DOI: https://doi.org/10.52756/ijerr.2024.v39spl.009 *Int. J. Exp. Res. Rev.*, Vol. 39: 118-128 (2024)

Original Article | Peer Reviewed | Open Access

International Journal of Experimental Research and Review (IJERR)

ISSN: 2455-4855 (Online)
www.iaph.in

PV-Based Design and Evaluation of Power Electronic Topologies for EV Applications

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Article History:

Received: 26th Jan., 2024
Accepted: 20th May, 2024
Published: 30th May, 2024

Keywords:
Electric vehicle, Incremental conductance, Modified SEPIC converter, Maximum power point tracking, Perturb and observe, Photovoltaic

How to cite this Article:
Bondu Pavan Kumar Reddy and Vyza Usha Reddy(2024). PV-Based Design and Evaluation of Power Electronic Topologies for EV Applications. *International Journal of Experimental Research and Review, 39*(spl.) 118-128.
DOI: https://doi.org/10.52756/ijerr.2024.v39spl.009

Abstract: This study presents a unique concept for an electric vehicle (EV) charging system that is powered by photovoltaic (PV) technology. The core of the system is a modified single-ended primary inductance converter, chosen for its high efficiency, reduced switch voltage stress, and ample operating range for maximum power point tracking (MPPT). This study details the redesigned SEPIC converter architecture, including with and without the MPPT algorithm. Additionally, an optimized parameter selection, design methodology, and simulation technique are presented for analyzing converter performance in EV charging applications. Two MPPT approaches, Perturb and Observe (P&O) and incremental conductance (IC), are investigated and compared based on their impact on the converter switching time under standard solar PV panel testing conditions. To comprehensively evaluate the system's performance, a MATLAB/Simulink model is developed, simulating the charging of a 48 V, 200 Ah battery using a 2 kW solar PV input through the modified SEPIC converter and variations in the battery state of charge (SoC), battery voltage, and charging current are monitored. The simulation results demonstrate that under identical simulated conditions (10 Sec), the battery SoC increases from 50% to 50.034% without MPPT and to 50.042% with MPPT, highlighting the effectiveness of the MPPT algorithms in maximizing harvested solar energy.

Introduction

The increasing adoption of electric vehicles necessitates the development of efficient and readily available charging infrastructure. This paper presents a novel approach to EV charging by utilizing a PV-powered system with a modified SEPIC converter. Compared to traditional boost converters, the modified SEPIC offers several advantages, including nearly double the static gain, a wider operating range for the MPPT controller and reduced switch voltage stress, thereby enhancing the converter's reliability and lifespan (Eltamaly and Abdelaziz, 2019).

The adoption of renewable energy alternatives has increased dramatically due to the rising costs and depletion of nonrenewable energy sources. Among these, photovoltaic (PV) energy has drawn much interest as a potential remedy for the problems posed by increased energy demand and global warming. Fuel independence, environmental friendliness, durability, and cheap maintenance are just a few advantages of PV energy (Chilakapati and Manohar, 2023; Ramesh et al., 2023). Many processes are involved in integrating PV systems into the grid, one of which is raising the output voltage to meet grid requirements. Boost converters or high-frequency step-up transformers are used in conventional methods. Even though DC-DC converters are frequently used to boost PV system voltage, traditional topologies frequently have poor static gain, which lowers the output voltage (Suryoatmojo et al., 2018).

For instance, the maximum input voltage increase that a SEPIC converter with a duty cycle of 0.82 can achieve is a factor of 5. A tenfold increase in the input voltage is needed to fulfil grid requirements, making the use of a

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step-up transformer redundant. This study suggests a modified SEPIC converter architecture to overcome these drawbacks. With the addition of a diode and a capacitor, the converter may increase the input voltage by up to ten times. Because of these improved capabilities, a step-up transformer is no longer necessary, simplifying the system design and perhaps increasing efficiency. By investigating modified SEPIC converter architectures that deliver higher output voltages and better efficiency, this research seeks to integrate further PV systems (Suryoatmojo et al., 2018).

Background of the Work

Mouli et al. (2015) and Bhatti et al. (2016) systematically study various topologies and system architectures of PV charging systems in the context of electric vehicles. Three primary conclusions emerge regarding PV charging systems for EVs: grid-connected systems are more preferred against off-grid systems, a topology with a DC-link is the most effective for the overall system arrangement, and standards require that EV converters be isolated.

Mouli et al. (2015) present four different architectures of integrated EV-PV systems as follows: the PV system and the EV system use either a power converter integrated or separate converters for both PV and EV, and whether the connection is through AC or DC circuitry (Yadav et al., 2023; Thota et al., 2023). At the same time, many researchers (Tulpule et al., 2013; Verma et al., 2016) consider the power exchange to be carried out through AC, suggesting a separate PV inverter and an AC EV charger and possibly integrated energy storage to perform this function). The downside to this strategy is that both PV and EV equipment are essentially DC devices. Subsequently, power exchange over AC leads to added losses and necessitates two inverters in place of one. Thus, a design featuring an integrated converter and a DC link for exchanging power between the EV and the PV is more optimal (Goli and Shireen, 2014).

Methodology & Designing

Solar PV Specifications

The design and development of a MATLAB/Simulink model for a solar photovoltaic (PV) system intended to recharge an electric vehicle's (EV) battery is described in the present article. The system was configured to deliver 48 V and 200 Ah to the battery using a modified SEPIC converter. One of its main benefits is the 48V 200Ah battery's capacity to give electric cars a longer range. Electric vehicles (EVs) can cover greater distances on a single charge due to their larger capacity and higher voltage. The 48V 200Ah battery is considered for simulation since it also provides better efficiency compared to conventional battery technologies.

Table 1. Solar PV Module Specifications at STC.

Parameter	Specification
Voltage at MPP (V_{MPP})	30.9 V
Current at MPP (I_{MPP})	8.1 A
Power at MPP (P_{MPP})	250.29 W
Open Circuit Voltage (V_{OC})	36.6 V
Short Circuit Current (I_{SC})	8.75 A

A constant irradiation of 1000 W/m^2 and a temperature of 25°C are assumed in the simulation. The PV system incorporates the maximum power point tracking (MPPT) functionality to maximize the power output. The simulated system has eight parallel modules, and each module has sixty solar cells. The specific design parameters of the PV modules are detailed in Table 1 (Datasheet, 2023).

Perturb & Observe MPPT

The prime motive of Perturb and Observe is to ensure that the solar module operates at its peak efficiency by continuously perturbing the operating point of the solar panel and observing the corresponding change in power output. This algorithm alters the operating point till it attains the maximum power point (MPP). This is a widely used technique in the field of photovoltaic systems aimed at optimizing the efficiency of solar energy conversion. P&O MPPT is renowned for its simplicity, cost-effectiveness, and adaptability to various environmental conditions. The flow chart of P&O MPPT is shown in Figure 1(Eltamaly and Abdelaziz, 2019).

Incremental Conductance MPPT

The primary intention of the Incremental Conductance Maximum Power Point Tracking (MPPT) technique is to make sure that it operates at the maximum power point (MPP) under varying environmental conditions. This is a sophisticated algorithm employed in photovoltaic systems to optimize the energy output from solar panels. Unlike conventional fixed-point methods, Incremental Conductance MPPT dynamically tracks changes in the solar array's voltage and current characteristics, making it highly responsive to fluctuations in sunlight intensity. By comparing the incremental conductance, which is the rate of change of power concerning voltage, with the instantaneous conductance, the algorithm effectively and efficiently converges toward the MPP. The flow chart of incremental conductance MPPT can be seen in Figure 2 (Eltamaly and Abdelaziz, 2019).

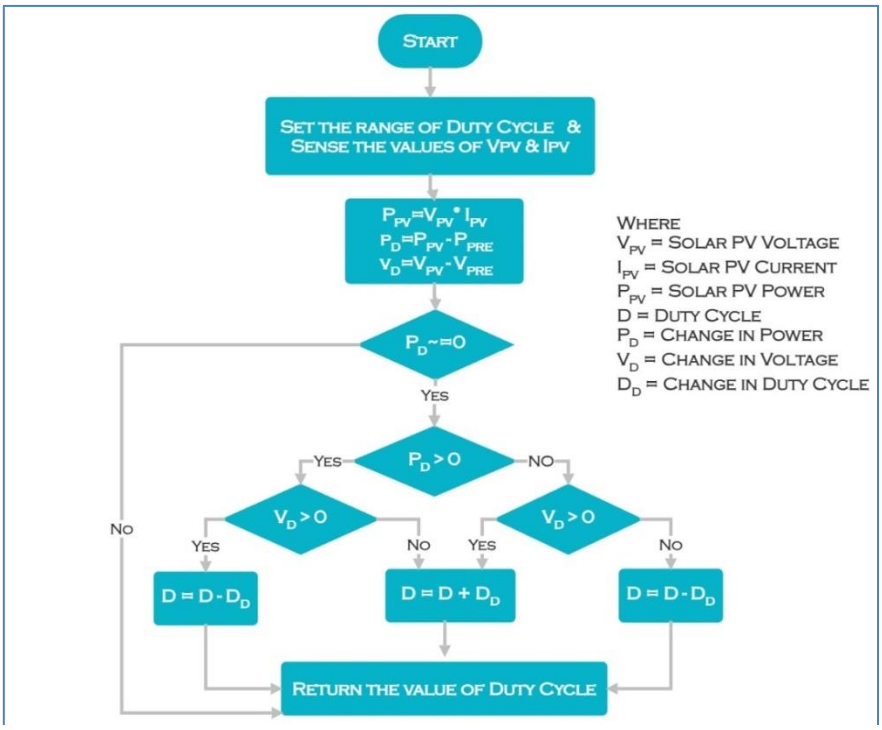

Figure 1. Flowchart for Perturb & Observe MPPT.

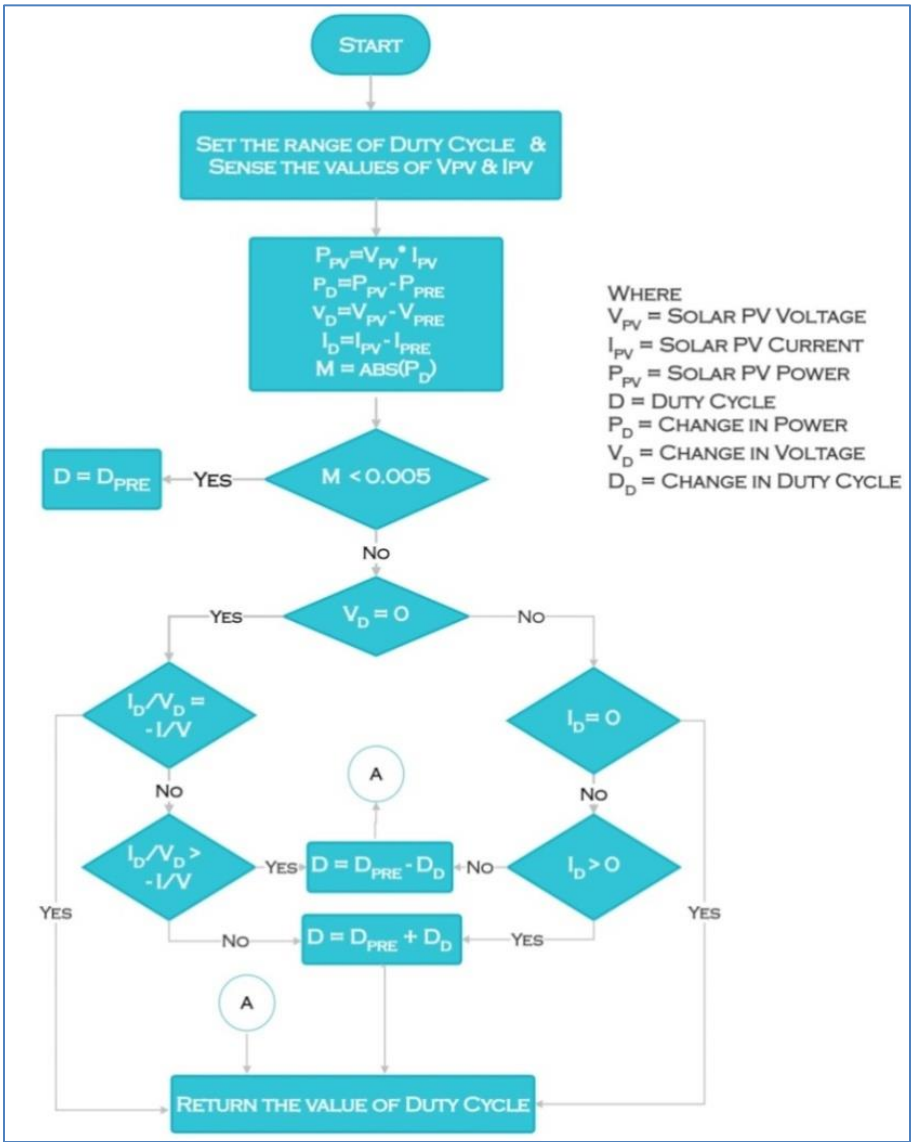

Figure 2. Flowchart for Incremental Conductance MPPT.

DOI: https://doi.org/10.52756/ijerr.2024.v39spl.009

Design of Modified SEPIC Converter

The power circuitry of the traditional SEPIC converter is presented in Figure 3. A key feature of the SEPIC converter is its ability to both boost (step-up) and buck (step-down) the input voltage, making it suitable for applications with a wide range of input voltages. However, the switch voltage is equal to the sum of the input and output voltages (Falin, 2023; Babaei and Mahmoodieh, 2014).

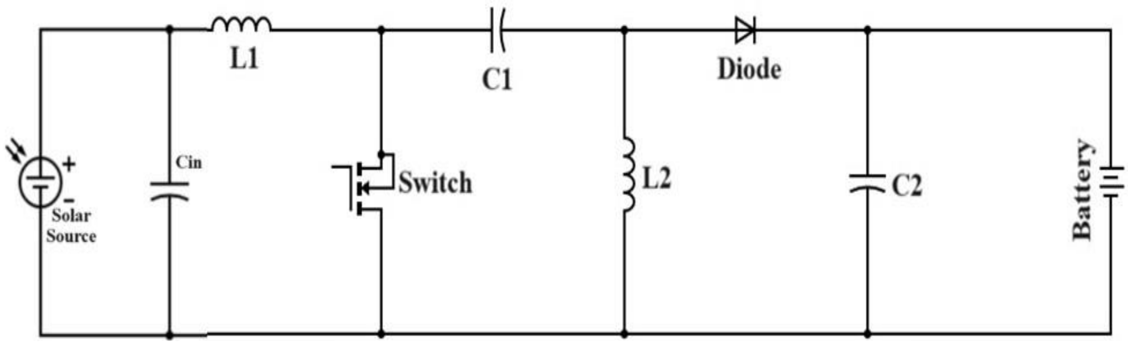

Figure 3. Schematic of the traditional SEPIC converter.

This topology is modified by incorporating additional components and rearranging the existing components. A schematic of the modified SEPIC topology is shown in Figure 4 below (Gules et al., 2011; Mishra and Singh, 2018; Maroti et al., 2019; Parthasarathy et al., 2022; Muranda et al., 2017).

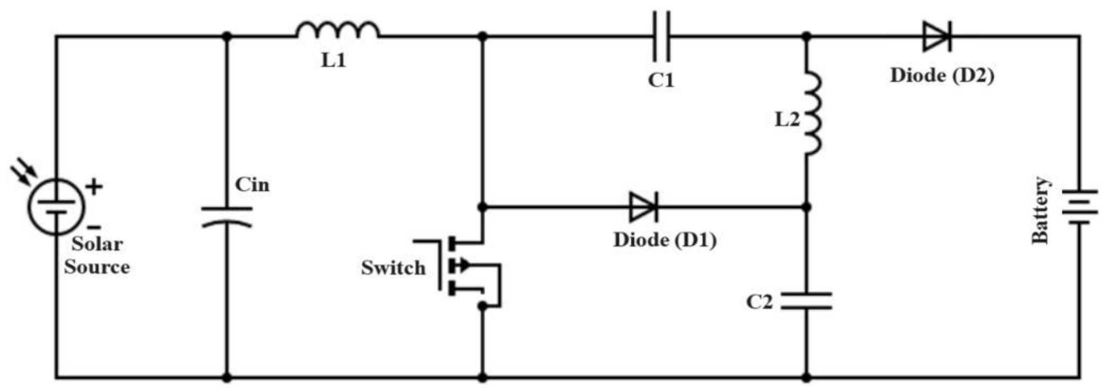

Figure 4. Schematic of the modified SEPIC converter

In continuous conduction mode, the duty cycle of the modified SEPIC converter can be determined by eq.(1).

$$Duty\ Cycle\ (D) = \frac{V_{Out} - V_{In}}{V_{Out} + V_{In}} \quad \ldots (1)$$

The input current is given by eq.(2).

$$Input\ Current\ (I_{in}) = \frac{Input\ Power}{V_{In}} \quad \ldots (2)$$

The first step in designing a PWM switching regulator is determining how much inductor ripple current (ΔI_l) to permit. The inductor ripple current of this topology can be calculated using the eq.(3).

$$Inductor\ Ripple\ Current\ (\Delta I_l) = 0.1 * I_{in} \ldots (3)$$

The inductances can be calculated using eq.(4).

$$Inductances\ L_1 = L_2 = \frac{V_{In} \times D}{\Delta I_l \times F_s} \quad \ldots (4)$$

The maximum allowable output ripple is considered to be 2%. The capacitance can be determined using eq. (5).

$$Capacitances\ C_1 = C_2 = \frac{I_O}{\Delta V_C \times F_s} \quad \ldots (5)$$

The change in voltage across the capacitors is determined by eq.(6).

$$\Delta V_C = 0.02\ X\ \frac{V_{out}}{(1-D)} \quad \ldots (6)$$

For a switching frequency of 20 kHz and analogous input power and load, the various parameters of the ZETA, SEPIC and modified SEPIC converters are calculated and the values are tabulated in Table 2 (Reddy and Reddy, 2024).

Results & Discussion

This study investigated the charging performance of a 48 V, 200 Ah electric vehicle (EV) battery using a 2kW solar photovoltaic (PV) source with a modified SEPIC converter. The simulation is conducted within the MATLAB/Simulink environment.

DOI: https://doi.org/10.52756/ijerr.2024.v39spl.009

Table 2. Evaluated parameters of the ZETA, SEPIC and Modified SEPIC Topologies.

Sl. No	Parameter	ZETA Topology	SEPIC Topology	Modified SEPIC Topology
1	Switching Frequency	20kHz	20kHz	20kHz
2	Max. Duty Cycle (D_{Max})	64%	64%	25.6%
3	Min. Duty Cycle (D_{Min})	60.83%	60.83%	21.7%
4	Inductor (L_1)	362 mH	225 µH	7 mH
5	Inductor (L_2)	362 mH	350 µH	7 mH
6	Capacitor (C_1)	2.6 mf	410 µf	1.7 mf
7	Capacitor (C_2)	3.9 µf	264 µf	1.7 mf

Key parameters such as voltage, current, and power from the PV panel are monitored alongside the battery's state of charge (SoC), charging current, and voltage. The test conditions were kept consistent across all the scenarios. Figures 5 to 13 present the MATLAB/Simulink models, PV characteristics (voltage, current, and power), battery SoC, charging current, and voltage for the modified SEPIC converter under three configurations: without maximum power

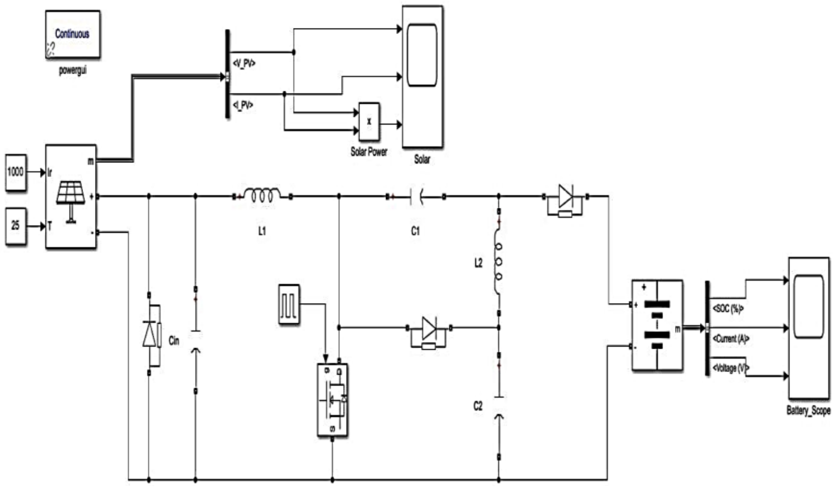

Figure 5. MATLAB/Simulink Model of the modified SEPIC converter without MPPT.

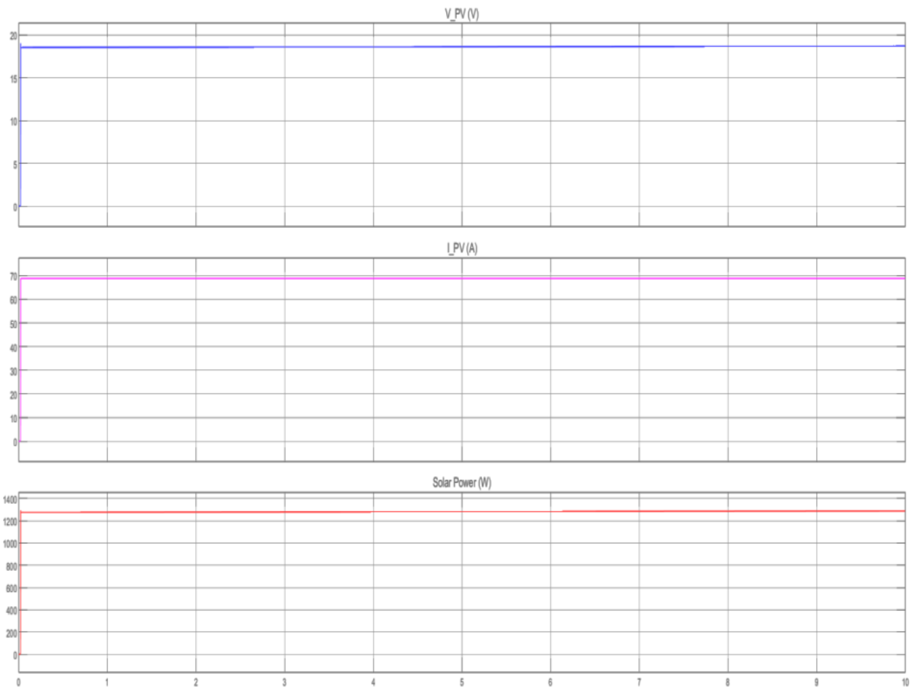

Figure 6. PV characteristics results for the modified SEPIC converter without MPPT.

DOI: https://doi.org/10.52756/ijerr.2024.v39spl.009

point tracking (MPPT), with Perturb and Observe (P&O) MPPT, and with incremental conductance MPPT.

Under identical test conditions, the performances of the EV charging system powered by solar PV employing ZETA, SEPIC and modified SEPIC converters with and without MPPT methodologies are presented in Table 3. Without using Maximum Power Point Tracking (MPPT), a Zeta converter takes roughly 6.94 hours to charge a battery, while a SEPIC converter completes the task in a significantly shorter 4.63 hours. This advantage persists even with MPPT techniques. For example, Incremental Conductance MPPT allows a SEPIC converter to finish charging in just 3.97 hours, whereas a Zeta converter under the same MPPT method still requires 5.5 hours (Reddy and Reddy, 2024).

Furthermore, advancements in SEPIC converter technology show even greater promise. A modified SEPIC converter can achieve the same charging level in a mere 4.09 hours without MPPT, and a remarkable 3.3 hours with MPPT. This represents a substantial improvement in charging efficiency. These results unequivocally show that utilizing solar electricity to charge the batteries of electric vehicles is a more efficient use of the modified SEPIC converter.

It is important to note that negative battery current values indicate that the battery is in charging mode.

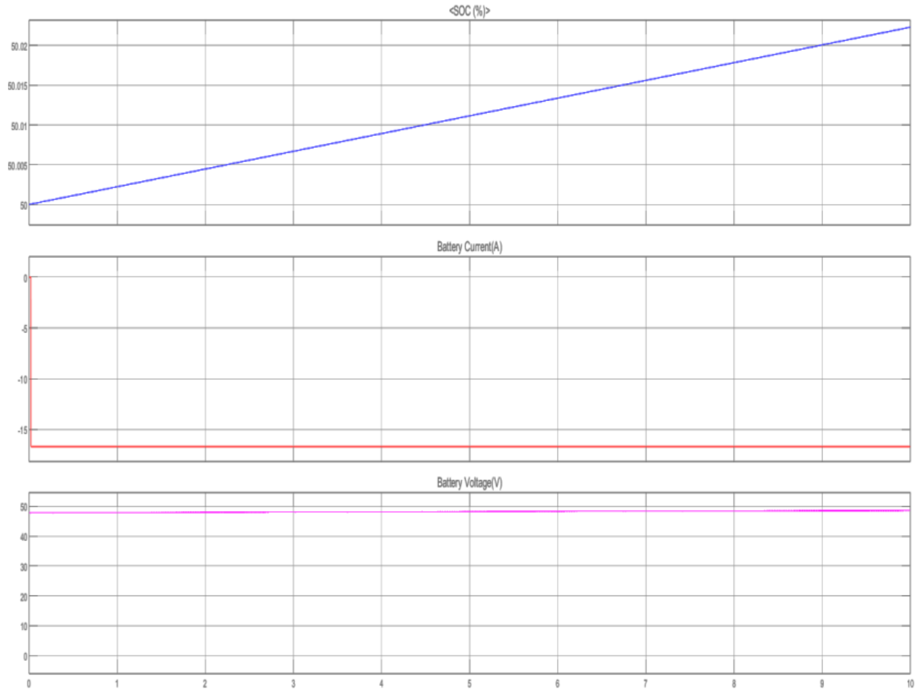

Figure 7. Battery charging results for the modified SEPIC converter without MPPT.

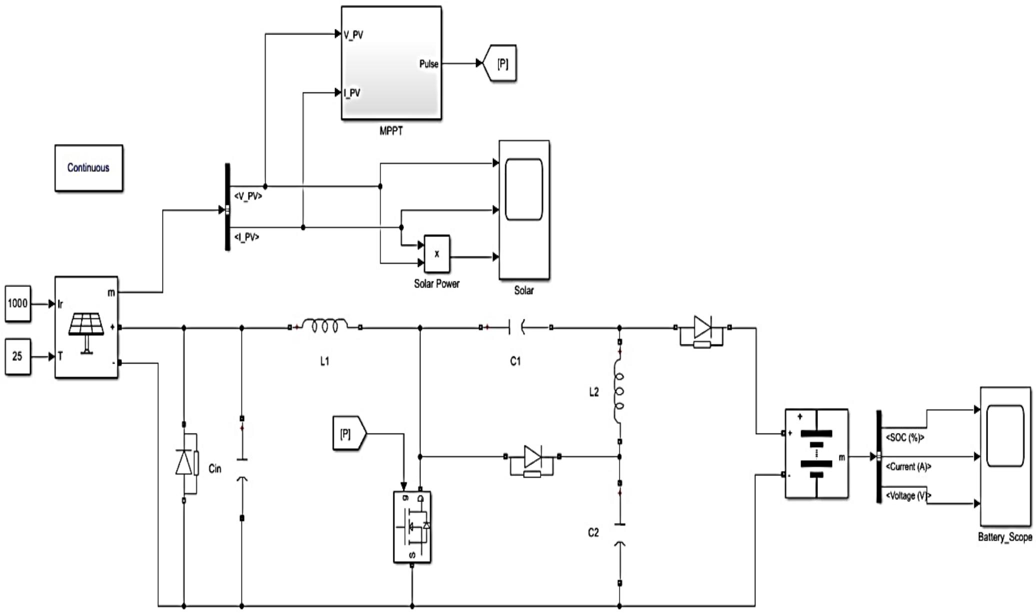

Figure 8. MATLAB/Simulink model of the modified SEPIC converter with P&O MPPT.

DOI: https://doi.org/10.52756/ijerr.2024.v39spl.009

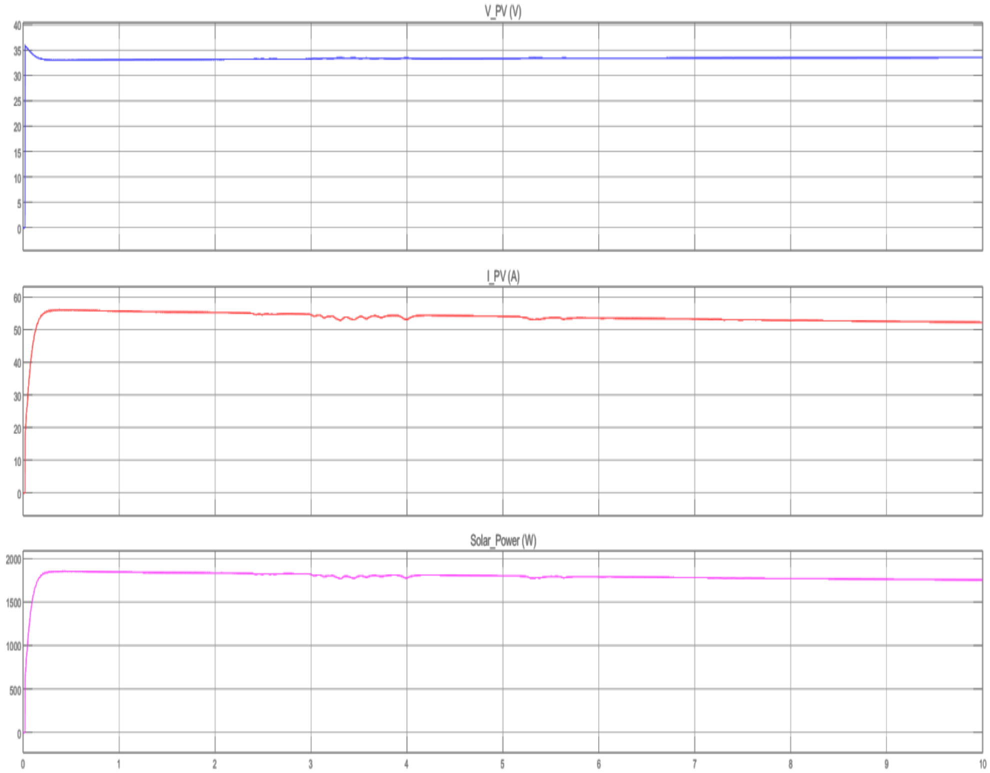

Figure 9. PV characteristics results for the modified SEPIC converter with P&O MPPT.

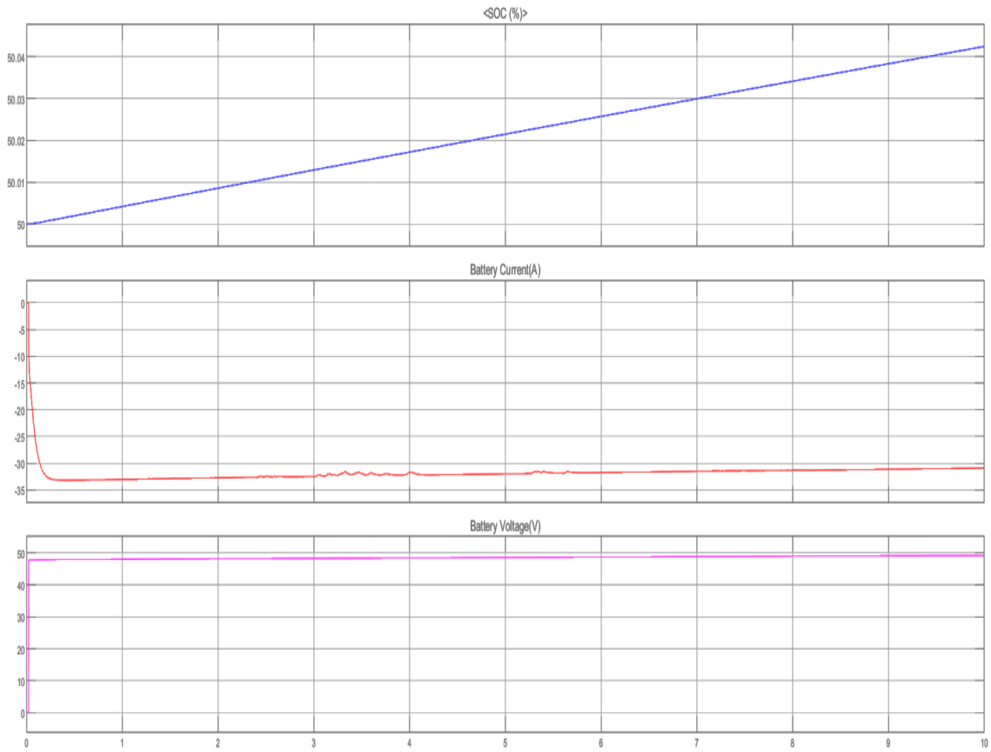

Figure 10. Battery charging results for the modified SEPIC converter with P&O MPPT.

DOI: https://doi.org/10.52756/ijerr.2024.v39spl.009

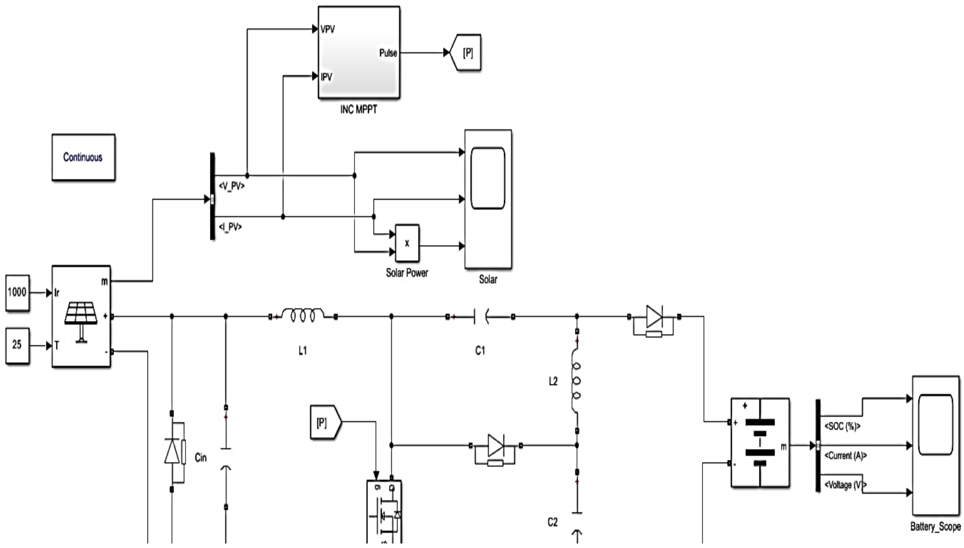

Figure 11. MATLAB/Simulink Model of the modified SEPIC converter with INC MPPT.

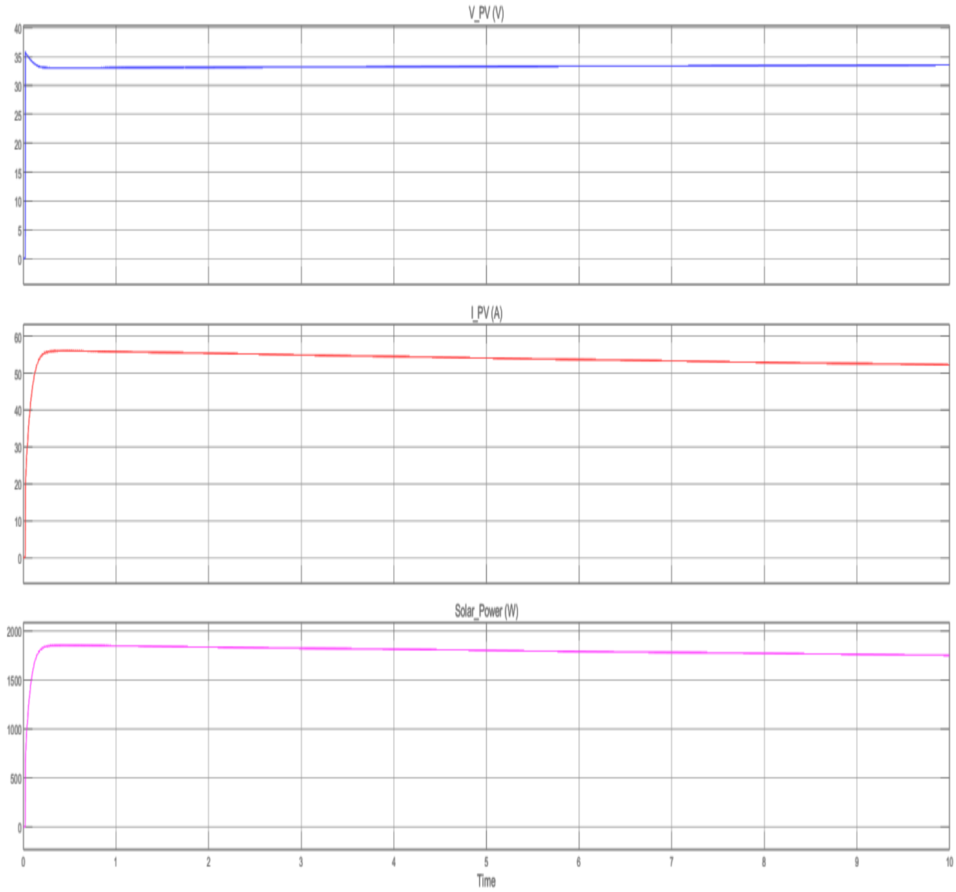

Figure 12. PV characteristics results of the modified SEPIC converter with INC MPPT.

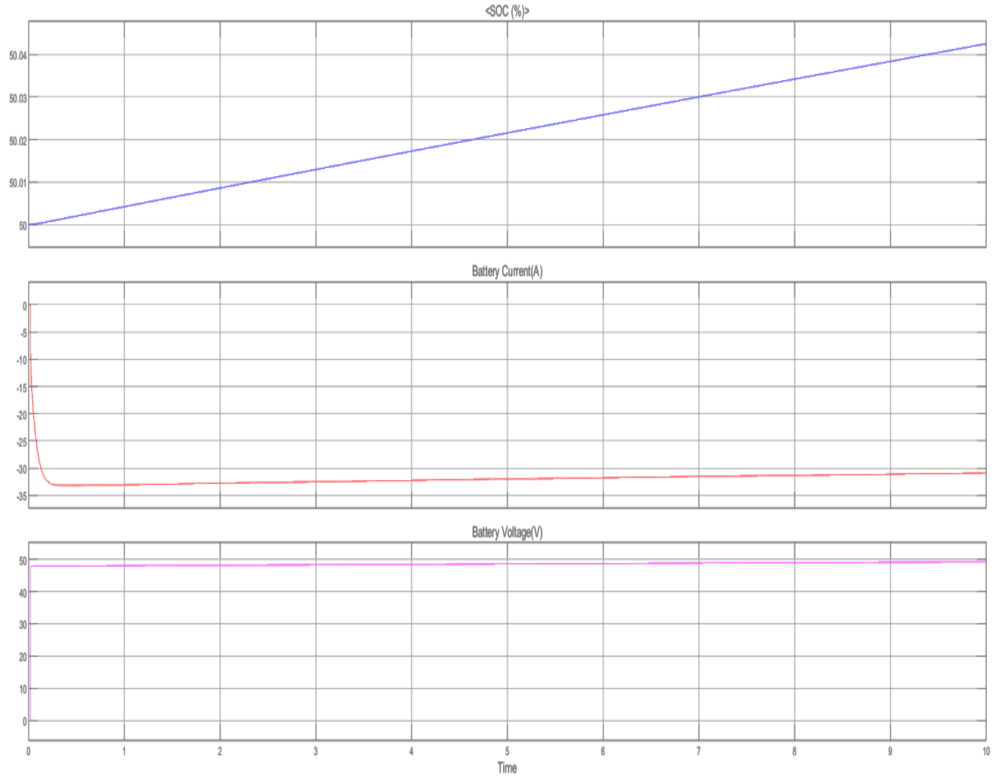

Figure 13. Battery charging results for the modified SEPIC converter with INC MPPT.

Table 3. Comparative study of Simulation results for various Power Electronic Topologies.

Parameter	ZETA Converter			SEPIC Converter			Modified SEPIC Converter		
	With out MPPT	With P&O	With IC	With out MPPT	With P&O	With IC	With out MPPT	With P&O	With IC
SoC (%)	50.017	50.025	50.025	50.02	50.03	50.035	50.034	50.042	50.042
V_b (V)	48.32	48.51	48.51	48.52	48.93	49.01	48.9	49.2	49.3
I_b (A)	-12.03	-16.56	-16.85	-14.84	-23.2	-25.1	-24.17	-30.92	-30.94
V_{pv} (V)	35.46	34.12	32.38	35.59	34.47	34.05	34.76	33.52	33.5
I_{pv} (A)	19.41	30.4	35.08	23.16	41.37	46.6	37.57	52.2	52.25
P_{pv} (W)	688.4	1035	1136	824.2	1426	1587	1306	1751	1752

DOI: https://doi.org/10.52756/ijerr.2024.v39spl.009

Conclusion

This paper presented a novel PV-fed EV charging system utilizing a modified SEPIC converter. The proposed system offers several advantages, including high efficiency, reduced switch voltage stress, and the integration of MPPT algorithms to maximize power extraction from PV panels. The simulation results demonstrated the effectiveness of the implemented MPPT techniques in enhancing the system's performance compared to the scenario without MPPT. This study paves the way for further research and development of efficient and sustainable EV charging solutions utilizing renewable energy sources. The simulation results demonstrate that the modified SEPIC converter delivers a significantly greater current than the traditional SEPIC converter and ZETA converter, leading to a faster increase in the battery's state of charge. For instance, charging a battery without maximum power point tracking (MPPT) takes approximately 6.94 hours with a ZETA converter and 4.63 hours with a SEPIC converter, while the modified SEPIC converter achieves the same result in only 4.09 hours. The advantage persists even with MPPT techniques. Regardless of the MPPT method employed, the modified SEPIC converter consistently achieves faster charging times (3.3 hours) than the ZETA and SEPIC converter. These findings indicate that the modified SEPIC converter offers a more effective solution for charging electric vehicle batteries using solar power.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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How to cite this Article:

Bondu Pavan Kumar Reddy and Vyza Usha Reddy(2024). PV-Based Design and Evaluation of Power Electronic Topologies for EV Applications. *International Journal of Experimental Research and Review*, *39*(spl.) 118-128.

DOI : https://doi.org/10.52756/ijerr.2024.v39spl.009