested under different environmental conditions, such as Standard Testing Conditions (STCs) and rapid change in insolation.

The paper is organized as follows. Section 2 presents the operation of the proposed battery charging strategy. Section 3 discusses the design procedures of the SEPIC converter. Section 4 discusses the INC MPPT method and controller to regulate the voltage. Section 5 discusses the simulation results, and Section 6 concludes the paper.

II. PROPOSED BATTERY CHARGING SYSTEM

The proposed system for EV battery charging is provided in Fig.1. This proposed electric vehicle system with a PV source operates in two modes: grid charging and PV charging. It comprises an integrated SEPIC converter with PV as a source and the battery as an energy storage device and load parameters such as voltage, power generated, and power consumed along with the battery's state of charge. The auxiliary switches are used for controlling the operational modes.

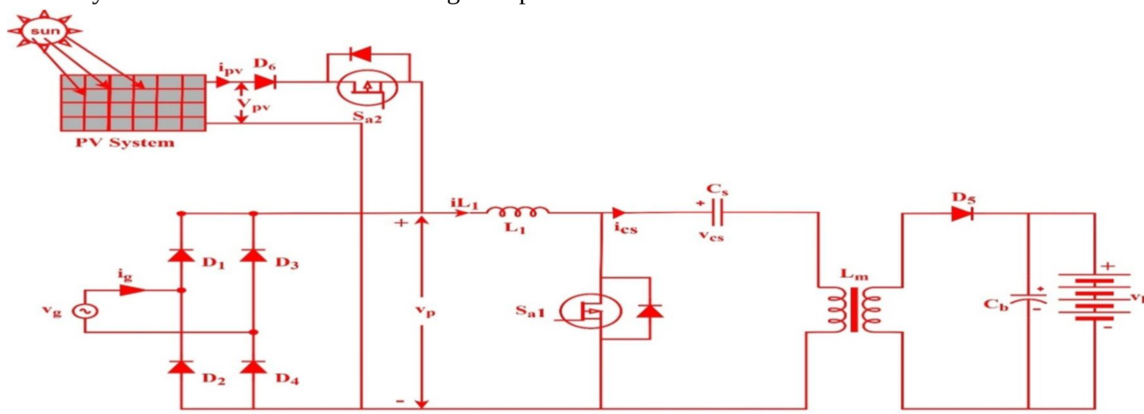

Fig. 1. Proposed electric vehicle system with PV and grid sources

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 10 Issue XII Dec 2022- Available at www.ijraset.com

A. PV Cell Modelling

This study selects the PV panel with 12V and 100W ratings for energy generation. A single-diode model of PV cell representation is provided in Fig. 2. A five-parameter model (I_s, I_o, n, $R_{s,}$ and R_p) of solar cells are provided in the following equation [27].

$$I = I_s - I_d\left(e^{\frac{v*IR_s}{R_s V_T}} - 1\right) - \frac{V*IR_s}{R_p} \quad (1)$$

where I_s is PV cell current (A), I_d is diode saturation current (A), n is diode ideality factor (ranges from 1 to 2), R_s is series equivalent resistance (Ω), and R_p is shunt equivalent resistance (Ω) of the solar cell.

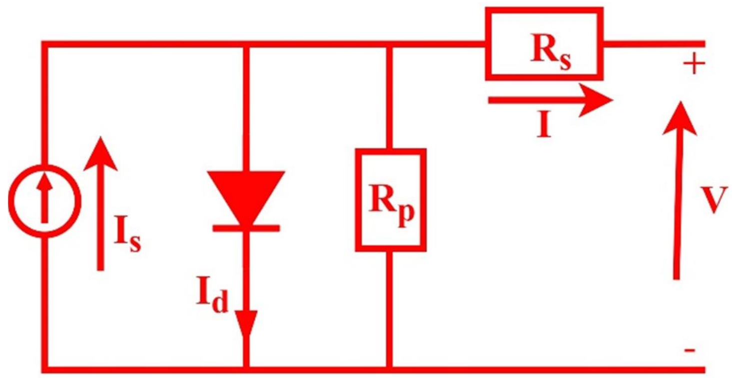

Fig. 2. Solar diode model of solar cell

B. Solar-Fed Battery Charger

A solar-fed EV battery charging setup using the SEPIC dc-dc converter topology is shown in Fig. 3. In this case, the converter regulates the load voltage to be lower, higher, or equal to its input [28]. The pulse width of the converter switch is used to control the output**.**

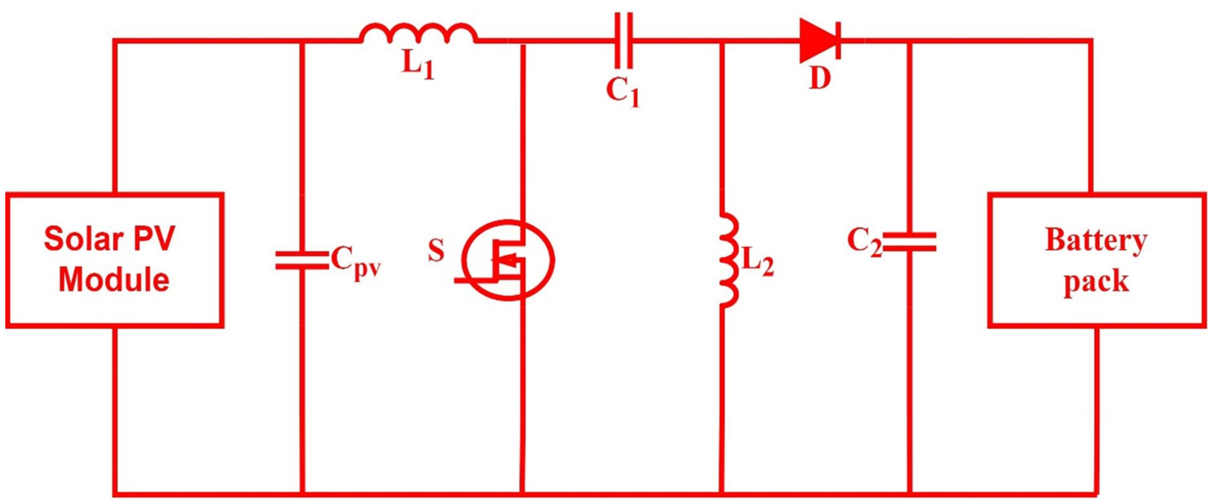

Fig. 3. Schematic of a SEPIC-based DC-DC charger

There are two operating modes in the SEPIC converter. The MOSFET turns on when the pulse rate is high. Inductors L_1 and L_2 are charged by the input voltage Vin and the capacitor C_1. When the diode is not conducting, the load is supplied by the output side capacitance C_2. When the pulse is low, the MOSFET is off, and the inductor current is allowed to flow to the load, the capacitors charge up. The voltage across the load increases as the duty cycle increases because longer charge durations result in higher inductor voltage. The following equation can be used to calculate the duty cycle (D).

$$D = \frac{V_{out}}{V_{in} + V_{out}} \quad (2)$$

where V_{out} denotes the output voltage and V_{in} denotes the input voltage to the converter.

MODE 1: Grid Charging **-** The PV panel is disconnected in this mode. When S_{a1} is turned-on magnetizing inductor L_m and inductor L_1 are charged, and The direction of the current in both inductors is represented with thicker lines in Fig. 4. In this, the capacitor C_b provides energy to the storage device. As S_{a1} is turned OFF, magnetizing inductor L_m and inductor L_1 are discharged, C_s are charged, and the load is supplied.

MODE 2: PV Charging **-** When the PV power crosses a certain limit, the proposed system operates in this mode. The switch S_{a2} is in the ON state during this mode. This mode's converter operation follows a similar logic as the operation of the previous mode. The MPPT operates and uses its maximum power to charge the battery. The maximum power, in this instance, changes according to the changes in solar irradiation, which varies. Figure 5 depicts the equivalent circuit of this mode. When the targeted EV charging is not needed, the PV panel can charge other distinct batteries. Therefore, the switch S_{a2} enhances the performance of the PV panel in such circumstances.

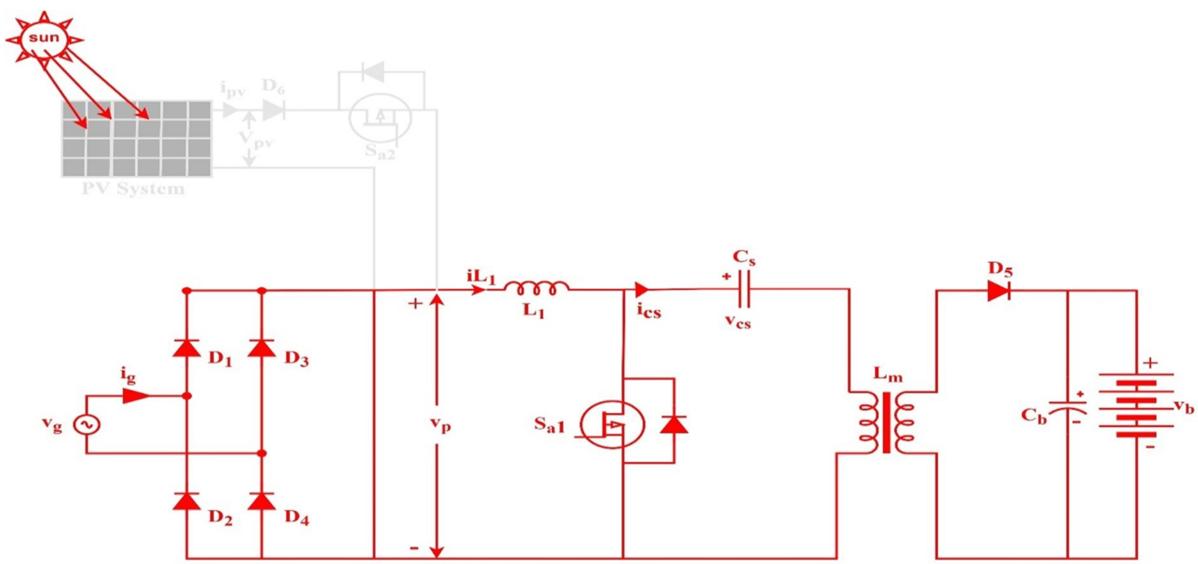

Fig. 4. Equivalent circuit of mode 1 operation of proposed Converter

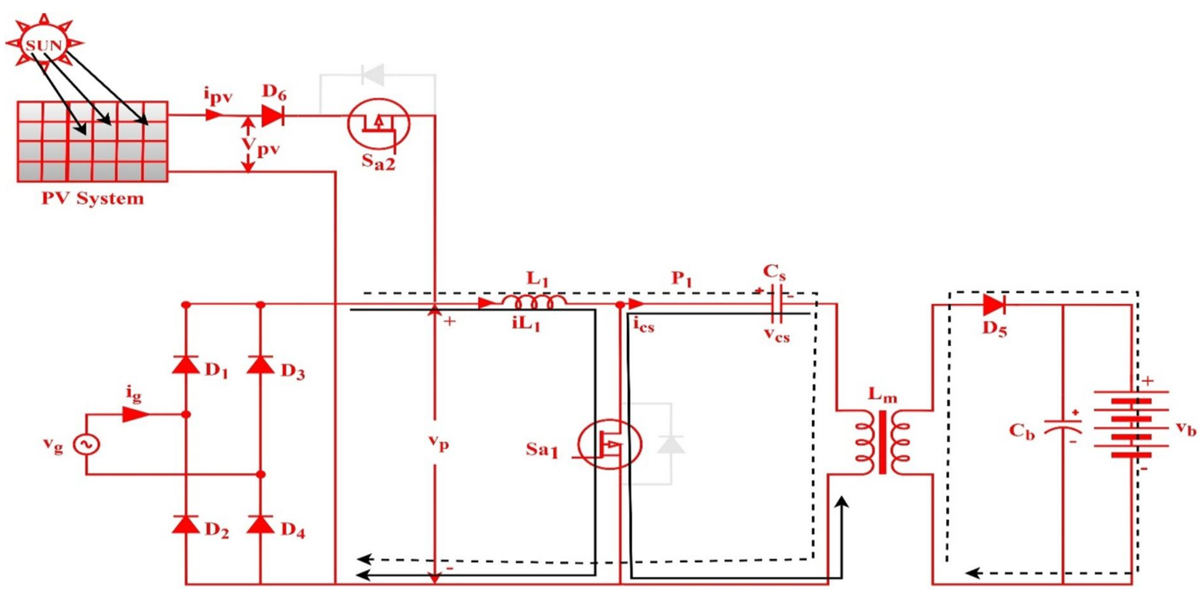

Fig. 5. Equivalent circuit of mode 2 operations of proposed Converter

III. DESIGN PROCEDURE OF THE PROPOSED CONVERTER

Mode 1**:** In this mode, Sa1 is turned ON, L_1 and L_m are charged, and the capacitor C_b supplies the battery. When S_{a1} is OFF, L_1 and L_m discharges, the C_s is charged, and the load is supplied. The inductor value in this mode is provided as follows.

$$L_1 = \frac{V_S + d_1}{\Delta I_{L1} * F_s} \quad (3)$$

The L_m is provided as follows.

$$L_m = V_b \frac{1 - d_1}{\Delta I_{Lm} * F_s} \quad (4)$$

The C_s for k% of capacitor ripple voltage in V_{cs} is provided as follows.

$$C_s = V_b \frac{d_1(t)}{KV_c(t) * F_s R_L} \quad (5)$$

The C_b is provided as follows.

$$C_b = \frac{I_b}{2\omega \Delta V_{cb}} \quad (6)$$

Where V_S denotes the source voltage, d_1 denotes the duty ratio of switch 1, ΔI_{L1} denotes the change in the inductor ripple current, F_s denotes the switching frequency, V_b denotes the battery voltage, V_c denotes the capacitor voltage ripple, I_b denotes the battery current, and R_L denotes the load resistance.

MODE 2**:** In this mode, switch S_{a2} are ON, and the power generated from PV is used to charge the battery. Similar to mode 1, the L_1 is designed as follows.

$$L_1 = \frac{V_{pv} - d_2}{\Delta I_{L1} * F_s} \quad (7)$$

The L_m is designed similar to mode 1, which is provided as follows.

$$L_m = V_b \frac{1 - d_2}{\Delta I_{Lm} * F_s} \quad (8)$$

Where V_{pv} denotes the PV voltage and d_2 denotes the duty ratio of switch 2.

IV. MAXIMUM POWER POINT TRACKING (MPPT) ALGORITHM

A. Selection of MPPT Algorithm

The MPPT provides maximum power extracted from PV despite the changes in solar irradiance, thereby improving efficiency. The voltage quickly falls to zero when solar energy is delivered to the load using the direct coupled method or without MPPT. The MPPT provides the P-V curve to determine the voltage at the maximum power point. There are numerous MPPT Algorithms available [29-31].

B. Incremental Conductance-Based MPPT Algorithm

The power relation is provided as follows.

$$P_{pv} = V_{pv} * I_{pv} \quad (9)$$

Subjecting the above equation to differentiation, we get,

$$\frac{dP_{pv}}{dV_{pv}} = I_{pv} + V_{pv} * \left(\frac{dI_{pv}}{dV_{pv}}\right) \quad (10)$$

The PV power slope dP_{pv}/dV_{pv} must be equal to zero to extract the maximum PV power.

$$\frac{dI_{pv}}{dV_{pv}} = -\left(\frac{I_{pv}}{V_{pv}}\right) \quad (11)$$

To track the PV panel's MPP, the equation above is provided in MATLAB using the INC mppt algorithm in Fig. 6.

The Proportional-Integral (PI) controller is used in mode 1, and the MPPT is used in mode 2. Mode2 operates with two loops of PI controllers. S_{a1} is turned ON by a flipflop set by a clock pulse or gating pulse and turned OFF when the input voltage is equal to the inductor voltage. The control strategy is illustrated in Fig. 7.

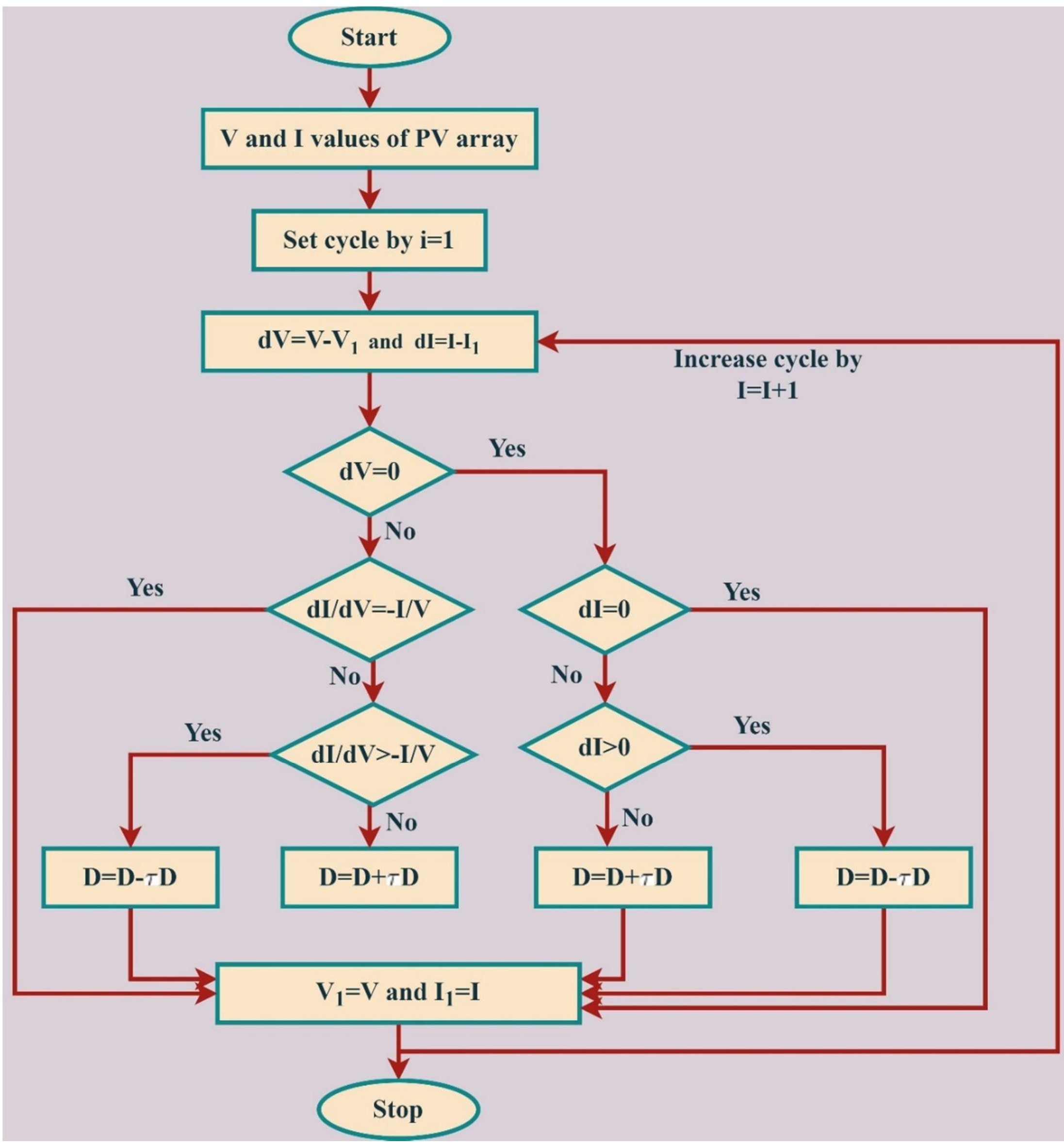

Fig. 6. Flowchart for incremental conductance algorithm

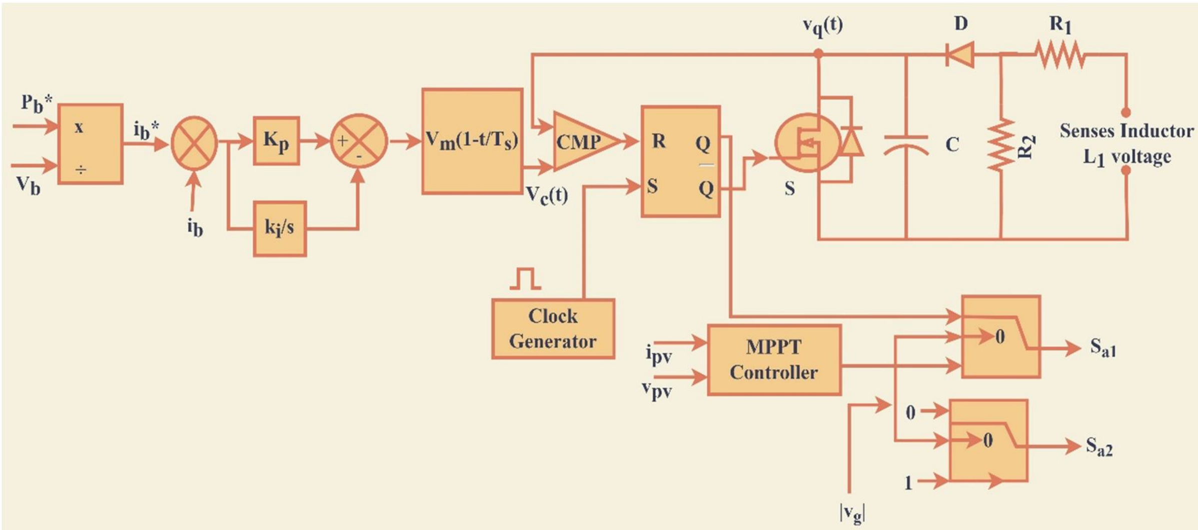

Fig. 7. Proposed control strategy

V. SIMULATION RESULTS

As discussed earlier, the complete system is modeled in MATLAB/Simulink software tool and simulated for different operating conditions. In Mode 1, the supply voltage of 150V is applied to the SEPIC converter from t=0 to t=0.5s. Then the supply is tripped, and PV is connected as the source from t=0.5s to t=2s. During these two modes, the battery gets charged.

1) MODE 1: Grid Charging

The grid voltage and current waveforms are provided in Fig. 8. The peak values of the grid voltage and the current is around 210V and 20A, respectively. The voltage across the grid and current is of zero phase difference between each other, leading to the power factor improvement. The grid charges the battery, and the battery voltage and current waveforms are provided in Fig. 9. and Fig. 10.

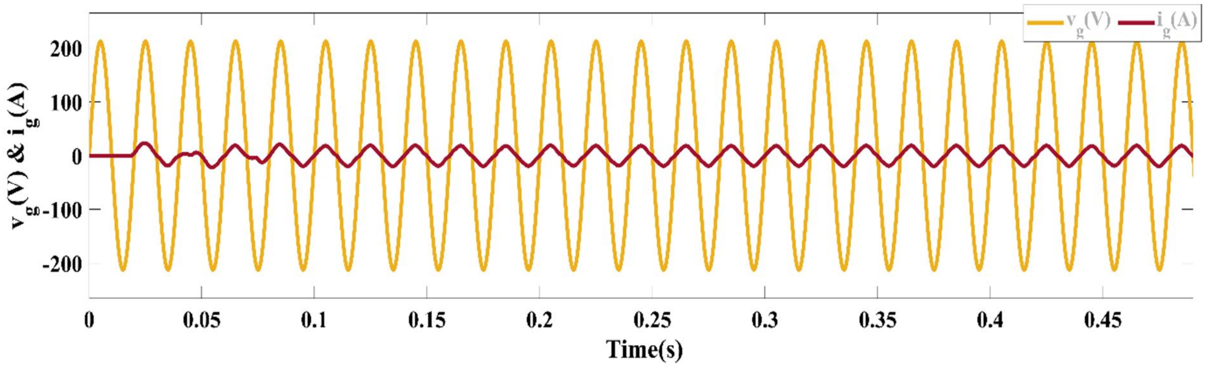

Fig. 8. Grid Voltage and current waveforms

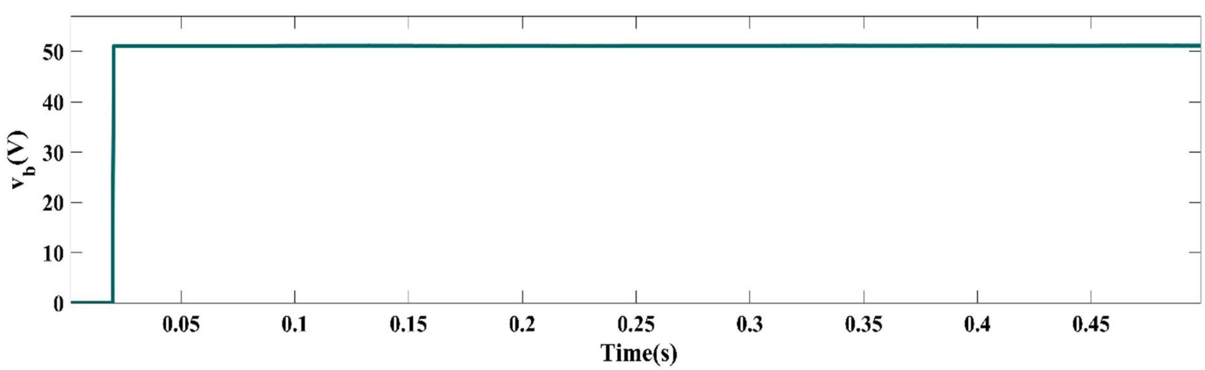

Fig. 9. Battery Voltage waveform in mode 1

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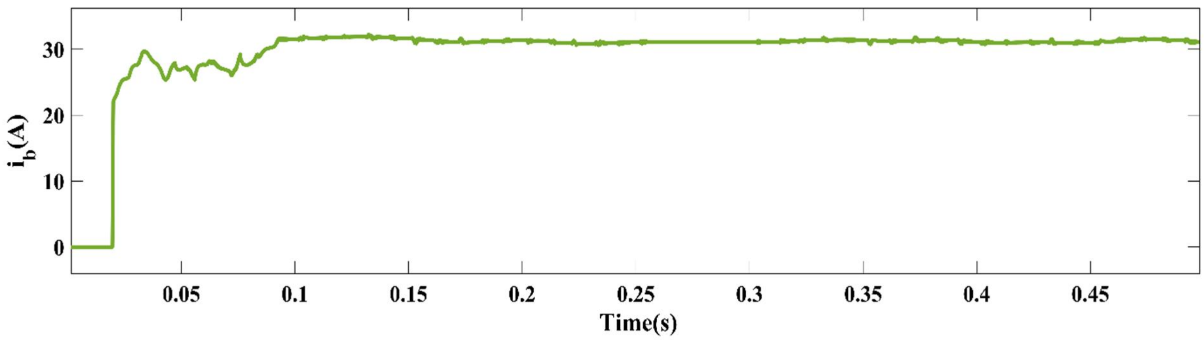

Fig. 10. Battery current waveform in mode 1

2) MODE 2: PV Charging

The battery voltage is maintained at 52V (higher than the battery nominal voltage, 48V), and the current is around 25A. The grid is disconnected at t=0.5s, and PV provides power to charge the battery. The irradiation for PV power generation is provided below in Fig. 11. The solar irradiation is around 500 W/m^2 from t=0.5s to t=1s and from t=1s to 1.5s, the irradiation is 1000W/m^{2,} and from t=1.5s to 2s, irradiation is reduced to 500W/m^2. After 2s, the irradiation is reduced to zero. The PV power due to the above-mentioned solar irradiation is provided in Fig. 12. The PV power generated from t=0.5s to 1s is around 409W, and from t=1s to 1.5s, the power generated is around 809W (97.94%), and from t=1.5s to 2s, the PV power is 409W (99.03%). The battery voltage and current in mode 2 are provided in Fig.13 and Fig. 14. The current flow proves that the PV operates in mode 2 only. It charges the battery in the absence of supply voltage. The battery current is around 10A from t=0.5s to t=1s and from t=1s to 1.5s, the current is 15.6A and from t=1.5s to 2s, irradiation is reduced to 10A

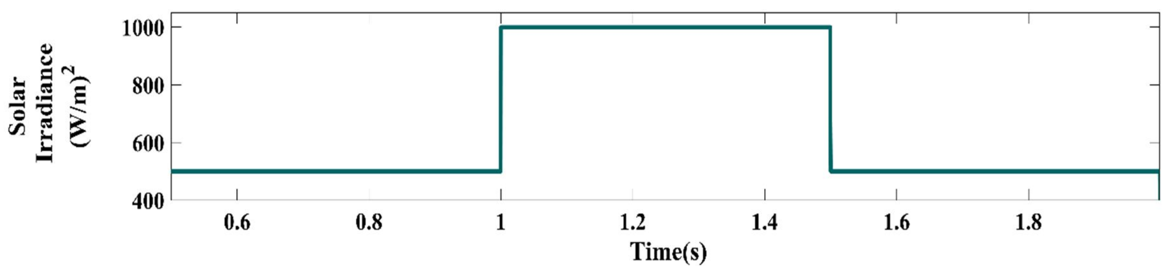

Fig. 11. Solar Irradiation with time

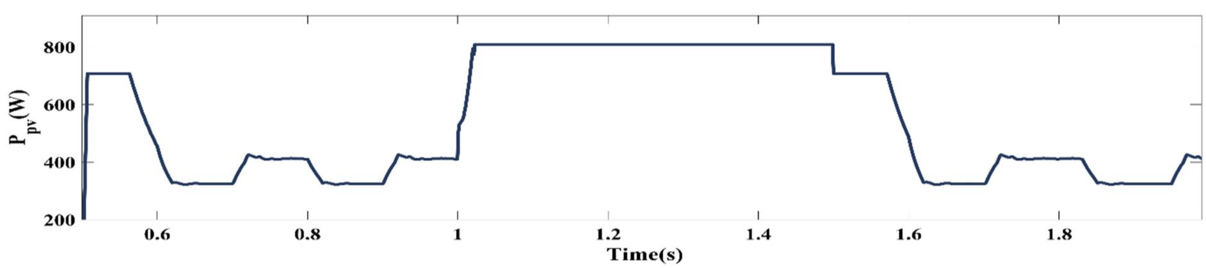

Fig. 12. PV Power in mode 2 with INC algorithm

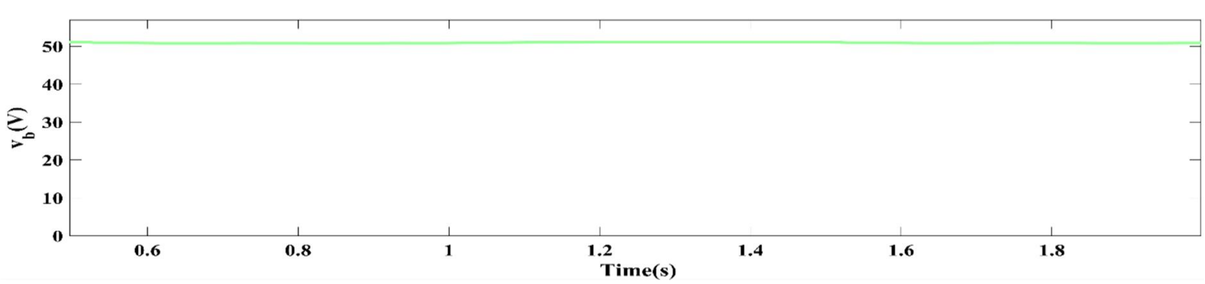

Fig. 13. Battery Voltage waveform in mode 2

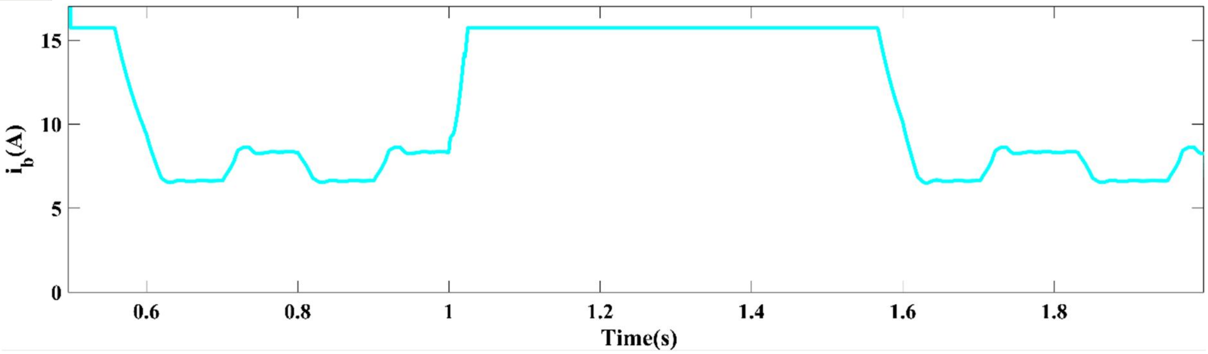

Fig. 14. Battery current waveforms in mode 2

VI. CONCLUSION

In this paper, a SEPIC converter was designed and analyzed for battery charging in electric vehicle applications. In the proposed system, the grid and Solar PV act as sources, however, the PV can serve as the primary source of charging during the day, and grid power can be used to recharge batteries at night. A control structure is introduced to control the operational modes based on the PV power generation. An INC algorithm-based MPPT is proposed by including the change in current (dI) and voltage and power conditional statements in the MPPT algorithm. The proposed system is simulated, and the effectiveness of the proposed method was tested with fixed and variable irradiations.

The proposed strategy can also be extended to the standalone PV pumping systems. The proposed system may be tested under dynamic shading conditions with different MPPT algorithms. The experimental analysis is also considered as the future scope of this work.

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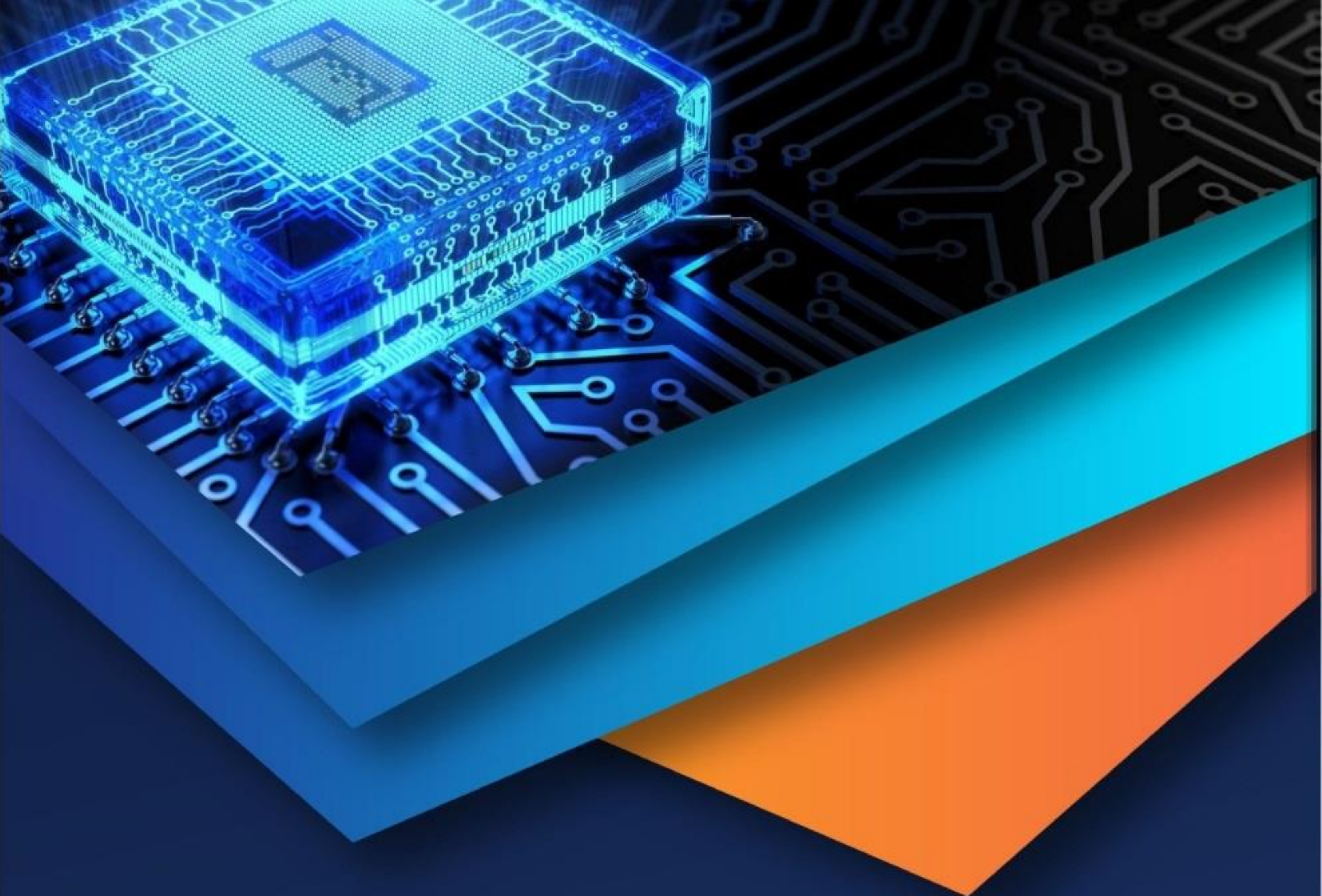

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