Enhancing Electric Vehicle Charging Reliability Through Solar System

Mr. Ashish A. Patil[1], Mr. Anand B. Kumbhar[2]
[1]Postgraduate Student (M. Tech), Department of Electrical Engineering, Sanjay Ghodawat University, Atigre, Maharashtra, India
[2]Assistant Professor, Department of Electrical Engineering, Sanjay Ghodawat University, Atigre, Maharashtra, India

***Abstract*— The increasing adoption of electric vehicles (EVs) has emphasized the need for sustainable and efficient charging infrastructure. High energy usage and higher operating expenses are two consequences of traditional grid-powered charging stations. This study presents a solar-powered external charging setup for electric vehicle batteries, offering a renewable and eco-friendly energy solution. To regulate voltage, the architecture integrates a SEPIC converter, while a bidirectional, multi-phase DC-DC converter facilitates effective power flow between the solar array, auxiliary battery, and EV battery pack. Depending on solar irradiance conditions, the system functions through three operational modes, supporting seamless charging and smart energy distribution. MATLAB/Simulink simulations verify the system's effectiveness in stabilizing voltage, managing power flow, and enhancing overall efficiency. The findings highlight the potential of solar-powered Standalone EV charging unit in reducing grid dependency and promoting clean energy integration for EVs.**

Index term: Bidirectional DC-DC Converter (BIDC), Electric Vehicles, MATLAB Simulation, Renewable Energy Integration, SEPIC (Single-Ended Primary Inductor Converter), Solar Energy.

I. INTRODUCTION

The rising levels of greenhouse gases from traditional internal combustion (IC) engines are causing serious environmental issues, leading to a growing interest in pollution-free electric vehicles (EVs). However, charging these EVs from the power grid rises the demand on power supplies, which in turn raises electricity bills for EV owners. This situation highlights the demand for substitute energy sources to charge EV batteries. Renewable energy sources (RESs), which are abundant and environmentally friendly, can effectively address this challenge, making RES-driven EVs a form of "green transportation." (1). Solar energy is a particularly promising RES that can be easily harnessed to charge EV batteries. A range of power electronic converter architectures is employed in the system to convert solar energy from the PV array into usable form for charging the electric vehicle battery. Lithium-ion batteries are favoured in EVs because to their high-power density, efficiency, lightweight, compact size, fast charging capabilities, and long-life cycles with low self-discharge rates. Safety considerations in battery design aim to prevent hazardous outcomes, such as explosions, particularly during overcharging or electrical faults. However, they need for accurate voltage regulation during charging, which is managed by different power electronic converters. (2, 3, 4). On-board charging refers to electric vehicle (EV) charging systems integrated directly within the vehicle, utilizing a built-in charger that connects to external power sources like home or public charging stations. This system allows for convenient charging anywhere a compatible outlet is available but may have limitations in charging speed and battery capacity due to space constraints. In contrast, Standalone EV charging unit involves external charging stations that provide power to the vehicle through a separate charger, often allowing for higher charging speeds and greater flexibility in energy management. Standalone EV charging unit can incorporate advanced technologies such as high-power DC charging and RES, making them ideal for rapid charging in commercial settings or large installations. (5, 6). In this configuration, the photovoltaic array and the backup battery bank are positioned at a stationary charging station, whereas the electric vehicle's battery remains onboard and is charged externally via an off-vehicle charging system. The setup incorporates a Single-Ended Primary Inductor Converter (SEPIC) capable of operating in both buck and boost modes, facilitating efficient and flexible energy management. Because the availability of solar energy can change, a backup battery bank is provided to guarantee continuous charging. A BIDC is used to manage the flow of energy to and from this battery bank, accommodating both charging and discharging functions. (7, 8, 9)

The BIDC is favoured among the various varieties of non-isolated bidirectional converters. All things considered, the BIDC, backup battery bank, PV array, and SEPIC converter work together to offer a dependable and effective EV charging option, even when the sun isn't shining. To alleviate the design burden on electric vehicles, the PV modules and secondary battery storage are integrated into an off-vehicle charging platform. The SEPIC converter is utilized to ensure seamless voltage adaptation for varied input and output levels. Since solar power alone is insufficient during low irradiation, a backup battery with a BIDC ensures continuous charging. This setup enhances sustainability by integrating renewable energy, reducing reliance on fossil fuels, and lowering EV costs while ensuring uninterrupted charging. (7,8,9,10)

1.1 Proposed system

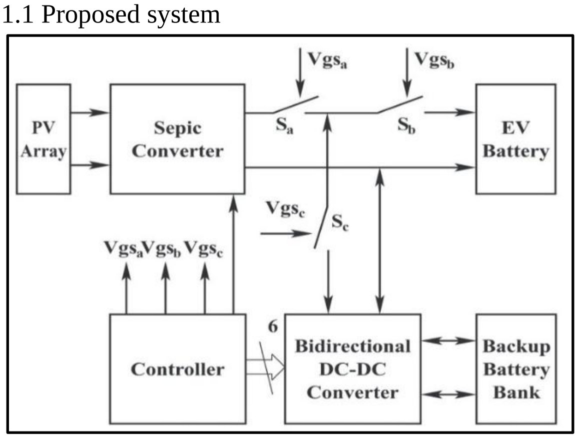

Fig.1.1 Proposed system

The proposed system leverages a photovoltaic (PV) array as its primary energy source to enable efficient and sustainable power conversion. It integrates an BIDC converter and a SEPIC to manage power flow and regulate voltage across the PV array, the EV battery, and the auxiliary battery bank. A control unit dynamically governs the switching actions of the converters by responding to real-time energy availability and demand. For charging the EV battery, the SEPIC converter transforms the variable DC output from the PV array into a stable, regulated voltage level. The switching elements (Sa, Sb, and Sc) are actuated using gate drive signals (Vgsa, Vgsb, and Vgsc), ensuring synchronized operation. The BIDC converter facilitates bidirectional energy exchange between the backup battery and the EV battery, maintaining the charging process even under conditions of low solar irradiance. The controller continuously monitors system parameters such as input voltage, output current, and load profiles to optimize converter performance. Based on solar irradiance levels, the system operates under three distinct modes to ensure reliable and adaptive energy management.

Mode 1 – Peak Sunshine Operation:

To facilitate concurrent charging of both the electric vehicle battery and the auxiliary energy storage during peak solar generation periods, all supporting switches are activated. The EV battery is charged through a SEPIC, while the backup battery is energized using an BIDC. In this operational mode, the BIDC elevates the DC bus voltage to efficiently charge the backup battery.

Mode 2 – Low Irradiance or Non-Sunshine Operation:

In scenarios where sunlight is unavailable, the photovoltaic (PV) array is unable to provide sufficient energy to charge the electric vehicle (EV) battery. To address this limitation, a bidirectional DC-DC converter (BIDC) is employed to establish a connection between the EV battery and a secondary backup battery. Under this operating condition, switches Sa, Sb, and Sc are appropriately configured to enable the BIDC to operate in a buck mode, thereby stepping down the voltage from the backup battery and supplying power to the EV battery.

Mode 3 – Moderate Sunshine Operation:

Switches Sa and Sb are activated when the photovoltaic (PV) array is capable of independently supplying sufficient power to charge the electric vehicle (EV) battery. During this mode, switch Sc remains deactivated to isolate the backup battery bank and the bidirectional DC-DC converter (BIDC) from the DC bus, thereby allowing direct energy transfer from the PV array to the EV battery.

By utilizing MATLAB/Simulink simulations, the system's performance is analysed to validate its efficiency, stability, and ability to manage power flow dynamically. The proposed design minimizes dependency on the grid, reduces energy costs, and enhances the reliability of EV charging infrastructure through the integration of renewable energy.

II. DESIGN OF SEPIC CONVERTER AND BIDC

SEPIC Converter Design:

The SEPIC converter is integral to the proposed charging architecture, as it ensures a regulated DC link voltage despite dynamic variations in the photovoltaic (PV) array output. It achieves this by dynamically adjusting its duty cycle using a PI controller. Two inductors, two capacitors, a diode, and a single IGBT switch make up the converter, which can function in both buck and boost modes as required. By ensuring consistent and controlled power flow to the EV battery, this improves the charging system's dependability and efficiency. The SEPIC converter's voltage gain is determined by the equation below:

$$\frac{V_{dc}}{V_{PV}} = \frac{D}{1-D} \quad \text{.............1}$$

where:

- Output voltage (DC link voltage), Vdc=28V
- PV array voltage, Vpv=33.3V

Duty cycle, D=0.457

Maximum duty ratio:

$$D_{max} = \frac{V_{dc} + V_D}{V_{PV\,min} + V_{dc} + V_D} \quad \text{.......2}$$

where:

- Output voltage (DC link voltage), Vdc=28V
- Diode voltage drops, V_D=0.8V
- Minimum PV voltage, Vpv min=30V

Maximum Duty Cycle, Dmax=0.4637

a) Inductor Design

Two inductors La and Lb are required. Their values are determined using:

$$L_a = L_b = \frac{V_{PV\,min} D_{max}}{2\Delta i_{PV} f_{sw}} \quad \text{......3}$$

where:

- Minimum PV voltage, Vpvmin=30V
  - Maximum duty ratio, Dmax=0.4637
  - Allowed ΔIpv =0.274A
  - fsw=25 KHz

La=1.015mH

Lb=1.015mH

b) Capacitors Design

$$C_1 = \frac{I_{dc} D_{max}}{\Delta V_{C1} f_{sw}} \quad \text{.......4}$$

where:

- Output DC link current, Idc=8.76A
- Maximum duty ratio, Dmax=0.4637
- Allowed voltage ripple in C1, V_{C1}=0.16V
- Switching frequency, Fsw=25KHz

C_1=1000 µF

$$C_2 = \frac{I_{dc} D_{max}}{\Delta V_{dc} f_{sw}} \quad \text{..........5}$$

where:

- Output DC link current, Idc=8.76A
- Maximum duty ratio, Dmax=0.4637
- Allowed output voltage ripple, ΔVdc=0.267
- Switching frequency, fsw=25000Hz

C_2=608.54 µF

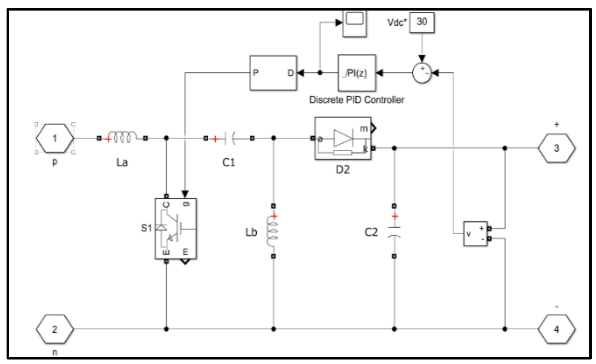

Fig.2.1: Circuit diagram of SEPIC converter

BIDC Design:

In the proposed charging architecture, the Bidirectional DC-DC Converter (BIDC) enables energy exchange between the low-voltage DC link and the high-voltage backup battery system. When operating in buck mode (reverse power flow), it supplies energy from the backup battery to the electric vehicle (EV) battery. Conversely, in boost mode (forward power flow), the converter charges the backup battery. During boost operation, switches SL1, SL2, and SL3 are turned on, while switches SU1, SU2, and SU3 function in buck mode. An anti-parallel diode and a parallel snubber capacitor are features of every switch that increase efficiency and reduce switching losses. In forward motion, the inductors L1, L2, and

L3 function as boost inductors, and in reverse motion, they function as low-pass filters, while the capacitors CL and CH are energy storage components. Performance and efficiency are increased by the interleaved structure's reduction of current ripple. The performance of a single-leg topology is examined to better understand the converter's operation, enabling improved control strategies and efficient power management. In both boost and buck modes, the voltage conversion ratio of the BIDC is calculated by

1. Voltage Conversion Ratios:
   a) Boost Mode:

$$\frac{V_{\mathrm{BackupBatt}}}{V_{\mathrm{dc}}} = \frac{1}{1 - D_{\mathrm{Boost}}}$$

where:

- Backup battery voltage, $V_{BackupBatt}$ =60.60V
- Output voltage (DC link voltage), Vdc=28V

Duty cycle in Boost mode, D_{Boost} =0.5379

   b) Buck Mode:

$$\frac{V_{\mathrm{dc}}}{V_{\mathrm{BackupBatt}}} = D_{\mathrm{Buck}}$$

where:

- Backup battery voltage, $V_{BackupBatt}$ =60.60V
- Output voltage (DC link voltage), Vdc=28V

Duty cycle in Buck modes, D_{Buck} =0.4620

2. Inductor Design

To enhance efficiency, the converter operates in Discontinuous Conduction Mode (DCM) in both boost and buck configurations when the inductance is below the critical threshold

a) Critical Inductance in Boost Mode:

$$L_{\mathrm{cric}} = \frac{3V_{\mathrm{BackupBatt}}^2 D_{\mathrm{Boost}}(1 - D_{\mathrm{Boost}})^2}{2Pf_{\mathrm{s}}}$$

where:

- $V_{BackupBatt}$ =60.60V
- Duty cycle, D_{Boost} =0.5379
- Power of backup battery, P=240W
- Switching frequency, fs=25000

Lcric=105.45 μH

b) Critical Inductance in Buck Mode:

$$L_{\mathrm{cric}} = \frac{3V_{\mathrm{dc}}^2(1 - D_{\mathrm{Buck}})}{2Pf_{\mathrm{s}}}$$

where:

- Output voltage (DC link voltage), Vdc=28V
- Duty cycle in Buck modes, D_{Buck} =0.4620
- Power of backup battery, P=240W
- Switching frequency, fs=25000Hz

Lcric=105.448Micro H

3. Capacitor Design

a) High Voltage Side (Backup Battery)

$$C_H = \frac{D_{\mathrm{Boost}}P}{2f_{\mathrm{s}}V_{\mathrm{BackupBatt}}^2}$$

where:

- Duty cycle, D_{Boost} =0.5379
- P=240W
- Switching frequency, fs=25000Hz
- $V_{BackupBatt}$ =60.60V

C_H=70.30 μF

b) Low Voltage Side (DC Link)

$$C_L = \frac{V_{\mathrm{BackupBatt}} D_{\mathrm{Buck}}(1 - D_{\mathrm{Buck}})}{8f_{\mathrm{s}}^2 L \Delta V_{\mathrm{dc}}}$$

where:

- $V_{BackupBatt}$ =60.60V
- Duty cycle in Buck modes, D_{Buck} =0.4620
- Switching frequency, fs=25000Hz
- L=85 μH
- ΔVdc=0.267

C_L=132.73 μF

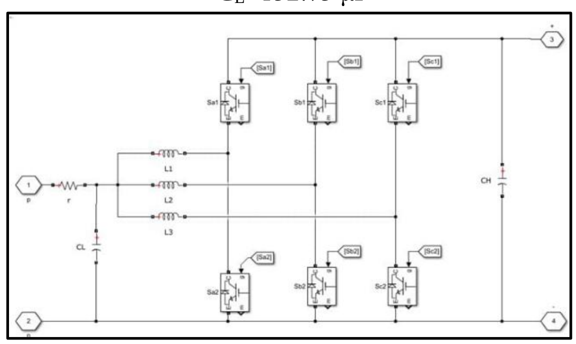

Fig.2.2: Circuit diagram of BIDC Interleaved converter

III. RESULTS

The performance of the proposed Standalone EV charging unit for electric vehicle battery charging system was evaluated using MATLAB/Simulink simulations under varying solar irradiance conditions. The results demonstrate the system's ability to regulate voltage, ensure efficient power transfer, and provide uninterrupted charging for electric vehicle (EV) batteries. The waveform analysis validates the system's performance in different operational modes, highlighting its efficiency in energy management and adaptability to changing environmental conditions.

3.1 PV Array Performance

The waveforms Vpv, Ipv, Ir, and Ppv are critical indicators of a photovoltaic (PV) system's performance. Ipv is the current passing through the PV array, and Vpv is the voltage produced by it; both are dependent on the irradiance (Ir), which gauges the intensity of the sun. Ppv, the power output, is the product of Vpv and Ipv. These parameters dynamically respond to environmental changes throughout the day. During peak sunshine (Ir ≈ 1000 W/m²), the system operates at maximum efficiency, with Vpv reaching up to 42V, Ipv up to 11A, and Ppv about 470W. Under non-sunshine conditions (Ir ≈ 200 W/m²), performance drops sharply, with Vpv at 23.8V, Ipv at 2.5A, and Ppv at 59W. In moderate sunshine (Ir ≈ 750 W/m²), the system performs moderately well, with Vpv up to 23V, Ipv up to 9.4A, and Ppv around 215W. Clearly, irradiance is a key factor influencing the PV system's voltage, current, and power generation.

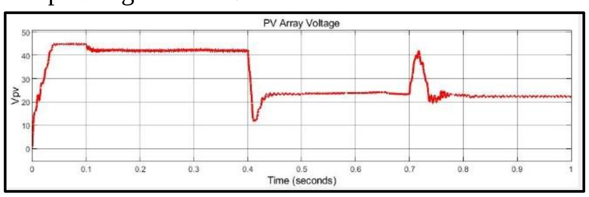

Fig.3.1: Waveform of PV Array Voltage V_{PV}

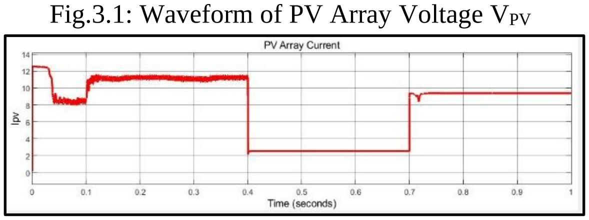

Fig.3.2: Waveform of PV Array Current I_{PV}

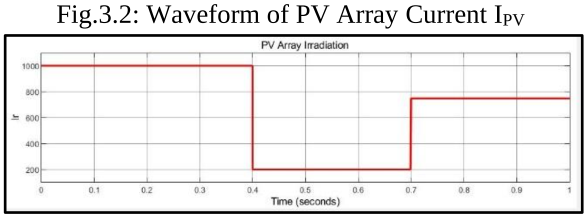

Fig.3.3: Waveform of PV Array irradiation Ir

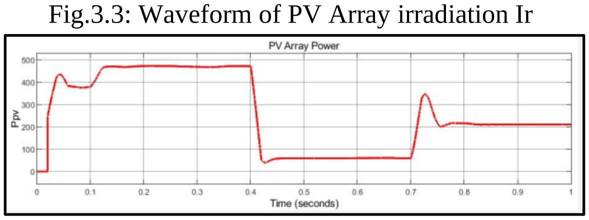

Fig.3.4: Waveform of PV Array Power Ppv

3.2 EV Battery Profile

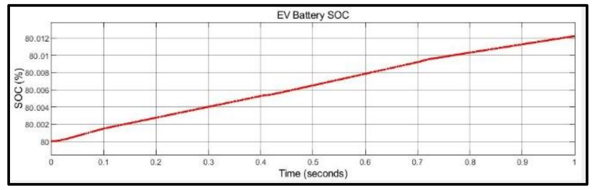

Fig.3.5 EV battery SOC

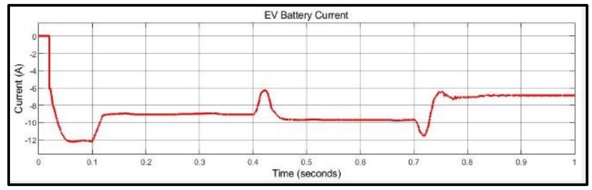

Fig.3.6 EV battery Current I_{Batt}

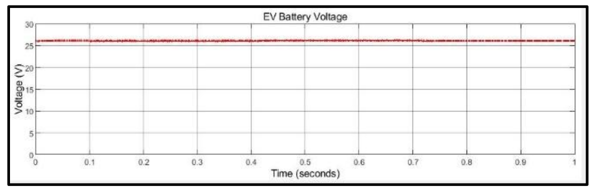

Fig.3.7 EV battery Voltage V_{Batt}

The waveform analysis reflects the battery's behavior under varying sunlight conditions. In Mode one (Peak Sunshine: 0.1s–0.4s), the SOC increases steadily, indicating efficient and fast charging due to maximum power from the PV array. The charging current reaches approximately -9A, showing stable and strong energy flow into the battery, while the voltage remains constant around 26V. In Mode 2 (Non-Sunshine: 0.4s–0.7s), the SOC still increases but at a slightly reduced rate, reflecting limited power availability. However, the charging current slightly increases to -9.70A, possibly due to control action to maintain SOC growth, with voltage still at 26V. In Mode 3 (Moderate Sunshine: 0.7s–1s), SOC growth continues but is slower than Mode 1, and the current reduces to -7A, indicating partial sunlight and moderate power. Despite these changes, the battery voltage remains almost constant at 26V, demonstrating stable system behavior.

3.3 Backup Battery Profile

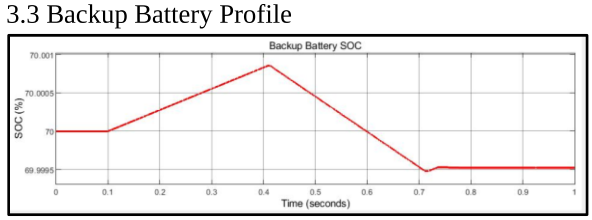

Fig.3.8 Backup battery SOC

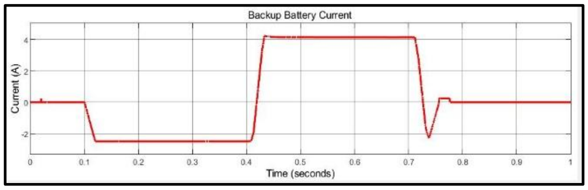

Fig.3.9 Backup battery Current $I_{BackupBatt}$

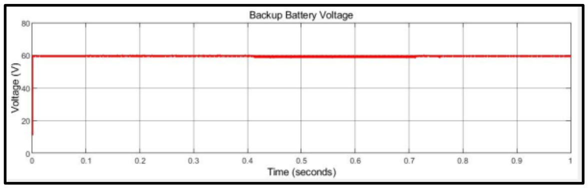

Fig.3.10 Backup battery Voltage $V_{Backup\ Batt}$

This set of waveforms illustrates the functioning of a backup battery system in an EV under different sunlight conditions. In Peak Sunshine Mode, the PV array delivers maximum power, enabling efficient and fast charging. The SOC rises steadily, the charging current is around -2.50A, and voltage remains constant at 60V, ensuring safe and stable battery operation. During periods without sunlight, the photovoltaic (PV) array becomes inactive, and the energy required to operate the load is supplied through battery discharge. The SOC decreases gradually, the discharging current is about 4.15A, and the voltage is maintained at 60V, indicating effective voltage regulation during discharge. In Moderate Sunshine Mode, the PV generates limited power, and the backup battery is isolated, with zero current flow. Despite this, the system voltage stays stable at 60V, ensuring operational consistency. These modes reflect the dynamic energy management in EVs based on real-time solar availability.

3.4 DC link voltage Waveform

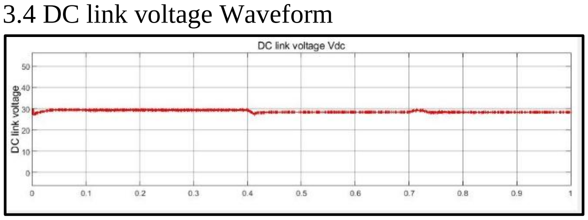

Fig.3.11: DC link voltage Vdc

DC link voltage waveform demonstrates the effectiveness of a Standalone EV charging unit powered by solar energy. Utilizing SEPIC and BIDC converters, the system ensures stable operation by regulating voltage fluctuations. The SEPIC converter adjusts PV array voltage, while the BIDC converter manages bidirectional power flow, maintaining reliable power transfer between the PV array, backup battery, and EV battery.

3.5 Switches Waveform of gate pulses to auxiliary switches (Firing instant):

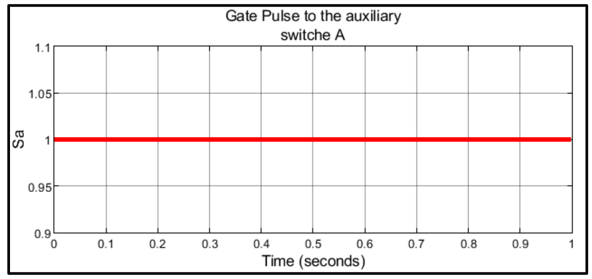

Figure 3.12: gate pulses to the auxiliary switches a

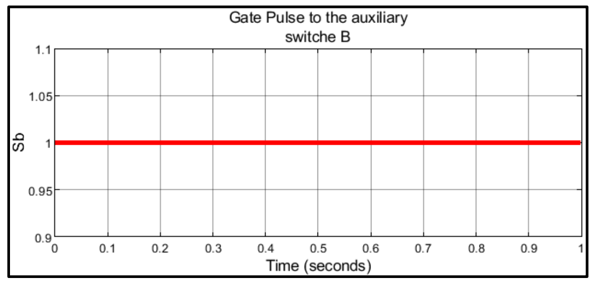

Figure 3.13: gate pulses to the auxiliary switches b

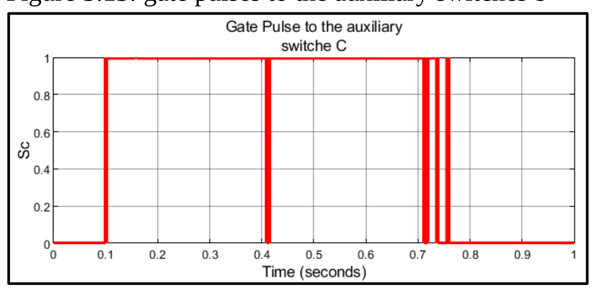

Figure 3.14: gate pulses to the auxiliary switches c

The waveform illustrates the switching behavior of three key switches—Sa, Sb, and Sc—integrated within the control architecture of an off-board electric vehicle (EV) battery charging system powered by a photovoltaic (PV) array. These switches are configured with a SEPIC (Single-Ended Primary-Inductor Converter), a Bidirectional DC-DC (BIDC) converter, and a backup battery to facilitate optimized power flow and energy management. Switch Sa, represented by the topmost waveform, ensures continuous regulation of energy from the PV array to the SEPIC converter, maintaining a stable power input. The middle waveform corresponds to Switch Sb, which operates intermittently to govern bidirectional energy transfer between the EV battery and the backup storage via the BIDC converter, depending on load requirements. The bottommost waveform indicates the switching activity of Sc, which appears to control the backup battery based on the EV battery's state of charge and PV availability. This coordinated switching strategy supports efficient energy utilization and adaptive power flow within the charging infrastructure.

IV. CONCLUSION

The development of a photovoltaic (PV) array-based electric vehicle (EV) battery charging infrastructure presents a sustainable, efficient, and grid-independent solution for energy replenishment. The proposed architecture employs a SEPIC for precise voltage regulation, coupled with a BIDC to facilitate intelligent energy distribution between the PV source, auxiliary energy storage, and the EV battery. The MATLAB/Simulink simulation results validate the system's efficiency, reliability, and adaptability under varying solar irradiance levels, ensuring uninterrupted power flow. The SEPIC converter stabilizes voltage fluctuations, providing a consistent and ripple-free power supply to the EV battery. By guaranteeing bidirectional energy transmission, the BIDC enables surplus solar energy to be stored in the backup battery and released when solar energy is not enough. The waveform analysis confirms that the proposed system can maintain a steady power supply, efficiently regulate voltage and current, and ensure a reliable charging process. By minimizing dependency on the grid, this system contributes to reducing fossil fuel consumption and promoting clean energy integration in EV infrastructure. The research concludes that the proposed Standalone EV charging system provides a practical and scalable solution for renewable energy-based EV charging. Future work may focus on real-time hardware implementation, optimization of control strategies, and performance evaluation under real-world operating conditions to further enhance system efficiency and feasibility.

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