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Efficient power management for sustainable EV charging station in DC microgrids

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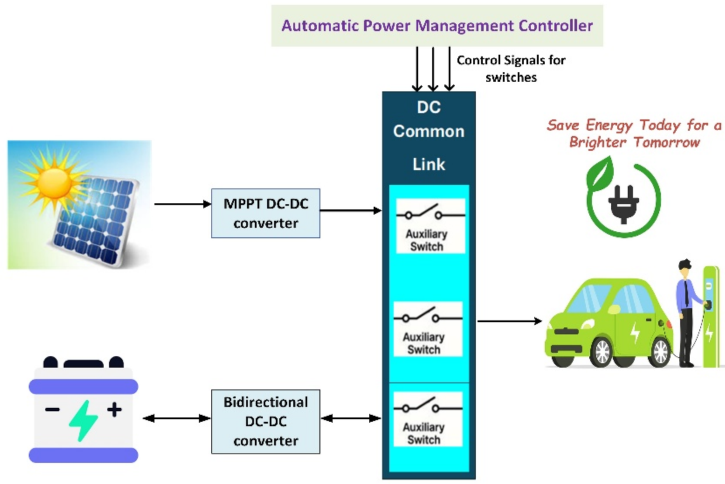
Article

ABSTRACT



As the world shifts to sustainable transportation with electric vehicles, it's essential to boost power generation to meet the growing demand. Renewable energy emerges as a superior alternative to conventional power sources for electric vehicle charging. The study explores the operational reliability and efficiency of renewable energy-powered EV charging in various modes, including direct charging from solar PV, battery-assisted charging, and hybrid modes combining both sources. The multimode operation of the proposed scheme is simulated in the MATLAB/Simulink platform. It is observed that integrating solar PV and Battery Energy Storage (BES) for EV charging offers a flexible and robust solution in remote areas and results in reduced grid dependency. This proposed system offers valuable insights into the development and implementation of sustainable electric vehicle charging systems, supporting the progress of green transportation technologies.

Keywords: Solar Photovoltaic Charging, Electric Vehicle Integration, Battery Energy Storage, Renewable Energy Systems

INTRODUCTION

The popularity of EVs has surged recently due to their numerous advantages over conventional petrol and diesel vehicles. Less carbon emission, overall cost reduction, noise-free operation, lower maintenance, high efficiency, the convenience of charging at home, etc., are some of the major advantages of using EVs as a better choice of transportation in the near future. Many governments worldwide offer incentives and regulations to promote electric vehicle adoption, leading to a growing market and the development of new, improved models. The increasing EV sales in the whole world are shown in Figure 1.[1] India has abundant solar energy resources, receiving near about 5,000 trillion kWh of solar energy annually across its land area. Most regions receive an ample amount of solar energy daily. Solar off-grid, decentralized systems, and low-temperature applications are particularly beneficial for rural areas. India has witnessed a remarkable surge in solar installation capacity, reflecting the nation's swift embrace of renewable energy solutions.[2] This increase reflects India's commitment to sustainable energy and its efforts to meet rising energy demands through clean sources.

Charging stations play a vital role, offering significant opportunities for both technological innovation and business growth in this expanding market. Electric vehicles can be charged particularly when vehicles are parked for extended periods in locations such as office parking spaces, malls, commercial complexes, educational institutions, hospitals, airports, railway stations, and government buildings, etc.[3] Sustainable Development Goal 7 emphasizes guaranteeing everyone access to modern, economical, reliable, and eco-conscious energy, which can be advanced through solar-powered EV charging solutions. Combining solar (PV) systems with electric vehicle (EV) charging stations reduces pollution and dependency on fossil fuels. By making solar-based charging infrastructure widely accessible, we can drive forward both sustainable transportation and clean energy access.[4]

The primary goal of EV charging infrastructure is to provide fast, reliable, safe, and cost-effective charging facilities that are

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efficient. The need for more charging stations will grow with increasing EV adoption[2]. They can work in either a grid-tied mode or in a standalone mode, depending upon renewable energy sources' accessibility.

Electric vehicles (EVs) require frequent charging, often relying on grid power, which presents several challenges [3]. If grid electricity is generated through traditional means, such as coal-fired power plants, the environmental benefits of EV adoption are diminished[5]. Moreover, the growing number of EVs can strain local distribution grids, especially during peak charging times, such as when owners plug in their vehicles after work. This simultaneous demand can lead to issues like voltage instability, harmonic distortion, and frequency fluctuations, complicating load management for utilities[6,7]. Green energy sources like wind, biomass, solar, etc., known for their inexhaustible and pollution-free nature, present a viable solution for charging EV batteries, paving the way for 'green transportation' [2,8,9]. Literature[10] reviews various power converter topologies for solar and wind-powered EV battery chargers, focusing on their suitability for stand-alone and grid-connected systems. Among different clean energy sources, solar energy emerges as a promising option, easily harnessed through photovoltaic (PV) arrays to charge EV batteries[11].

Grid-integrated electric vehicle charging stations that utilize solar power primarily have been explored in the literature[12,13,14]. The various operating modes of such EV charging systems based on solar power availability have been analyzed in [2,11,15,16]. However, off-grid solar charging systems are vital in remote areas and regions with fewer EV owners, where grid access is limited, and the installation cost of conventional EV stations is high[5,17,18]. These systems offer a cost-effective and sustainable solution, enabling energy independence and promoting EV adoption in underserved locations[19,20].

A thorough examination of EV battery charging systems with integrated solar PV arrays and battery energy storage that may be used in a variety of modes is presented in this research. These modes include direct charging from solar PV, battery-assisted charging, and a hybrid mode that combines both sources. This research offers valuable insights into designing and implementing sustainable EV charging systems, helping advance green transportation technologies. The methodology adopted for system integration and the development of the control strategy will be outlined in the next sections. Subsequently, the simulation results are presented, and their implications are discussed.

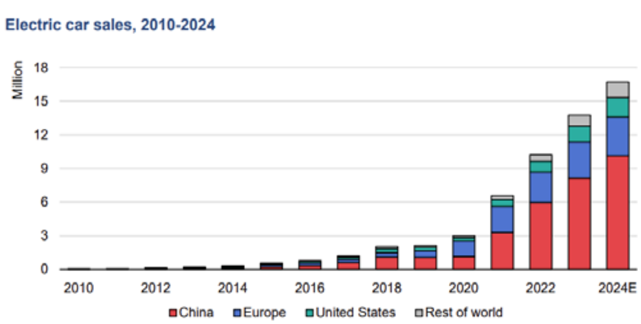

Figure 1. Total EV sales in the whole world (2010-2024) [1]

DESIGN OF SOLAR-POWERED EV CHARGING STATION

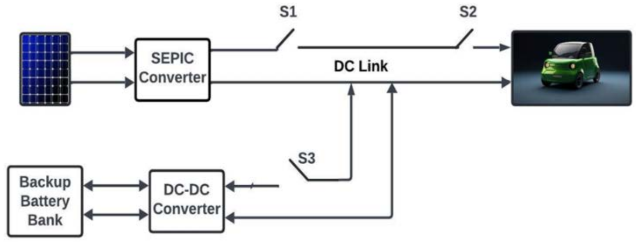

Figure 2. Solar PV and backup battery-powered EV charging method

Figure 2 illustrates the block diagram of the proposed EV charging system. In this setup, the solar PV array is interfaced with the system using a SEPIC converter, while the backup battery is linked to the common DC bus through a bidirectional DC-DC converter[21]. Auxiliary switches S1, S2, and S3 operate automatically and coordinate power transfer across various elements of the system.

Solar photovoltaic output fluctuates due to changing temperature and irradiance conditions. To achieve a stable output voltage, a SEPIC converter is utilized, which can operate in step-up and step-down modes depending on the solar PV array output[22]. A half-bridge bidirectional DC-DC converter is employed to facilitate bidirectional power exchange from the backup battery[21,23]. Switch S1 isolates the PV array from the system when PV generation is insufficient to charge the batteries, while Switch S2 disconnects the EV battery from the system when necessary. Switch S3 connects or disconnects the backup battery as required [22]. The switches operate automatically based on the available PV power and the state of charge of the batteries, with priority given to charging the EV battery. The control algorithm is designed accordingly to ensure efficient operation. In a stand-alone PV system, the charging setup must incorporate an energy storage unit, like a battery, to store the surplus amount of energy[24]. The stored energy can be used during times when solar PV generation is insufficient[11,19]. The following sections outline the design of the key components incorporated in the proposed EV charging system.

Modelling of solar PV array

This section thoroughly explains the modeling of the solar PV cell and the Maximum Power Point Tracking (MPPT) algorithm for the solar panel. The practical equivalent circuit of a PV array and the necessary design expressions are presented in the section below.

i) Equivalent electrical representation of a PV cell

In an ideal single-diode photovoltaic (PV) cell, a current source (I_{sc}) is connected in parallel with a diode. In this scenario, the series resistance (R_s) is zero, and the shunt resistance (R_{sh}) is infinite. However, in a practical system, both resistances have finite values, and those should be considered[15,23,25]. Figure 3 illustrates the practical equivalent circuit of a single-diode solar photovoltaic cell. As per KCL, the incoming current at a node is balanced by the outgoing current.

Hence,

$$I = Isc - Id - Ish \tag{1}$$

$$I = I_{sc} - I_0\left(e^{\frac{V+IR_S}{nV_T}} - 1\right) - \left(\frac{V+IR_S}{R_{sh}}\right) \tag{2}$$

Here, V_T: Thermal voltage
R_s: Series resistance
R_{sh}: Shunt resistance
I_{sc}: Short-circuit current (Variable in nature)
I_o: Reverse saturation current
I_d: Diode current
V, I: Output voltage and current of photovoltaic cell.

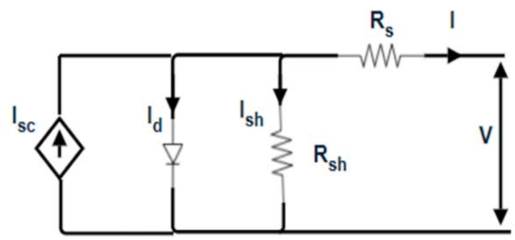

Figure 3. Practical Equivalent Circuit of a Solar PV Cell

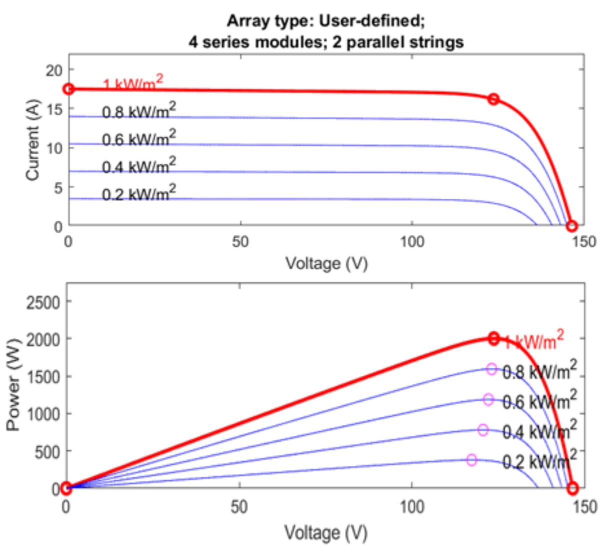

Figure 4. I-V and P-V characteristics curve for the solar PV array

At standard irradiation (1000 W/m²) and temperature (25°C), the I-V characteristics of photovoltaic cells are nonlinear in nature, as illustrated in Figure 4. These characteristics vary with changing environmental conditions[26]. The maximum power point is consistently located as indicated.

Figure 4 also shows the variation in solar power (P) versus the voltage (V) across the solar cell. The power initially rises with voltage and then reaches its peak, and further declines as the voltage continues to increase. As the voltage increases, the current initially stays relatively constant before dropping sharply as it nears the open-circuit voltage. The Maximum PowerPoint is indicated with red circles in the above figures.

ii) P and O MPPT algorithm

This algorithm is widely applied for Maximum Power Point Tracking in PV systems. It is easy and it ensures that the solar panels function at their Maximum PowerPoint despite changing irradiation and temperature conditions[27]. Also, this algorithm can be easily implemented through hardware.

As seen from the P-V characteristics in Figure 4, if PV power increases, the PV module operates left of the MPP, needing rightward perturbation; if it decreases, the module is right of the MPP, requiring leftward perturbation. Figure 5 shows the flowchart of the Perturb and Observe (P&O) MPPT algorithm[28]. It introduces small perturbations to the PV array voltage to vary power output. To vary the output voltage, the duty cycle of the converter is controlled based on whether power increases or decreases, guiding the perturbation direction[15,29].

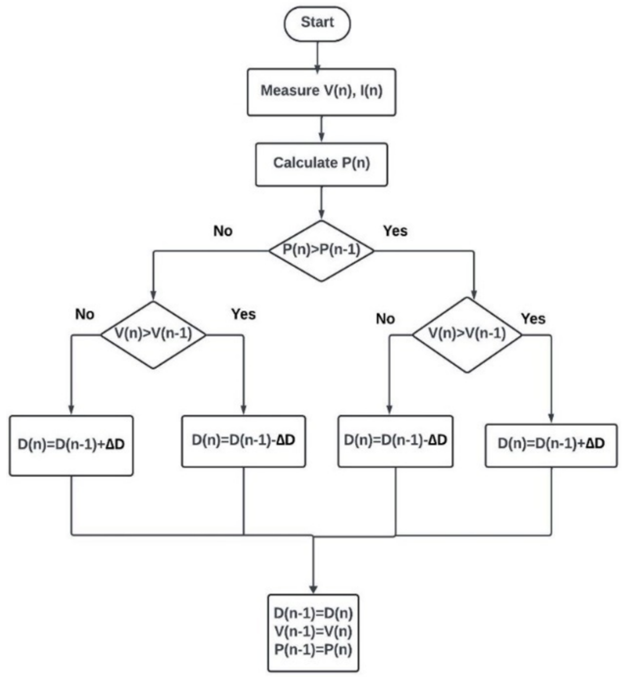

Figure 5. P & O MPPT algorithm flowchart

Design of Single-Ended Primary Inductor Converter

The SEPIC converter circuit is presented in Figure 6. It can function in either buck or boost mode, and it consistently delivers a non-inverting output voltage[22,30,31]. The voltage gain of this converter is given as

$$\frac{Vout}{Vin} = \frac{D}{1-D} \tag{3}$$

Here, D represents the duty ratio, Vin is the input PV voltage, and $Vout$ is the output DC voltage (Vdc). ΔIin is the input current ripple and $\Delta Vc1$, ΔVo are the voltage ripples in the capacitor and output voltages. The design parameters of the SEPIC converter are derived from the equations corresponding to the on-state and off-state conditions.

$$L1 = L2 = \frac{Vin*D}{2fs\,\Delta Iin} \tag{4}$$

$$C1 = \frac{Io*D}{fs*\Delta Vc1} \tag{5}$$

$$C2 = \frac{Io*D}{fs*\Delta Vo} \tag{6}$$

Where fs is the switching frequency, Io is the output current and ΔIin is the input current ripple.

Design of Bidirectional Converter

The half-bridge bidirectional converter typically includes two switches, each with an anti-parallel diode, along with inductors and capacitors, as shown in Figure 7[29,32]. This converter operates in both

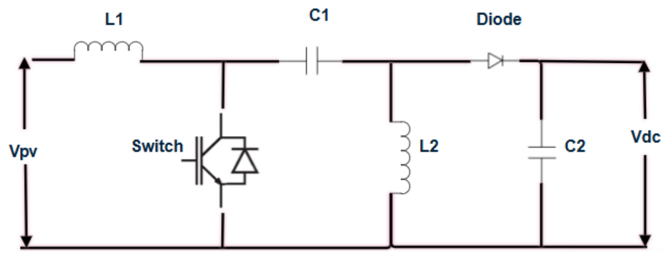

Figure 6. SEPIC converter circuit

buck and boost modes, allowing for efficient energy transfer between two voltage levels[33]. The design parameters can be selected with the help of the following expressions[29]. In the design equations, D is the duty ratio, V_{in} is the input voltage, V_{out} is the output voltage, f_s is the switching frequency, ΔI_L and ΔV_{out} are the inductor current ripple and output ripple voltage, respectively[29]. The values of the inductor and output voltage for various operating modes are outlined below.

During the buck operation

$$V_{out} = D * V_{in} \tag{7}$$

$$L = \frac{D*(V_{in}-V_{out})}{f_s*\Delta I_L} \tag{8}$$

During boost operation

$$V_{out} = \frac{1}{1-D} V_{in} \tag{9}$$

$$L = \frac{D*V_{out}}{f_s*\Delta I_L} \tag{10}$$

And capacitor can be designed as

$$C = \frac{\Delta I_L}{8 f_s * \Delta V_{out}} \tag{11}$$

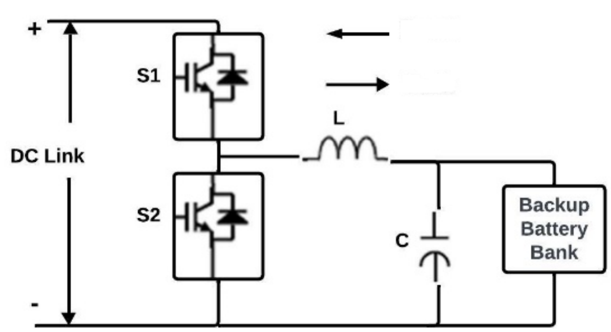

Figure 7. Half-bridge bidirectional DC-DC converter

The various selection parameters for MATLAB simulation of a proposed scheme consisting solar PV array, power electronic converter circuits, and batteries are illustrated in Table 1. Lithium-ion batteries are the favored choice for EVs due to their numerous advantages, as discussed in the literature[28,29]. Electric scooters, e-bikes, small vans, and similar vehicles generally operate with battery voltages between 12-48V and can reach up to 120V. The battery charging power varies from 50W to several kW, depending on the type of vehicle[5,28]. In the proposed system, a 2800W solar PV array has been designed with 4 series-connected modules per string and 2 parallel strings.

MULTIMODE OPERATION OF SOLAR-POWERED CHARGING STATION

The proposed electric vehicle charging system operates in various modes depending on the availability of solar power. The Maximum Power Point Tracking (MPPT) algorithm for the SEPIC converter guarantees the extraction of the maximum power from the PV array under all changing environmental conditions, so that it can be efficiently used for charging purposes. Whenever an EV is present, the key priority is to charge it. The backup battery is charged when there is surplus PV power and can be discharged as needed to meet the system's demand. A bidirectional DC-to-DC converter helps the charge/discharge operation of the backup battery as and when required. The optimization of available power through the control of the auxiliary switch is detailed in the following Table 2.

Table 1: Design parameters of various components

Solar Panel and SEPIC Converter	
Open Circuit Voltage (Voc)	51.5 V
Short circuit Current (Isc)	9.4 A
Maximum PowerPoint Voltage	43 V
Maximum PowerPoint Current	8.13 A
Maximum Power	349.59 Watts
Cells per Module	60
L1, L2	2 mH
C1,C2	3 µF,6 µF
Energy Storage (ES) and EV battery (Lithium-Ion)	
Nominal Voltage (ES)	120 V
Rated Capacity (ES)	150 Ah
Nominal Voltage (EV)	72 V
Rated Capacity (EV)	50 Ah
Bidirectional DC to DC Converter	
Inductor (L)	220µH
Capacitor(C)	57 µF
Switching Frequency	25 kHz

Table 2: Control of auxiliary switches

Switch	Turn On Condition	Remarks
S1	Sufficient solar power is available.	It disconnects solar panels when the power is too low to charge the batteries.
S2	EV is present, and SOC is less than 95%.	Prevent overcharging of the EV battery.
S3	Solar power is either low or high, and the backup battery SOC is greater than 10%.	- Low solar power: backup battery discharges. - High solar power: backup battery charges. Protects the backup battery from deep discharge.

The system operates in five distinct modes:

Mode 1

At peak sunlight hours, when the PV array generates an ample amount of power, but the EV is not present, the connection switches S1 and S3 are closed. This configuration allows the backup battery to charge directly from the PV array, and the bidirectional DC-DC converter operates in boost mode.

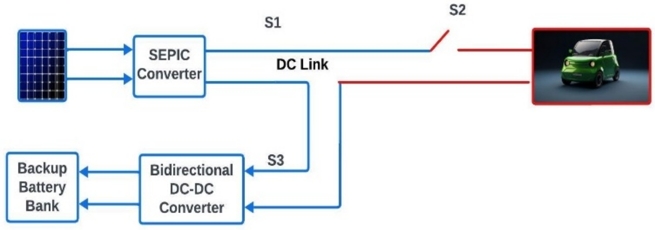

Figure 8. PV to backup battery charging mode (mode 1)

Mode 2

When a substantial amount of solar power is available, sufficient to charge both the EV and the backup batteries, all the auxiliary switches are closed so that they can be simultaneously charged.

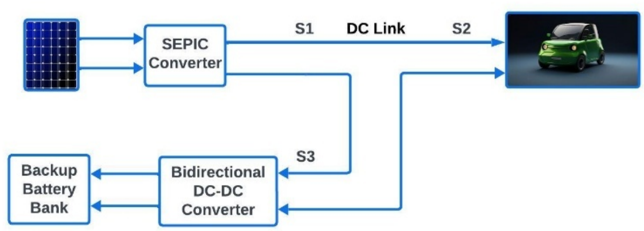

Figure 9. PV to backup battery and EV battery charging mode (mode 2)

Mode 3

When the PV array generates enough power to charge only the EV battery, switches S1 and S2 are turned on. The backup battery is isolated from the DC bus by disconnecting it with the switch S3.

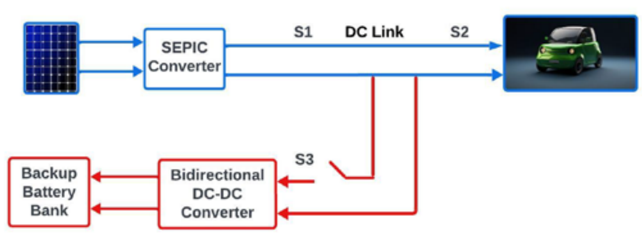

Figure 10. PV to EV charging mode (mode 3)

Mode 4

In low solar power conditions, when the PV system alone cannot charge the EV battery, the backup battery helps with the charging. Therefore, the PV system and the backup battery work together to charge the electric vehicle battery.

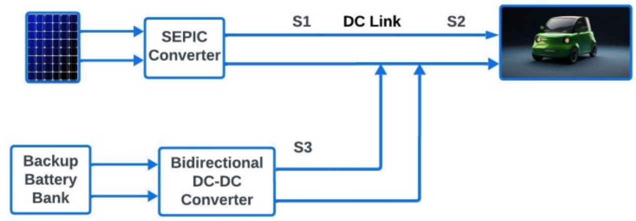

Figure 11. PV and backup battery to EV battery charging mode (mode 4)

Mode 5

Under conditions of minimal solar irradiation or at night, the power generated by the PV array is insufficient to charge the EV battery. In this scenario, switch S1 is turned off to disconnect the PV array from the DC link. At the same time, switches S2 and S3 stay on, linking the EV battery to the backup battery through a bidirectional DC-DC converter. The bidirectional converter then operates in step-down mode and charges the EV battery.

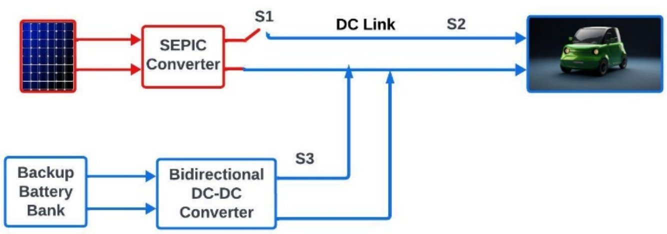

Figure 12. Backup battery to EV battery charging mode (mode 5)

In this manner, whenever an electric vehicle is present, it is charged through solar power or backup battery power, or both. The system operates well in all these modes, which is evident from the simulation results presented in the next section.

RESULTS AND DISCUSSION

The charging station is devised and simulated in MATLAB/Simulink software. The solar PV array is operated at various levels of irradiance while keeping the temperature constant at 25°C. Variations in solar irradiation directly affect the power output of solar photovoltaic systems and impact the operation of both the EV and backup batteries. As can be observed in Figure 13, the electric vehicle battery consistently remains in charging mode, while the backup battery discharges as needed to support the system. Overall, the system operates satisfactorily, even under fluctuating solar irradiation levels.

Figure 14 shows the behavior of the EV battery under various operating modes. A negative current signifies the battery charging process[34]. During the entire charging period, the battery voltage remains almost constant. The slope of the State of Charge (SOC) curve indicates that faster charging occurs when more power is available. During Mode 1 operation, when the EV is not present, both the SoC and the battery voltage remain constant, and the current is zero. In Mode 2, with the EV connected to the system, the SoC begins to increase, and the battery is charging. In all subsequent modes, the SoC continues to rise, and there is a slight increase in the EV battery voltage during the charging phases.

Figure 15 illustrates the charging behavior of the backup battery under distinct modes of operation. The charging and discharging operations are evident from the positive and negative battery current values. In modes 1 and 2, the SOC of the backup battery is on the rise, with a negative current indicating that the battery is being charged[34]. This results in a slight increase in the battery voltage. In mode 3, the SoC remains stable, and the current is zero, as the backup battery is separated. In modes 4 and 5, the SoC of the backup battery is decreasing. A positive current in these modes indicates that the battery is discharging, leading to a slight decrease in the battery voltage.

In all these operation modes, solar power availability plays an important role. The connection switches are operated to ensure both batteries' safe and reliable operation. The backup battery is used to store excess PV power, and it is then discharged whenever the required power demand is to be met[20,35]. In this case, 5 different modes of operation have been successfully analysed. The foremost objective of this work is to ensure uninterrupted charging of the EV battery in all these modes.

The following Figures 16-20 provide a detailed observation of the variations in PV power, along with the charging and discharging operations of the EV and backup batteries across the different modes discussed above. Table 3 provides comparative analysis of proposed scheme with existing studies.

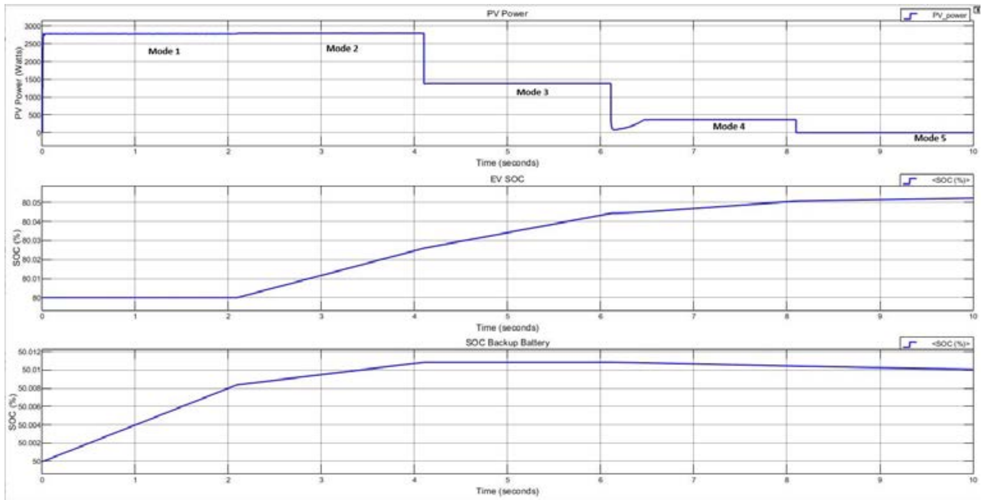

Figure 13. Effect of variations in PV Power due to changing irradiance on the SOCs of EV and Backup Batteries

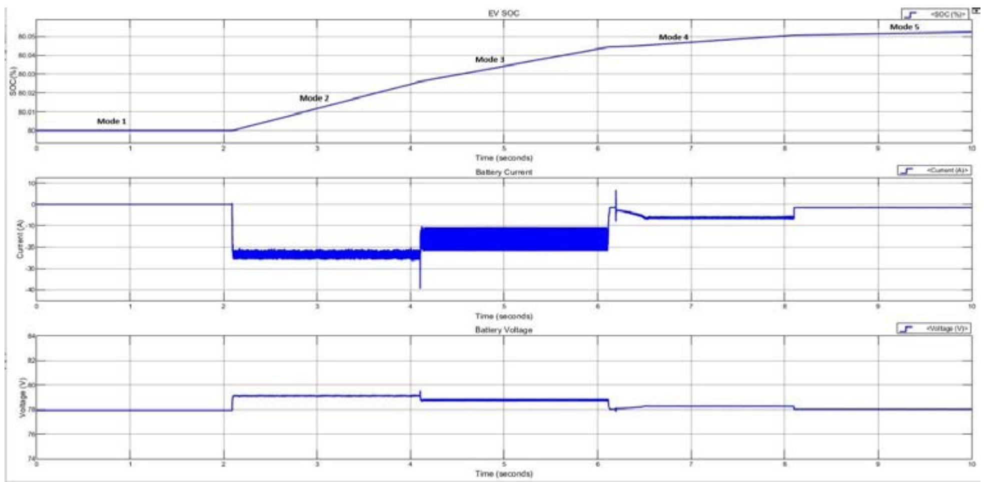

Figure 14. Waveforms of SOC, Current, and Voltage of EV battery during various modes of operation

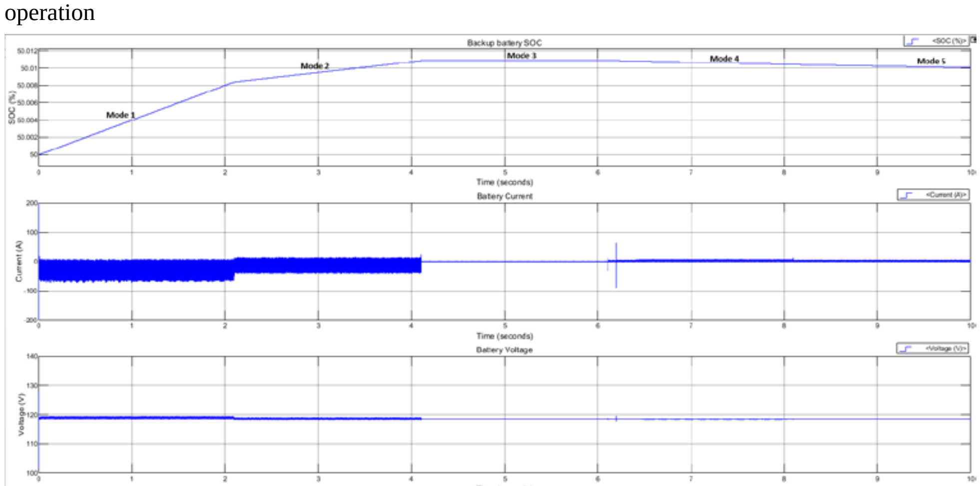

Figure 15. Waveforms of SOC, Current, and Voltage of backup battery for different modes of operation

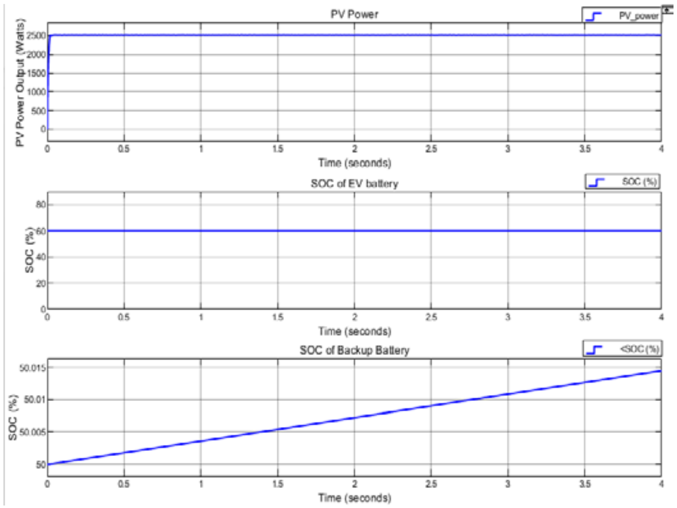

Figure 16. PV to backup battery charging

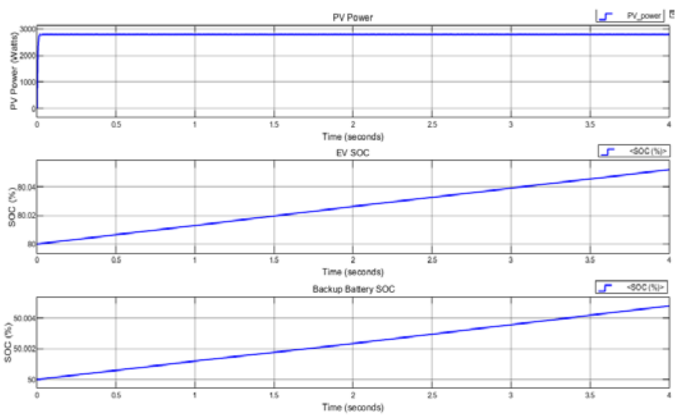

Figure 17. PV to EV and backup battery charging

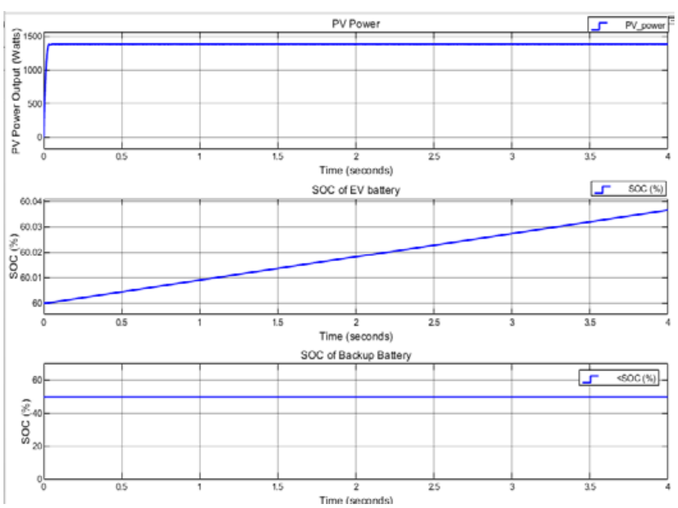

Figure 18. PV to EV battery charging

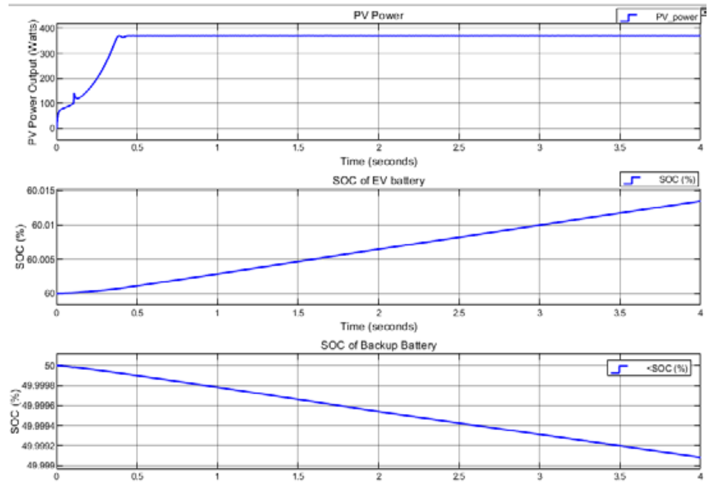

Figure 19. PV and backup battery for EV charging

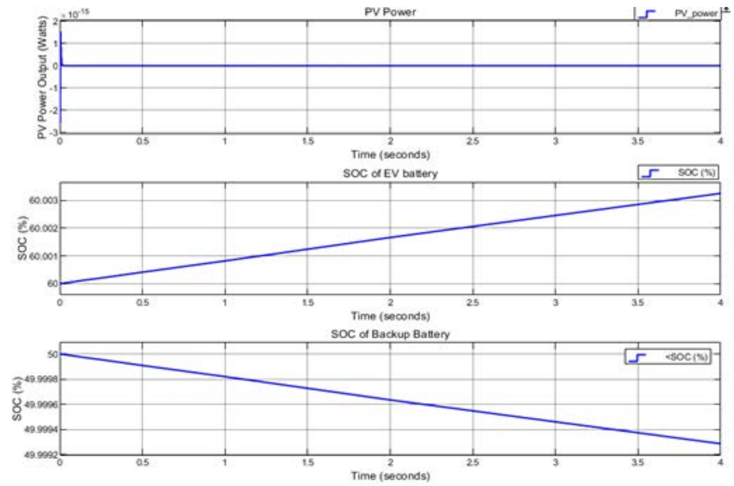

Figure 20. Backup battery to EV battery charging

Table 3: Comparative Analysis

Criteria	Sujitha et al.[22]	Proposed Scheme
System Architecture	SEPIC + Half-Bridge Bidirectional Interleaved DC-DC Converter (BIDC)	SEPIC + Half-Bridge Bidirectional DC-DC Converter
Number of Switches	6 main switches (3 legs, 2 switches per leg) in BIDC + 1 SEPIC switch + 3 auxiliary switches	2 bidirectional switches + 1 SEPIC switch + 3 auxiliary switches
Modes of Operation	3 Modes: 1) PV → EV & Backup battery 2) Backup battery→ EV 3) PV → EV	5 Modes: 1) PV → Backup battery 2) PV → EV & Backup battery 3) PV → EV 4) PV & Backup battery → EV 5) Backup battery → EV
Control Complexity	High – Requires phase-shifted PWM and current balancing across interleaved legs	Low – Uses conventional PWM or voltage/current control
Cost	High – Due to more components and complex control strategies	Low – Fewer components and simplified control implementation

Suitability for High Power	High – Interleaving improves thermal performance and ripple handling	Medium – Suited for moderate power applications

The operation of the overall system has been successfully demonstrated across five distinct modes, ensuring flexibility and reliability under varying conditions. Each mode is designed to optimize energy utilization, aligning with the system's objective of efficient EV charging and power management.

CONCLUSION

This paper proposes a standalone EV charging station, mainly designed to target rural and hilly areas where electricity is not easily accessible. Also, the proposed scheme is easier to install and will not cause power quality issues with the grid as it is operating independently. This will help to create awareness and promote the use of electric vehicles in such regions. Proper sizing and design of the system with advanced machine learning techniques and artificial intelligence will provide a practical solution for off-grid EV charging. The proposed system can be considered a normal household with an electric vehicle, such as an e-bike. In the future, additional considerations such as average daily trip distance, incoming vehicle SOC, charging time, etc., parameters can be considered for more clarity. The system faces limitations when solar power is inadequate and the backup battery bank is completely depleted. Additional green energy alternatives, like biomass or wind, or in some cases, a diesel generator, can be integrated to address these situations.

CONFLICT OF INTEREST STATEMENT

The authors declare that there is no conflict of interest for this work.

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