Journal of Engineering for THERMAL ENERGY AND POWER

ISSN: 1001-2060
Vol. 29 No. 1, 2026

POWER QUALITY IMPROVEMENT IN A PV BASED EV CHARGING STATION INTERFACED WITH THREE PHASE GRID

R. Sowmya[1], Dr. B Navothna[2]

[1]Mtech Student, Department of Electrical and Electronics Engineering, Institute of Aeronautical Engineering, Dundigal, Hyderabad–500043, Telangana, India.
Email: sowmyarapaku@gmail.com
[2]Assistant Professor, Department of Electrical and Electronics Engineering, Institute of Aeronautical Engineering, Dundigal, Hyderabad–500043, Telangana, India.
Email: b.navothna@iare.ac.in

Abstract

Received: 15/05/2026

Revised: 13/06/2026

Accepted: 01/07/2026

DOI: 10.12060/jet-ep-v29.i1-5

Funding:
This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

This paper deals with the power quality improvement in a solar photovoltaic (PV) array generation based EV (Electrical Vehicle) charging station. This charging station is capable of operating in standalone mode and charging the EV battery with the power generated by a PV array. Moreover, it also interfaces with the utility and feeds it the remaining power. Another advantage of the charging station is the compensation of the reactive power for the improvement of the grid power quality. The charging station serves the following purposes (i) harmonics current compensation, (ii) EV battery charging/discharging control, (iii) simultaneous EV battery charging and harmonics current compensation and (iv) simultaneous discharging and harmonics current compensation. The charging station is controlled in such a manner that it operates satisfactorily even under the unbalance grid voltages and total harmonics distortion of the grid currents is reduced below 5% as suggested in the IEEE-519 standard. The control strategy is designed in such a manner that the charging station operates in grid connected mode. However, if the charging station loses the synchronism, then it operates in standalone mode and PV array charges the EV battery. A synchronization control is also developed to connect the system to the grid, when it is available.

Keywords: PV Arrey, EV Battery, Bidirectional Converter, VSI(Voltage Source Converter) with MPPT, MATLAB.

1. INTRODUCTION

In contemporary energy and transportation systems, the integration of renewable energy resources with electric vehicle (EV) infrastructure has emerged as a critical strategy for achieving sustainable development, reducing greenhouse gas emissions, and enhancing energy efficiency [1], [2]. The rapid depletion of fossil fuel reserves, coupled with increasing environmental concerns such as air pollution and global warming, has accelerated the transition from conventional internal combustion engine vehicles to electric vehicles [3]. EVs are recognized as an environmentally friendly transportation alternative due to their zero tailpipe emissions, high efficiency, reduced maintenance requirements, and lower operational costs [4], [5]. Moreover, governments and international organizations across the world are promoting EV adoption through subsidies, tax incentives, and supportive regulatory policies aimed at reducing carbon emissions and achieving clean energy targets [6].

Despite the advantages of electric vehicles, the widespread adoption of EVs introduces significant challenges related to charging infrastructure, energy management, and grid stability [7]. Conventional EV charging stations primarily rely on utility grid power for charging vehicle batteries. However, the increasing penetration of EVs imposes substantial stress on the electrical grid, especially during peak demand periods [8]. Furthermore, traditional charging systems generally support only unidirectional power flow, where electricity flows from the grid to the vehicle, thereby limiting the utilization of EV batteries as distributed energy storage resources [9]. Recent advancements in smart grid technologies have introduced the concept of Vehicle-to-Grid (V2G), in which electric vehicles can return stored energy back to the grid during peak demand conditions [10]. This bidirectional power transfer capability enhances grid reliability, supports load balancing, and improves overall energy utilization efficiency [11].

In parallel, renewable energy sources such as solar photovoltaic (PV) systems, wind turbines, and fuel cells are increasingly being integrated into EV charging stations to minimize dependency on conventional fossil-fuel-based electricity generation [12], [13]. Among these renewable resources, solar PV technology has gained significant attention due to its abundant availability, clean operation, and compatibility with distributed charging applications [14]. However, the intermittent nature of solar energy generation creates challenges in maintaining continuous and stable power supply for EV charging operations [15]. To overcome these limitations, hybrid energy management approaches integrating PV systems with energy storage devices and smart converters have been proposed to ensure uninterrupted charging performance and efficient energy utilization [16].

Recent research emphasizes the importance of bidirectional off-board charging stations integrated with renewable energy sources for improving charging flexibility and grid interaction capabilities [17]. In such systems, the EV battery can function not only as a load during charging mode but also as an energy storage unit capable of supplying power back to the utility grid during peak demand or grid disturbances [18]. The implementation of bidirectional converters enables efficient charging and discharging operations while preventing second harmonic currents and DC-link ripple currents from affecting battery performance and lifetime [19]. In addition, voltage source converters (VSCs) employed in these charging stations provide reactive power compensation and enhance overall grid power quality [20].

Furthermore, smart PV-based EV charging stations offer operational flexibility under both grid-connected and standalone conditions [21]. During normal operation, solar energy generated from the PV array is utilized to charge EV batteries, while excess generated power can be supplied to the utility grid, thereby reducing the burden on centralized power generation systems [22]. During grid failure conditions, the charging station operates in standalone mode, where the PV system continues supporting EV charging independently [23]. Advanced control algorithms are also incorporated to manage dynamic operating conditions such as solar irradiance variations, grid voltage fluctuations, load unbalance, and synchronization during grid restoration [24].

In addition to environmental benefits, electric vehicles provide several technical and economic advantages over conventional vehicles [25]. EVs produce zero direct emissions of carbon dioxide (CO_2) and nitrogen oxides (NO_2), contributing significantly to improved air quality and reduced environmental pollution [26]. Electric motors possess fewer moving parts compared to internal combustion engines, resulting in reduced maintenance costs, enhanced reliability, and quieter operation [27]. Moreover, EVs offer lower energy consumption costs per kilometer and improved riding comfort due to the absence of engine vibration and noise [28]. These characteristics make EV technology a promising solution for sustainable transportation systems in future smart cities [29].

Therefore, the integration of solar photovoltaic systems with bidirectional EV charging infrastructure

ISSN: 1001-2060
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presents an effective and sustainable approach for supporting the growing demand for electric mobility while simultaneously improving grid stability, energy efficiency, and renewable energy utilization [30]. This paper focuses on the design and analysis of a single-stage PV-based bidirectional off-board EV charging station connected to the utility grid. The proposed system enables efficient charging and discharging of EV batteries, supports Vehicle-to-Grid (V2G) operation, enhances grid power quality through reactive power compensation, and ensures reliable operation under varying environmental and grid conditions [31], [32].

2. METHOD

The proposed system implements a single-stage solar photovoltaic (PV) based electric vehicle (EV) charging station capable of operating in both Grid-to-Vehicle (G2V) and Vehicle-to-Grid (V2G) modes. The charging station is designed to support bidirectional power flow, reactive power compensation, and seamless transition between grid-connected and standalone operating conditions. The overall methodology of the proposed system is divided into system configuration, control strategy, VSC control, synchronization control, and EV charging/discharging control.

A. System Configuration

The proposed charging station consists of a solar PV array, a DC-link capacitor, a bidirectional DC-DC converter, an EV battery, a Voltage Source Converter (VSC), and Static Transfer Switches (STS). The PV array is directly connected to the DC-link without using an intermediate boost converter, thereby reducing system complexity, switching losses, and overall cost. The bidirectional DC-DC converter is used for charging and discharging the EV battery according to system requirements.

An IGBT-based VSC is employed to convert the DC power into AC power for interfacing with the utility grid. The STS switches are used to connect or disconnect the charging station from the utility grid during abnormal grid conditions. The proposed configuration allows the EV battery to operate as both an energy storage device and a distributed energy source.

B. Control Strategy

The control scheme of the charging station is developed to achieve efficient utilization of solar energy while maintaining stable system operation under varying grid and load conditions. The control architecture is mainly based on two reference commands:

1. Active Power Reference Command (Pref)

The active power reference command determines the charging or discharging operation of the EV battery. This command is selected by the EV owner based on the operational requirement.

- When the EV battery receives power from the utility grid or PV array, the operation is called Grid-to-Vehicle (G2V) mode.
- When the EV battery supplies power back to the utility grid during peak demand conditions, the operation is called Vehicle-to-Grid (V2G) mode.

The active power command enables intelligent energy exchange between the EV battery and the utility grid while improving overall energy utilization efficiency.

2. Reactive Power Reference Command (Qref)

The reactive power reference command regulates the amount and type of reactive power exchanged between the charging station and the utility grid.

- Positive reactive power demand corresponds to inductive compensation.
- Negative reactive power demand corresponds to capacitive compensation.

The VSC utilizes this command to provide reactive power support to the grid, thereby improving power factor and enhancing grid power quality.

C. VSC Control in Grid-Connected Mode

In grid-connected operation, the VSC control scheme generates switching pulses based on the active and reactive power reference commands. The controller extracts the active current component (Ip) and

reactive current component (Iq) from Pref and Qref respectively.
The active current components for each phase are obtained using the in-phase unit templates:

$$i_{pa} = I_p u_{pa}, \quad i_{pb} = I_p u_{pb}, \quad i_{pc} = I_p u_{pc}$$

Similarly, the reactive current components are obtained using quadrature unit templates:

$$i_{qa} = I_q u_{qa}, \quad i_{qb} = I_q u_{qb}, \quad i_{qc} = I_q u_{qc}$$

The total reference currents are generated by combining the active and reactive current components. These reference currents are compared with actual grid currents, and the error signals are processed through PWM control to generate gating pulses for the VSC switches.

This control mechanism enables:

- Bidirectional active power transfer,
- Reactive power compensation,
- Harmonic reduction,
- Improved grid power quality.

D. Synchronization and Islanding Control

The synchronization control ensures safe operation of the charging station during transitions between grid-connected and standalone modes. The system continuously monitors the following grid parameters:

- Grid voltage magnitude,
- Grid frequency,
- Phase angle difference between grid voltage and PCC voltage.

The system enters islanding mode whenever any abnormal grid condition occurs, such as:

$$V_t > 1.1pu \quad \text{or} \quad V_t < 0.88pu$$

$$f_s > 50.5Hz \quad \text{or} \quad f_s < 49.5Hz$$

$$\theta_g \neq \theta_s$$

Under these abnormal conditions, the Static Transfer Switches disconnect the charging station from the utility grid to protect the system and maintain stable standalone operation.

When the utility grid returns to normal operating conditions, the synchronization controller matches the voltage magnitude, frequency, and phase angle of the charging station with the utility grid before reconnecting through the STS.

E. EV Charging/Discharging Control in Standalone Mode

During standalone operation, the PV array becomes the primary power source for EV charging. The reference DC-link voltage (Vdc∗)(V_{dc}^{*})(Vdc∗) is generated using the Maximum Power Point Tracking (MPPT) algorithm to ensure maximum utilization of solar energy.

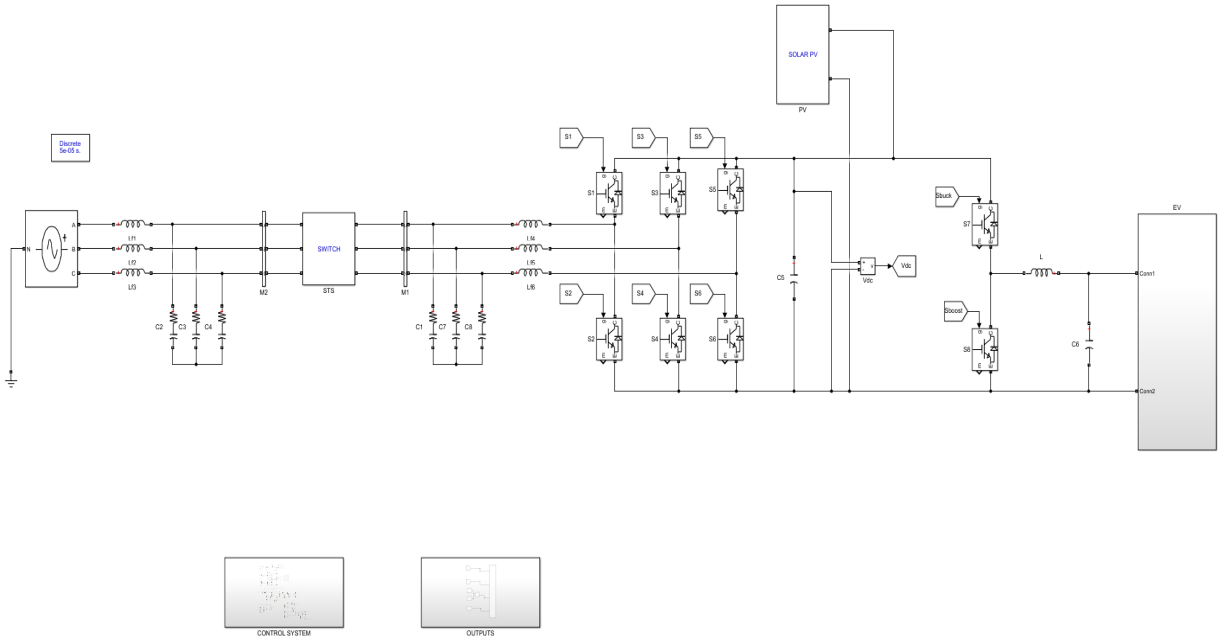
The bidirectional DC-DC converter regulates the charging and discharging of the EV battery while maintaining a constant DC-link voltage. The control strategy ensures that battery charging/discharging operations do not introduce disturbances in the DC-link voltage during dynamic operating conditions.
The standalone controller maintains:

- Stable DC-link voltage,
- Efficient solar energy utilization,
- Continuous EV charging operation,
- Smooth transition during grid restoration.

Journal of Engineering for THERMAL ENERGY AND POWER
ISSN: 1001-2060
Vol. 29 No. 1, 2026

Thus, the proposed methodology enables efficient integration of solar PV generation, EV charging infrastructure, and smart grid support functionalities within a unified and intelligent charging system.

3. RESULTS



The MATLAB/Simulink results of the proposed single-stage solar photovoltaic (PV) based bidirectional electric vehicle (EV) charging station confirm the effective operation of the system under both Grid-to-Vehicle (G2V) and Vehicle-to-Grid (V2G) modes. The simulation model demonstrates successful integration of the PV array, bidirectional DC-DC converter, Voltage Source Converter (VSC), EV battery, and utility grid with stable DC-link voltage regulation and efficient power management. During G2V operation, the EV battery is charged smoothly using power from the PV array and utility grid, whereas during V2G operation, the stored battery energy is successfully transferred back to the grid during peak demand conditions. The Maximum Power Point Tracking (MPPT) algorithm effectively extracts maximum solar power under varying irradiation conditions, thereby improving renewable energy utilization. The VSC maintains synchronized sinusoidal grid currents with reduced harmonic distortion while also providing reactive power compensation to improve grid power quality and power factor. The synchronization controller successfully detects abnormal grid conditions and shifts the system into standalone mode during grid failure, ensuring uninterrupted EV charging operation. After restoration of normal grid conditions, the charging station reconnects smoothly without instability or transient disturbances. Overall, the simulation results validate that the proposed charging station provides efficient bidirectional power flow, stable operation, enhanced grid support capability, improved renewable energy integration, and reliable EV charging performance suitable for future smart grid and sustainable transportation applications.

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THERMAL ENERGY
AND POWER

ISSN: 1001-2060
Vol. 29 No. 1, 2026

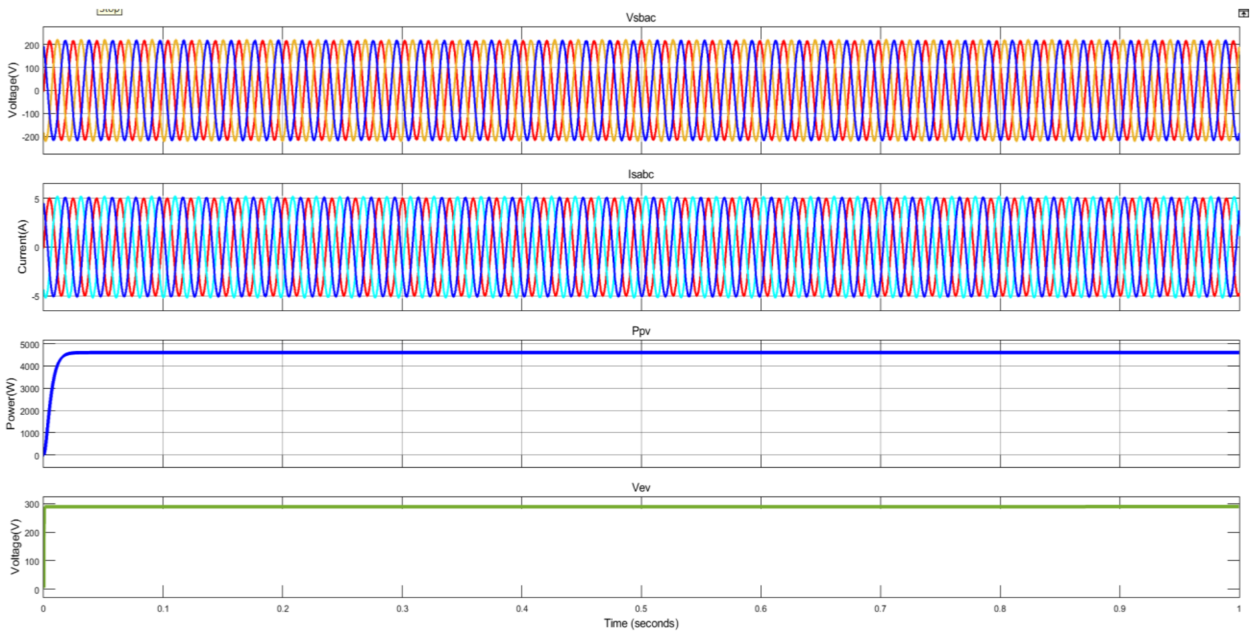

Figure 7. Simulation Model of Proposed PV-Based EV Charging Station

Figure 7 illustrates the complete MATLAB/Simulink model of the proposed single-stage solar photovoltaic (PV) based bidirectional EV charging station. The system consists of a PV array, bidirectional DC-DC converter, Voltage Source Converter (VSC), EV battery, DC-link capacitor, Static Transfer Switches (STS), and utility grid interface. The developed model supports both Grid-to-Vehicle (G2V) and Vehicle-to-Grid (V2G) operations. The control system effectively manages active and reactive power flow while maintaining DC-link voltage stability and grid synchronization under different operating conditions.

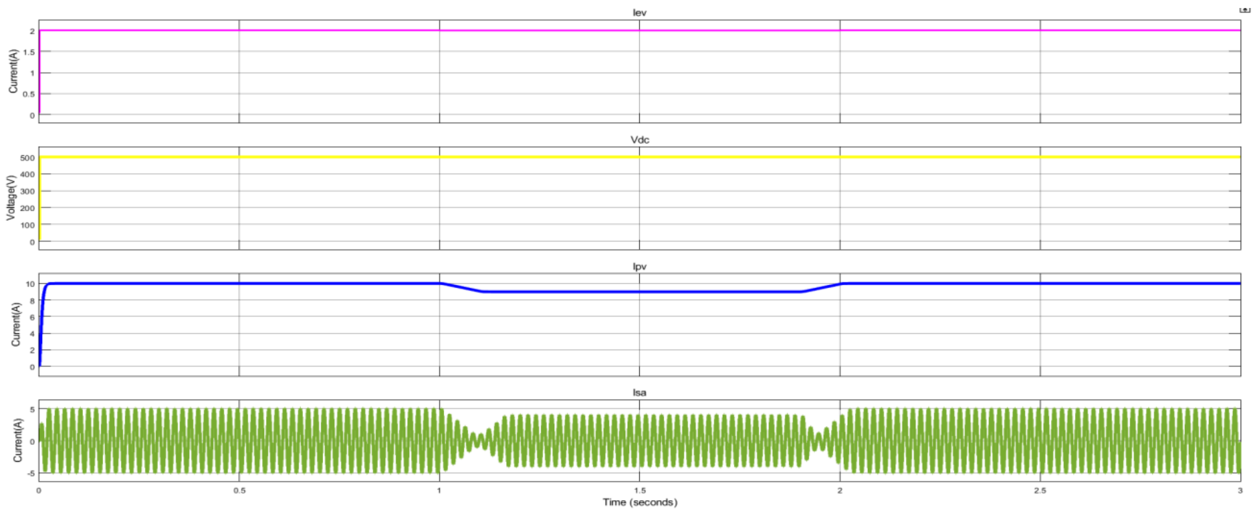

Figure.8. ab

Figure 8(a). PV Array Output Voltage Waveform

Figure 8(a) shows the output voltage waveform of the solar PV array under varying irradiation conditions. The waveform demonstrates that the PV system generates stable DC voltage suitable for charging the EV battery and supporting grid power requirements. The Maximum Power Point Tracking (MPPT) controller successfully extracts maximum available solar power and maintains stable operation during dynamic environmental conditions.

Figure 8(b). PV Array Output Current Waveform

Figure 8(b) presents the output current waveform of the solar PV array. The results indicate that the PV current varies according to solar irradiance and load demand conditions. During higher solar irradiation, the PV array supplies increased current to the DC-link and EV charging system. The waveform confirms efficient solar energy conversion and proper operation of the PV generation unit.

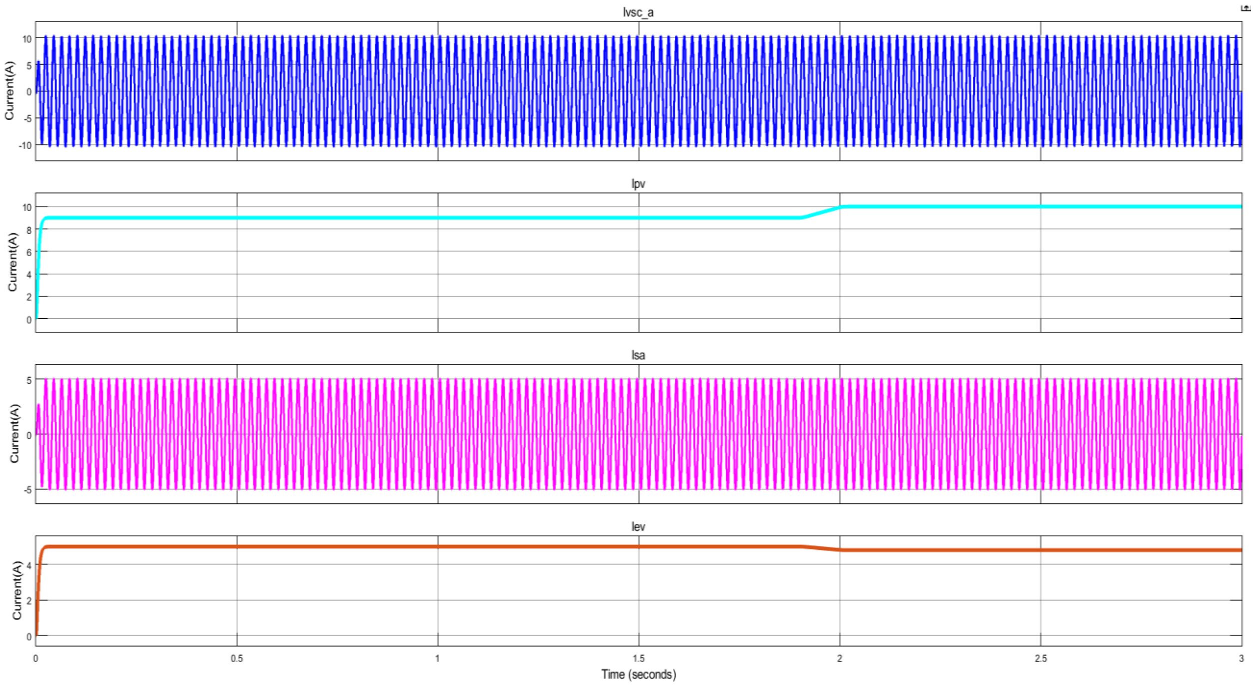

Figure 8(c). DC-Link Voltage Response

Figure 8(c) illustrates the DC-link voltage response of the charging station. The DC-link voltage is maintained at a constant reference value despite variations in PV generation, grid disturbances, and EV charging/discharging conditions. The bidirectional converter and VSC controller effectively regulate the DC-link voltage, thereby ensuring stable system operation and reliable power transfer.

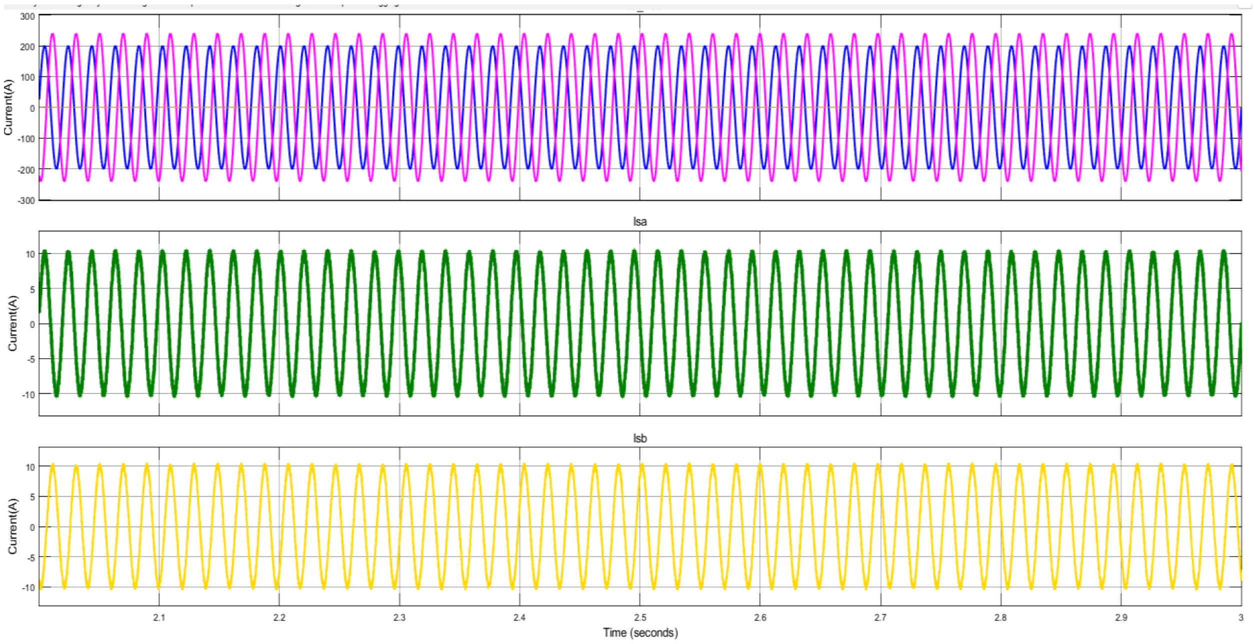

Figure 8(d). EV Battery Charging Current

Figure 8(d) shows the EV battery charging current during Grid-to-Vehicle (G2V) operation. The charging current waveform demonstrates smooth and regulated charging characteristics with reduced ripple content. The bidirectional DC-DC converter operates in buck mode and controls the charging current according to the battery requirements, thereby improving battery performance and charging efficiency.

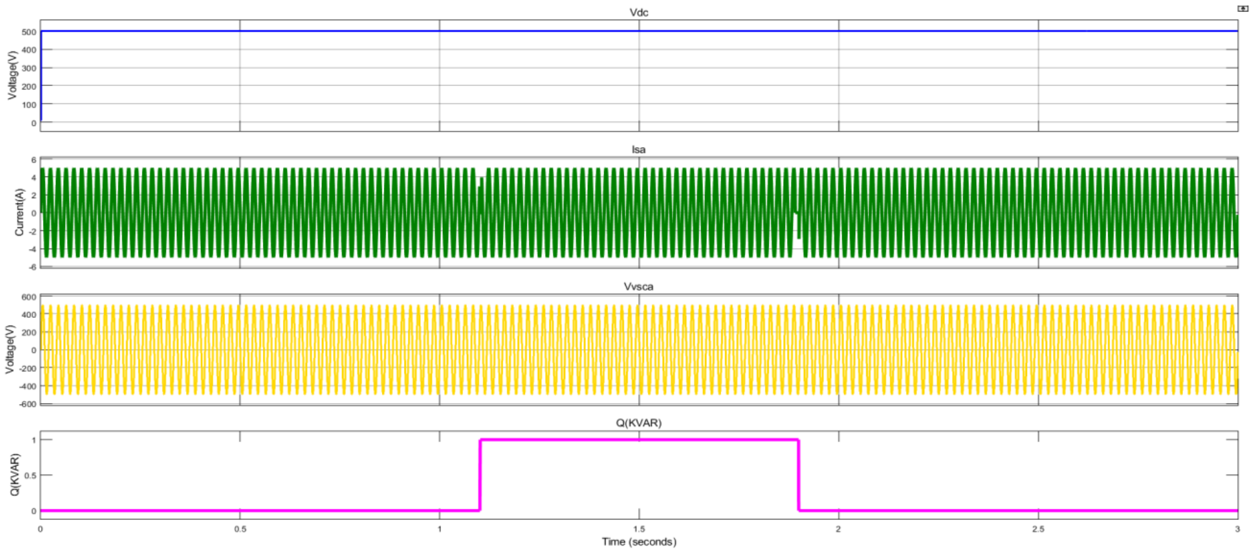

Figure.9 ab

Figure 9(a). Grid Voltage Waveform

Figure 9(a) presents the three-phase grid voltage waveform at the Point of Common Coupling (PCC). The waveform indicates balanced and sinusoidal grid voltages during grid-connected operation. The synchronization controller successfully maintains phase matching between the charging station and utility grid, ensuring stable power exchange and safe system operation.

Figure 9(b). Grid Current Waveform

Figure 9(b) illustrates the grid current waveform during power transfer operation. The current waveform remains sinusoidal with low harmonic distortion due to the effective operation of the VSC controller. The charging station injects or absorbs active and reactive power according to system requirements while maintaining improved grid power quality and power factor correction.

Figure 10(a). Vehicle-to-Grid (V2G) Power Transfer Response

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Figure 10(a) shows the V2G mode operation where the EV battery discharges stored energy back to the utility grid during peak load demand conditions. The bidirectional converter operates in boost mode, and the VSC transfers synchronized AC power to the grid. The results verify successful bidirectional power flow operation and demonstrate the capability of the EV battery to function as an auxiliary energy storage source.

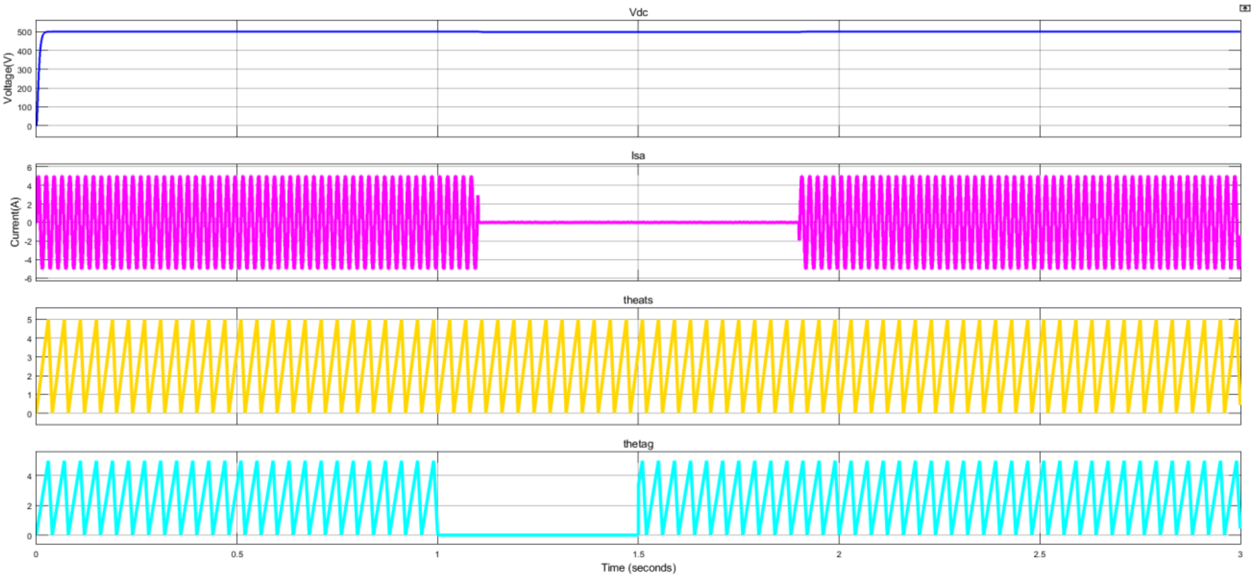

Figure 10.bc
Figure 10(b). Reactive Power Compensation Performance

Figure 10(b) demonstrates the reactive power compensation capability of the proposed charging station. The VSC provides both inductive and capacitive reactive power support depending on the grid requirements. The results show improved power factor, reduced reactive power burden on the utility grid, and enhanced voltage regulation at the PCC.

Figure 10(c). Standalone Mode Operation
Figure 10(c) illustrates the standalone operation of the charging station during grid failure conditions. When the utility grid is disconnected, the PV array continues supplying power to the EV battery through the DC-link. The synchronization and islanding controller ensure uninterrupted system operation and maintain stable voltage conditions during the transition from grid-connected mode to standalone mode.

4. DISCUSSION

The proposed single-stage solar photovoltaic (PV) based bidirectional electric vehicle (EV) charging station demonstrates an efficient and reliable solution for integrating renewable energy resources with modern EV charging infrastructure. The simulation results validate the capability of the system to perform both Grid-to-Vehicle (G2V) and Vehicle-to-Grid (V2G) operations effectively while maintaining stable power flow and improved grid performance. The direct integration of the PV array with the DC-link eliminates the requirement of an additional DC-DC boost converter, thereby reducing circuit complexity, switching losses, and overall system cost.

The developed control strategy plays a major role in ensuring efficient system performance under different operating conditions. The active power reference command enables flexible charging and discharging of the EV battery according to user requirements, whereas the reactive power reference command supports reactive power compensation for improving grid power quality. The Voltage Source Converter (VSC) successfully controls active and reactive power exchange with the utility grid while maintaining sinusoidal grid currents and stable DC-link voltage.

The bidirectional DC-DC converter effectively controls the EV battery charging and discharging process. During G2V operation, the converter operates in buck mode and provides smooth charging current with minimum ripple content, thereby improving charging efficiency and protecting the battery from excessive stress. During V2G operation, the converter operates in boost mode and transfers stored energy from the EV battery to the utility grid during peak demand conditions. This capability allows the EV battery to function as a distributed energy storage system and supports grid stability.

The incorporation of Maximum Power Point Tracking (MPPT) ensures maximum utilization of solar energy under varying irradiance conditions. The PV array successfully supplies power to the EV battery and utility grid simultaneously, thereby reducing dependency on conventional grid power and improving renewable energy penetration. Moreover, the charging station provides uninterrupted operation during grid failure conditions by shifting into standalone mode. The synchronization controller effectively monitors grid voltage, frequency, and phase angle conditions and ensures smooth transition between grid-connected and islanding modes without causing system instability.

The reactive power compensation capability of the proposed charging station further enhances its practical applicability in smart grid environments. By providing both inductive and capacitive reactive power support, the system improves power factor, reduces voltage fluctuations, and minimizes the reactive power burden on the utility grid. The obtained simulation results demonstrate stable operation under dynamic conditions such as solar irradiation variation, load changes, and grid disturbances, confirming the robustness and effectiveness of the proposed control scheme.

Overall, the proposed PV-based bidirectional EV charging station provides a sustainable, economical, and intelligent solution for future transportation and smart grid applications. The system improves energy efficiency, enhances renewable energy utilization, supports grid stability, and promotes environmentally friendly transportation infrastructure.

5. CONCLUSION

This paper presented the design, control, and simulation analysis of a single-stage solar photovoltaic (PV) based bidirectional electric vehicle (EV) charging station connected to the utility grid. The proposed system integrates a PV array, bidirectional DC-DC converter, Voltage Source Converter (VSC), and intelligent control strategy to support both Grid-to-Vehicle (G2V) and Vehicle-to-Grid (V2G) operations. The charging station effectively utilizes solar energy for EV charging while also enabling the EV battery to supply power back to the grid during peak demand conditions.

The developed control strategy successfully regulates active and reactive power flow, maintains stable DC-link voltage, and ensures smooth synchronization with the utility grid. The bidirectional converter effectively controls EV battery charging and discharging operations while minimizing ripple current and protecting battery life. Furthermore, the VSC provides reactive power compensation and improves overall grid power quality by maintaining sinusoidal grid current and improved power factor.

Simulation results confirm that the proposed charging station operates efficiently under various operating conditions including PV irradiation changes, grid disturbances, standalone operation, and dynamic load variations. During grid failure conditions, the system successfully operates in islanding mode and continues EV charging using the PV array. Once the grid is restored, the synchronization controller reconnects the charging station safely and smoothly.

The proposed PV-based EV charging station offers several advantages such as reduced dependency on fossil fuel-based electricity, enhanced renewable energy utilization, improved grid stability, reduced charging infrastructure cost, and support for sustainable transportation systems. Therefore, the developed system can serve as an effective solution for future smart grid and electric mobility applications. Future work may focus on real-time hardware implementation, advanced battery management techniques, and integration of multiple renewable energy sources for further improvement in system performance and reliability.

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