International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 03 , March - 2026

Design and Performance Evaluation of an MPPT-Controlled Solar-Grid Hybrid DC EV Charging Station with Intelligent Battery Mode Management Using MATLAB/Simulink

Karnati Sri Sri Naga Venkata Venugopal
Department of Electrical Engineering Parul University
Vadodara, India

Pamarthi Tharun
Department of Electrical Engineering Parul University
Vadodara, India

Dannuri Srinivas
Department of Electrical Engineering Parul University
Vadodara, India

Talla Shiva Charan
Department of Electrical Engineering Parul University
Vadodara, India

***Abstract*—The rapid growth of electric vehicles (EVs) has created a significant demand for reliable, energy-efficient, and renewable-integrated charging infrastructure while reducing dependence on conventional grid supply. This paper presents the design and simulation-based evaluation of a solar-grid hybrid DC EV charging station developed in MATLAB/Simulink.**

The proposed system incorporates a 4 kW photovoltaic (PV) array, an interleaved buck converter controlled by an incremental conductance maximum power point tracking (MPPT) algorithm, a regulated 400 V DC bus, a bidirectional DC-DC converter for battery interfacing, and a single-phase grid-connected inverter operating in current control mode. An intelligent battery mode management strategy enables the selective connection of either a stationary battery or an EV battery, ensuring coordinated energy flow and preventing operational conflicts.

The control framework prioritizes solar energy utilization and enables grid assistance only when PV generation is insufficient during EV charging. Simulation results under varying irradiance conditions demonstrate effective MPPT tracking, stable DC bus voltage regulation, controlled power sharing, and reduced dependency on the grid. The proposed architecture provides a reliable and scalable solution for renewable-integrated EV charging applications.

***Index Terms*—Electric vehicle charging, solar photovoltaic (PV), hybrid charging station, maximum power point tracking (MPPT), interleaved buck converter, bidirectional DC–DC converter, grid-assisted charging, DC microgrid.**

I. INTRODUCTION

The rapid growth of electric vehicle (EV) adoption has significantly increased the demand for reliable, efficient, and sustainable charging infrastructure [8]. Conventional grid-based charging stations impose peak load stress on the utility network, increase operational costs, and reduce the environmental benefits of EV deployment when powered by fossil-fuel-dominated grids [8]. Integrating renewable energy sources, particularly solar photovoltaic (PV) systems, into EV charging infrastructure offers a sustainable solution that reduces grid dependency and carbon emissions [1], [6].

However, standalone PV-based charging stations are inherently limited by the intermittency of solar irradiance. Variations in solar generation can lead to unstable charging performance if not properly managed [6]. Hybrid architectures that combine PV generation, battery energy storage, and controlled grid assistance provide improved reliability and operational flexibility [2], [5]. In such systems, effective energy management strategies are essential to coordinate power flow and maintain stable DC bus operation.

DC-based charging architectures further improve system efficiency by reducing unnecessary power conversion stages compared to conventional AC-based charging systems [12]. In addition, interleaved DC–DC converter topologies help reduce current ripple, enhance thermal performance, and improve dynamic response, making them suitable for medium-power EV charging applications [10].

This paper presents the design and simulation-based evaluation of a solar–grid hybrid DC EV charging station developed in MATLAB/Simulink. The proposed system integrates a 4 kW photovoltaic array, an interleaved buck converter controlled by an incremental conductance maximum power point tracking (MPPT) algorithm, a regulated 400 V DC bus, a bidirectional DC–DC converter for battery interfacing, and a single-phase grid-connected inverter operating in current control mode [9]. An intelligent battery mode management strategy enables selective connection of either a stationary battery or an EV battery, ensuring coordinated energy flow

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 03 , March - 2026

and preventing simultaneous operational conflicts.

The proposed system prioritizes renewable energy utilization and activates grid assistance only when PV generation is insufficient during EV charging. Simulation results demonstrate stable DC bus regulation, effective MPPT tracking, controlled power sharing, and reduced grid dependency under varying irradiance conditions.

The main contributions of this work are summarized as follows:

- Design of a solar–grid hybrid DC EV charging station integrating photovoltaic generation and controlled grid assistance.
- Implementation of an interleaved buck converter with incremental conductance MPPT for efficient solar power extraction.
- Development of an intelligent battery mode management strategy for selective operation of stationary and EV batteries.
- Performance evaluation of the proposed system through MATLAB/Simulink simulations under varying irradiance conditions.

II. RELATED WORK

Solar-assisted EV charging systems have been widely studied as a sustainable alternative to grid-dependent charging infrastructure [1], [4]. Standalone PV-based charging stations reduce carbon emissions but suffer from intermittency issues, leading to unreliable charging during low irradiance conditions [6].

To enhance reliability, hybrid configurations integrating PV systems with battery energy storage have been proposed [2], [5]. Battery-assisted charging enables energy buffering and load support during solar power fluctuations. However, many existing implementations rely on conventional single-phase DC–DC converters, which may exhibit higher ripple current and reduced efficiency under medium-power operation [3].

Maximum power point tracking (MPPT) techniques such as Perturb and Observe and Incremental Conductance are commonly applied to maximize solar energy extraction [9]. Among these, the incremental conductance method offers improved tracking accuracy under rapidly changing irradiance conditions.

Interleaved converter topologies have also been introduced to reduce ripple current and improve thermal performance in high-power DC–DC converter applications [10]. Despite their advantages, limited studies have focused on applying interleaved converters within hybrid DC EV charging systems incorporating intelligent battery mode management.

Grid-assisted EV charging architectures ensure continuous operation during insufficient solar generation [6], [7]. However, uncontrolled grid interaction may increase operational costs. Therefore, coordinated control strategies that prioritize renewable energy while activating grid support only when necessary are essential.

Motivated by these gaps, this work proposes a solar-grid hybrid DC EV charging station with interleaved conversion, regulated DC bus control, and intelligent battery mode switching to enhance efficiency, reliability, and grid utilization management.

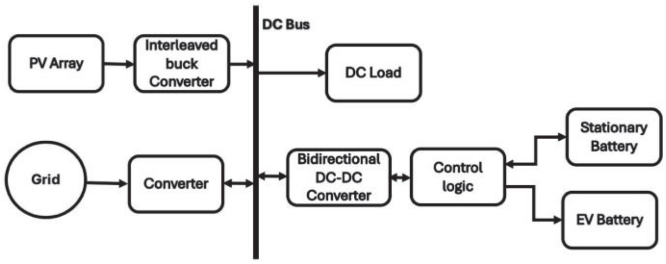

Fig. 1. Block diagram of the proposed solar–grid hybrid EV charging station.

III. SYSTEM ARCHITECTURE

The proposed solar–grid hybrid EV charging station integrates renewable energy generation, battery storage, and controlled grid assistance through a regulated DC bus architecture. The system is designed to ensure reliable EV charging while prioritizing solar energy utilization and minimizing dependency on the utility grid.

A. Overall System Configuration

Fig. 1 illustrates the overall configuration of the proposed hybrid EV charging station. The primary energy source is a 4 kW solar photovoltaic (PV) array consisting of sixteen 250 W series-connected modules. The PV output is interfaced with an interleaved buck converter operating under incremental conductance maximum power point tracking (MPPT) control.

The interleaved buck converter regulates the PV output voltage and maintains a stable 400 V DC bus. The DC bus acts as a common coupling point connecting the PV generation system, battery storage unit, DC load, and the grid-connected inverter.

A bidirectional DC–DC converter connects either a stationary battery or an EV battery to the DC bus through an intelligent battery mode management mechanism. A single-phase grid-connected inverter supplies supplementary power only when PV generation is insufficient during EV charging.

The system operates under two primary modes:

- Stationary battery mode (EV disconnected)
- EV charging mode (stationary battery isolated)

This architecture ensures coordinated energy management and prevents simultaneous battery interaction.

The key system parameters used in the simulation model are summarized in Table I.

B. Power Circuit Implementation

The detailed power circuit modeled in MATLAB/Simulink is shown in Fig. 2. The solar PV array feeds an interleaved buck converter composed of two parallel buck stages operating with 180-degree phase-shifted switching signals. This interleaving technique reduces input and output ripple current and improves converter efficiency.

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 03 , March - 2026

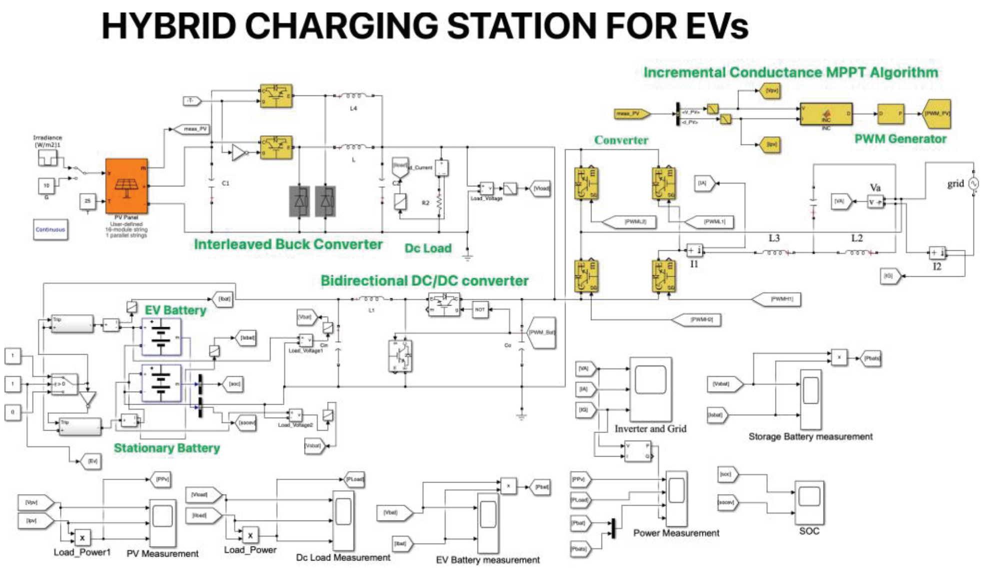

Fig. 2. Power circuit implementation of the proposed hybrid EV charging station modeled in MATLAB/Simulink.

TABLE I
SYSTEM PARAMETERS OF THE PROPOSED EV CHARGING STATION

Parameter	Value
PV array rating	4 kW
Number of PV modules	16
PV module rating	250 W
DC bus voltage	400 V
Grid voltage	230 V
Battery nominal voltage	300 V
Converter switching frequency	20 kHz
DC load power	1 kW

The regulated 400 V DC bus is connected to a bidirectional DC–DC converter that interfaces with either the stationary battery or the EV battery. The converter operates in buck mode during battery charging and in boost mode during battery discharging.

The DC bus is also connected to a single-phase voltage source inverter that interfaces with the 230 V AC grid. The inverter operates under current control mode to regulate grid power injection during EV charging when solar power is insufficient.

The proposed circuit architecture ensures stable DC bus regulation, controlled battery charging and discharging, and conditional grid-assisted operation. By maintaining a unified DC architecture, the system minimizes conversion stages and improves overall efficiency compared to conventional AC-based charging systems.

IV. MATHEMATICAL MODELING

This section presents the simplified mathematical modeling of the major components of the proposed solar–grid hybrid DC EV charging station. The objective is to describe system behavior while maintaining analytical clarity.

A. Photovoltaic Array

The output power of the photovoltaic (PV) array is expressed as:

$$P_{pv} = V_{pv} \times I_{pv} \tag{1}$$

Maximum power point tracking (MPPT) ensures that the PV system operates at the point where the power derivative is zero [9]:

$$\frac{dP}{dV} = 0 \tag{2}$$

Using $P = VI$, the maximum power condition becomes:

$$\frac{dI}{dV} = -\frac{I}{V} \tag{3}$$

The incremental conductance MPPT algorithm adjusts the duty cycle of the interleaved buck converter to satisfy this condition under varying irradiance.

B. Interleaved Buck Converter

The interleaved buck converter regulates the PV voltage to maintain a constant DC bus voltage. The average output voltage of the buck converter is:

$$V_{dc} = D \times V_{pv} \tag{4}$$

where D is the duty cycle.

The inductor current dynamics are given by:

$$L\frac{di_L}{dt} = V_{pv} - V_{dc} \tag{5}$$

Interleaving two buck phases with 180-degree phase shift reduces ripple current and improves overall efficiency [10].

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 03 , March - 2026

C. DC Bus Dynamics

The DC bus voltage is regulated at 400 V and follows the capacitor dynamic equation:

$$C_{dc}\frac{dV_{dc}}{dt} = I_{pv} + I_{bat} + I_{grid} - I_{load} \tag{6}$$

Stable DC bus operation is achieved when the net current into the capacitor is zero.

D. Bidirectional DC–DC Converter

The bidirectional converter connects either the stationary battery or the EV battery to the DC bus. The inductor equation is:

$$L_{bat}\frac{di_{bat}}{dt} = V_{dc} - V_{bat} \tag{7}$$

Battery power is expressed as:

$$P_{bat} = V_{bat} \times I_{bat} \tag{8}$$

Positive current represents charging mode, while negative current represents discharging mode.

E. Grid Interaction

The instantaneous grid power is:

$$P_{grid} = V_{grid} \times I_{grid} \tag{9}$$

The grid supplies power only when PV generation is insufficient during EV charging. The required grid current is determined by:

$$I_{grid} = \frac{P_{required} - P_{pv}}{V_{grid}} \tag{10}$$

This ensures controlled grid-assisted charging while prioritizing renewable energy utilization [11].

V. CONTROL STRATEGY

The proposed hybrid EV charging station employs a coordinated control framework to regulate solar power extraction, maintain DC bus stability, manage battery mode selection, and control grid assistance. The overall control structure consists of four main layers: MPPT control, DC bus voltage regulation, battery mode management, and grid current control.

A. MPPT Control of the Interleaved Buck Converter

The solar PV array is connected to the DC bus through an interleaved buck converter. An incremental conductance maximum power point tracking (MPPT) algorithm is used to ensure maximum energy extraction under varying irradiance conditions [9].

The MPPT controller continuously measures the PV voltage and current and evaluates the condition:

$$\frac{dI}{dV} = -\frac{I}{V} \tag{11}$$

If the operating point deviates from the maximum power point, the duty cycle of the buck converter is adjusted accordingly. The interleaved topology improves dynamic response and reduces ripple current, ensuring stable DC bus feeding [10].

B. DC Bus Voltage Regulation

The DC bus voltage is regulated at 400 V to ensure stable operation of the charging system. The DC bus voltage is measured and compared with the reference value. The resulting error is processed through a proportional-integral (PI) controller to generate the reference current for the bidirectional DC–DC converter.

The DC bus dynamic equation is:

$$C^{dc}\frac{dV_{dc}}{dt} = I^{pv} + I^{bat} + I^{grid} - I^{load} \tag{12}$$

The controller ensures that any imbalance between generation and load demand is compensated by controlled battery charging/discharging or grid assistance.

C. Battery Mode Management

An intelligent battery selection mechanism is implemented to prevent simultaneous interaction of the stationary battery and the EV battery. A binary control signal determines the active battery mode:

- When the control signal is 0, the EV battery is disconnected, and the stationary battery supports the DC load.
- When the control signal is 1, the EV battery is connected and the stationary battery is isolated.

This strategy prevents circulating currents and avoids conflicts between battery systems. The bidirectional converter operates in charging or discharging mode depending on the DC bus voltage deviation.

D. Grid-Assisted Power Control

The grid-connected inverter operates in current control mode and provides supplementary power only when required. The grid is activated under the following conditions:

- If the EV is connected and PV generation is insufficient to meet charging demand, the grid supplies the deficit power.
- If PV generation is sufficient, the grid current reference is set to zero.
- When only the stationary battery is connected, the grid remains inactive.

The inverter uses a PI-based current control loop to regulate grid current and ensure stable synchronization with the utility supply [11].

Overall, the coordinated control strategy ensures prioritized renewable energy utilization, stable DC bus regulation, controlled battery operation, and minimized grid dependency under dynamic operating conditions.

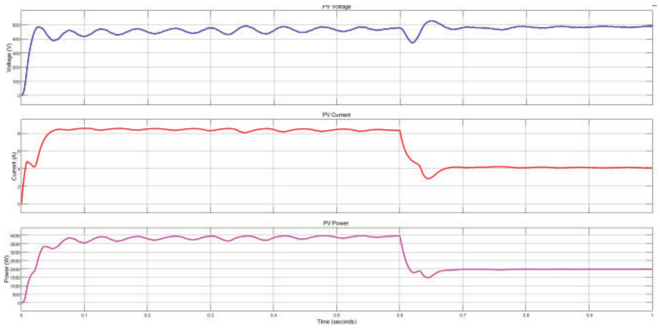

Fig. 3. PV power variation in stationary battery mode under changing irradiance conditions.

VI. Simulation Results and Discussion

The proposed solar-grid hybrid DC EV charging station is modeled and simulated in MATLAB/Simulink to evaluate system performance under varying irradiance conditions and battery connection modes. The PV array is rated at 4 kW under standard test conditions, and the DC bus reference voltage is maintained at 400 V throughout the simulation.

The simulation was carried out for a duration of 10 seconds under varying irradiance conditions ranging from 1000 W/m^2 to lower values.

The system is analyzed under two primary operating modes: (i) Stationary battery mode and (ii) EV charging mode.

A. Mode 1: Stationary Battery Connected

In this operating mode, the EV battery is disconnected, and the stationary battery is connected to the DC bus. The grid remains inactive in this condition. The PV power variation under changing irradiance conditions is illustrated in Fig. 3. At peak irradiance (1000 W/m^2), the PV array generates approximately 4 kW. The DC load consumes about 1 kW, while the remaining power is utilized for charging the stationary battery.

Fig. 4 shows the stationary battery current profile. During high irradiance, the battery current is positive, indicating a charging operation. When irradiance decreases significantly or reaches zero, the battery current becomes negative, indicating discharge to support the DC load. This demonstrates proper bidirectional converter operation.

Throughout this mode, grid power remains zero, confirming autonomous operation without grid assistance.

B. Mode 2: EV Charging Mode

In this mode, the EV battery is connected, and the stationary battery is disconnected through the intelligent battery selection logic.

Fig. 5 illustrates the PV power variation during EV connection. At peak irradiance, PV generation reaches approximately 4 kW. With a DC load demand of 1 kW, the remaining power is utilized for EV battery charging.

When irradiance decreases, and PV generation becomes insufficient to meet charging demand, the grid supplies the deficit power. This behavior is shown in Fig. 6. The grid power

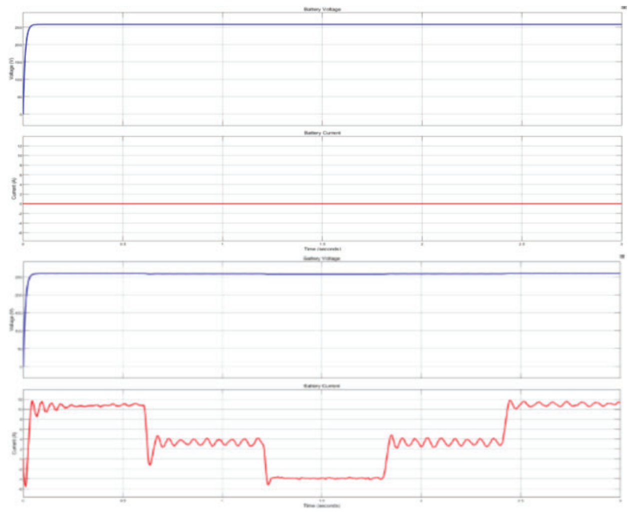

Fig. 4. Stationary battery current profile showing charging and discharging behavior under varying irradiance.

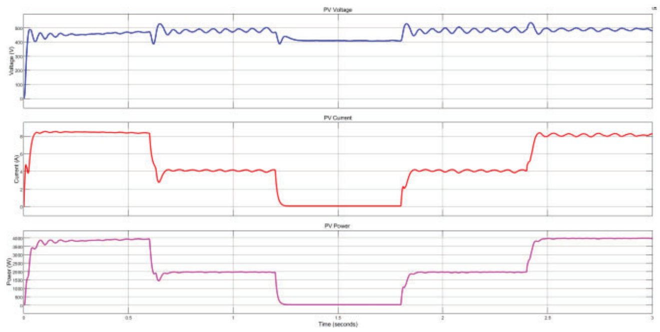

Fig. 5. PV power variation during EV charging mode under changing irradiance conditions.

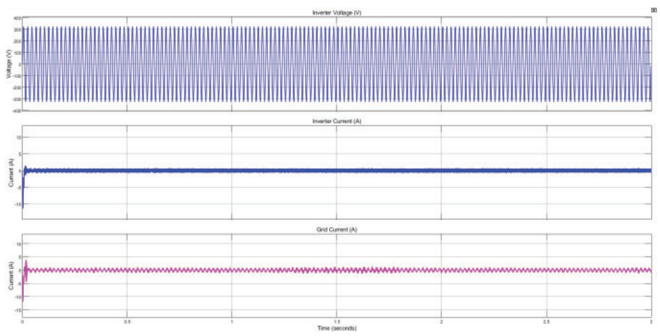

Fig. 6. Grid power contribution during EV charging mode under varying irradiance conditions.

remains zero during high irradiance and increases only when PV power drops below the required charging level.

The EV battery current profile is shown in Fig. 7. The battery current remains positive throughout this mode, indicating continuous charging. The stationary battery current remains zero, confirming correct battery mode switching.

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 03 , March - 2026

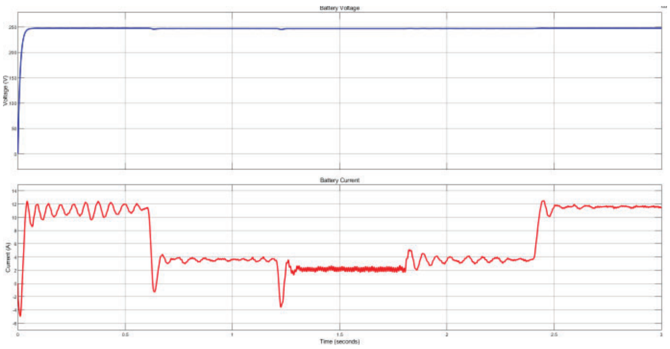

Fig. 7. EV battery charging current during EV connection mode under varying irradiance conditions.

C. Performance Analysis

The simulation results validate the following key observations:

- Effective maximum power extraction from the PV array under varying irradiance conditions.
- Proper bidirectional battery operation with clear charging and discharging transitions.
- Intelligent battery mode switching, preventing simultaneous battery interaction.
- Grid participation only during PV power deficit conditions, minimizing electricity purchase.
- Stable DC bus voltage regulation at 400 V throughout mode transitions.

Overall, the obtained results demonstrate that the proposed hybrid charging system ensures consistent EV charging performance, enhances the utilization of renewable energy, and enables controlled grid support under dynamically changing operating conditions.

VII. CONCLUSION

This paper presented the design and simulation-based evaluation of a solar-grid hybrid DC EV charging station developed in MATLAB/Simulink. The proposed architecture integrates a 4 kW photovoltaic array, an interleaved buck converter with incremental conductance MPPT, a regulated 400 V DC bus, a bidirectional DC–DC converter for battery interfacing, and a single-phase grid-connected inverter operating in current control mode.

An intelligent battery mode management strategy was implemented to enable selective connection of either a stationary battery or an EV battery to the DC bus. This approach prevents simultaneous battery interaction and ensures coordinated power flow within the hybrid system. The grid operates as a supplementary source and is activated only when photovoltaic generation is insufficient during EV charging, thereby minimizing unnecessary grid power consumption.

Simulation results under varying irradiance conditions demonstrate effective maximum power extraction, reduced ripple through interleaved conversion, stable DC bus regulation, controlled battery charging and discharging behavior, and proper grid-assisted power support. The system successfully prioritizes renewable energy utilization while maintaining reliable EV charging operation.

The proposed hybrid charging architecture provides an energy-efficient and scalable solution for renewable-integrated EV infrastructure. Future work will focus on hardware implementation, real-time controller validation, and optimization of the energy management strategy for improved efficiency and system scalability.

AUTHOR CONTRIBUTIONS

Both Karnati Sri Sri Naga Venkata Venugopal and Pamarthi Tharun contributed significantly to the development of the proposed system. Venugopal developed the MATLAB/Simulink model and implemented the control strategies, while Tharun coordinated the project and contributed to MPPT and converter analysis. Talla Shiva Charan assisted in battery modeling, grid integration, and simulation validation. Dannuri Srinivas contributed to performance analysis, literature review, and technical review of the manuscript. All authors reviewed and approved the final version of the paper.

ACKNOWLEDGMENT

The authors would like to express their sincere gratitude to Dr. Shubhrajyoti Kundu for his valuable guidance and continuous support throughout the development of this work. The authors also thank the Department of Electrical Engineering, Parul University, for providing the necessary laboratory and simulation facilities.

REFERENCES

[1] P. Singla et al., "Design and Simulation of 4 kW Solar Power-Based Hybrid EV Charging Station," Scientific Reports, vol. 14, 2024.
[2] P. K. Kanth, P. K. Tiwari, and N. Boda, "A Control Scheme for Grid Connected Solar Powered EV Charging Station With Hybrid Energy Storage System," IEEE SILCON, 2023.
[3] S. Verma, K. Chatterjee, and K. Sandhya, "Electrical Vehicle Charging Station Mathematical Modeling and Stability Analysis," IEEE ICAECT, 2022.
[4] B. Premkumar et al., "Hybrid Electric Vehicle Charging Station Design – A Case Study," IEEE NPSC, 2022.
[5] N. Thaitae et al., "Hybrid PV and BES for EV Charging Stations in Microgrid Systems," IEEE ECTI-CON, 2023.
[6] H. Arya and M. Das, "Solar Powered EV Fast Charging Station to Support Distribution Grid," IEEE ICPS, 2021.
[7] T. Aldhanhani, A. Al-Durra, and E. F. El-Saadany, "Optimal Design of Electric Vehicle Charging Stations Integrated with Renewable DG," IEEE SGTECH, 2017.
[8] Y. A. M. Yousuf et al., "Electric Vehicle Charging Station Infrastructure: A Comprehensive Review," IEEE CCECE, 2023.
[9] T. Esram and P. L. Chapman, "Comparison of Photovoltaic Array Maximum Power Point Tracking Techniques," IEEE Trans. Energy Conversion, vol. 22, no. 2, pp. 439–449, 2007.
[10] J. Zhang, J. Shao, and H. Wang, "Analysis and Design of Interleaved DC–DC Converters for High Power Applications," IEEE Trans. Power Electronics, vol. 24, no. 8, pp. 1839–1846, 2009.
[11] R. Teodorescu, M. Liserre, and P. Rodr´ıguez, Grid Converters for Photovoltaic and Wind Power Systems. Wiley-IEEE Press, 2011.
[12] J. M. Guerrero et al., "Hierarchical Control of Droop-Controlled AC and DC Microgrids," IEEE Trans. Industrial Electronics, vol. 58, no. 1, pp. 158–172, 2011.
[13] A. Ahmad, M. Saeed, and S. Khan, "Solar-Powered EV Charging Stations Integrated With DC Microgrids," *IEEE Access*, vol. 11, pp. 12345–12356, 2023.