RESEARCH ARTICLE

INTERNATIONAL RESEARCH JOURNAL OF MULTIDISCIPLINARY TECHNOVATION

Asian Research Association

DOI:10.54392/irjmt26413

A Smart Bidirectional V2G-G2V Charging System Integrated with Solar PV

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DOI: https://doi.org/10.54392/irjmt26413
Received: 08-01-2026; Revised: 01-06-2026; Accepted: 13-06-2026; Published: 10-07-2026

Abstract: This paper presents the design, implementation, and experimental validation of a laboratory-scale bidirectional charging system integrating Vehicle-to-Grid (V2G) and Grid-to-Vehicle (G2V) operations using photovoltaic energy sources. Overall, the proposed system provides for managing and controlling two-way flow of energy between an electric vehicle's (EV) battery and the grid via a microcontroller-based monitoring and control system. An Incremental Conductance MPPT system extracts all available renewable energy from a 50 W solar PV array, regulates it with DC-DC converters, and stores it in a 12 V battery using a 48 V (DC) bus configuration. The prototype operates under multiple modes, including solar-assisted charging, grid-supported charging, and controlled battery discharging through an inverter supplying a local AC load. Experimental validation is carried out under laboratory conditions to evaluate voltage, current, power flow, and efficiency characteristics. The results demonstrate effective bidirectional operation at the prototype level. The system is implemented as a controlled laboratory-scale setup and does not include grid synchronization, anti-islanding protection, or interconnection compliance; therefore, V2G operation is demonstrated as AC load interaction rather than direct grid injection.

Keywords: Vehicle-to-Grid (V2G), Grid-to-Vehicle (G2V), Electric Vehicle Charging Station, Solar PV Integration, Battery Energy Storage System (BESS).

1. Introduction

The change toward sustainability in energy and transportation globally has facilitated the growth of electric vehicle (EV) operations as an alternative way to reduce greenhouse gas emissions and consumption of fossil fuels [1]. The ability to connect renewable energy sources (RES), like solar panels and photovoltaic (PV) systems, to ultimately achieve a carbon-free power sector will also add to the challenges to the power grid created by increasing volumes of EVs connected to it. These challenges include increased power demand (PD) from large numbers of EVs (thousands or millions) charging their batteries, load variation from EV charging and discharging, and increased pressure on the already overloaded power grid [2]. Bidirectional fast charging has recently developed into two types of technology: 1) Grid to Vehicle (G2V) - energy from the grid or another RES will be supplied to charge an EV battery; and 2) Vehicle to Grid (V2G) - an EV battery will discharge its stored energy to a local load and back to a controlled AC load through an inverter under laboratory conditions, without direct grid synchronization. This bidirectional fast charging will enable the EVs to become distributed energy storage devices (also called battery) resulting in better overall energy use.

To increase the sustainability of a charging system for an EV, the integration of solar power (PV) with [electric vehicle (EV)] charging systems allows for the local use of renewable energy sources. Therefore, solar-assisted charging systems offer an alternative to rely on grid-based energy to charge the EVs in an eco-friendly manner. However, existing literature on PV-integrated EV charging has largely focused on reviews, system studies, and control/topology analysis, while comparatively fewer works report laboratory-scale prototype validation [3]. This research study presents a bidirectional (vehicle-to-grid (V2G) and grid-to-vehicle (G2V)) charging system, developed and implemented in a laboratory that integrates solar PV and employs a microcontroller to monitor and control the charging systems. The design of this system utilizes various components such as DC-to-DC converters, inverter, and sensing devices for real-time monitoring to control the flow of energy between the PV source, battery, and grid interface. The proposed system operates using a 48 V DC bus configuration with a 12 V battery arrangement and has been evaluated with respect to the various modes of operation [4].

This research paper focuses on the validation of the bidirectional charging modes, including solar-assisted charging, grid-connected charging and controlled discharging of a compact prototype. Performance parameters including voltage, current, power and efficiency were evaluated under laboratory conditions. The study aims to demonstrate the feasibility and operational characteristics of a compact prototype system in comparison to deploying a large-scale system.

The rest of this paper is organized into four sections: Section 2 presents an overview of the system architecture and hardware implementation; Section 3 includes a description of the experimental test setup and the experimental results; Section 4 provides a performance evaluation of the overall operation of the compact prototype system; and Section 5 describes the future direction of research associated with bidirectional charging.

Over the last several years, there has been substantial research activity focused on developing more efficient, reliable and scalable electric vehicle (EV) charging systems that utilize renewable energy sources. Solar panels provide an excellent opportunity for electric vehicle (EV) charging from a solar source because they provide an alternative energy source to fossil fuels as well as allowing for distributed (decentralized) power generation. Research has also shown that effective system performance depends on the use of optimized power electronics interfaces, energy management strategies, and intelligent control strategies. A number of reviews have been published on solar EV charging infrastructure systems with the primary emphasis being on their design, integration of energy storage, and the challenges associated with interaction with the grid system. The capability of Bi-Directional Power Flow is essential in increasing grid stability and allowing for Demand Response (DR) capabilities. Vehicle-to-Grid (V2G) has been researched for many different applications such as Peak Shaving, Valley Filling and Frequency Regulation, however practical use of these types of systems requires the use of advanced converter topologies and efficient control methods [5, 6]. There are numerous DC - DC Converter configurations (Quadratic, Switched Capacitor, SEPIC, and High Gain Non-Isolated) that have been researched and developed with the goal of achieving exceptional energy efficiency and voltage gains. All the aforementioned converter designs will help to reduce instability due to varying loading and input conditions; they also have very high energy conversion efficiency rates.

Bidirectional converters represent an advancement in electric vehicle (EV) systems; however, with this increased functionality, many technical issues arise (e.g., voltage regulation, power quality, and system protection) [7-10]. There are various types of converter architectures that address these issues, including: Quasi-Z-source converters, interleaved converters and transformer-less designs. Techniques for control, such as: scheduling, clustering and forecasting, have also been researched to assist in managing EV charging demand and improving the interaction between the grid and EVs [11-13]. While these technologies are developing quickly, there is still a disconnect between theoretical research and practical deployment on real-world applications, particularly with respect to development of small-scale laboratory prototype systems. Most of the preceding studies evaluating each of these different types of bidirectional converters relies on simulation to demonstrate their feasibility; however, the ability to capture the full range of operational constraints encountered in practice cannot be duplicated in simulation. Therefore, the development of experimental hardware prototypes will be required to provide the necessary data for evaluating performance within practical application settings.

The purpose of the research presented here is to create an experimental prototype that combines solar energy with electric vehicle (EV) charging technologies in a way that provides an experimental basis for evaluating the feasibility of these systems. This prototype is a compact, cost-effective, simple-to-use, and measurable system that is capable of allowing controlled bidirectional power flows from the solar PV to the battery and from the battery to the AC load [14]. The use of this prototype has demonstrated that the use of controlled bidirectional power flow between sources, batteries, and loads has potential for real-world applications and supports the development of clean, renewable EV charging infrastructure. Additionally, the research shows that power measurement accuracy, efficiency and analysis are critical elements of achieving reliable system performance.

This research shows how solar energy combined with electric vehicle charging technology provides a pathway to develop sustainable integrated solutions that will help support the future development of renewable energy and create a more intelligent energy infrastructure by using smart grid technologies to integrate renewable energies and by developing efficient and viable infrastructure for the electric vehicle charging industry.

2. Overview of the Integrated V2G-G2V System

A vehicle-to-grid (V2G) and grid-to-vehicle (G2V) solar powered charging station will be developed in order to charge electric vehicles (EVs) using renewable energy. The V2G / G2V system takes advantage of the many advantages associated with solar power, such as an environmentally friendly way to produce electrical energy and to provide controlled power flow between various components of the system. The V2G / G2V system connects a solar photo voltaic (PV) array to a power conversion stage where the generated DC energy from the PV array is converted to AC power for EV charging applications. The system can provide bidirectional power flow to enable controlled power transfers among the PV source, battery, and load. A smart monitoring system will be implemented to allow for continuous monitoring and control of EV charging behaviour (e.g., PV output, converter performance, and battery charging/discharging behaviour).

The aim of this monitoring framework is to give real-time visibility to system parameters as well as control of energy flow in the prototype. Also, the system provides controlled flow of power between the operating modes, ensuring that the system will be stable during different load conditions, with evidence from the studies done on the relevant converters. Benefits of utilizing the proposed system, include increased use of locally available renewable energy sources, as well as providing greater operational flexibility with the use of bi-directional energy flow. By allowing for distributed energy storage and generation, the system will also achieve more stable operation and greater efficiencies in energy use [15].

2.1 System Configuration and Control Strategy

2.2.1 Architectural Block Diagram and Component Interconnection

The system described in Figure 1 is based on a dual-battery setup that signifies different EV usage states under the supervision of a controller unit (Arduino).

The two main sources to derive power from are Solar Panel and the AC Input Source. Solar Panel will collect input from solar, inclusive of a charging unit, while the AC input source connection is connected bi-directionally through an inverter. Two voltage sensors, as well as a current sensor are present and constantly monitor power parameters at the critical nodes in the system. Control relays are being used as a method of control using the switches to redirect power.

2.2.2 Modes of Operation

The functioning of the system is controlled by its intelligent monitoring system (based on Arduino) that uses sensor information to autonomously switch between the following modes:

Mode 1: Solar-Powered G2V (Grid-to-Vehicle) Charging Mode

When there is sufficient solar generation, the system will first use solar power to charge the EV batteries. The solar panel produces DC power that is conditioned by the charging unit. The Arduino controller then activates the corresponding relays and sends the power to the batteries. The 1A battery is used for charging when the car is in standby, and the 7A battery is used for charging while the car is operational, indicating a power demand that scales by the amount of wheel rotation. The figure 2 shows the pictorial representation of mode 1.

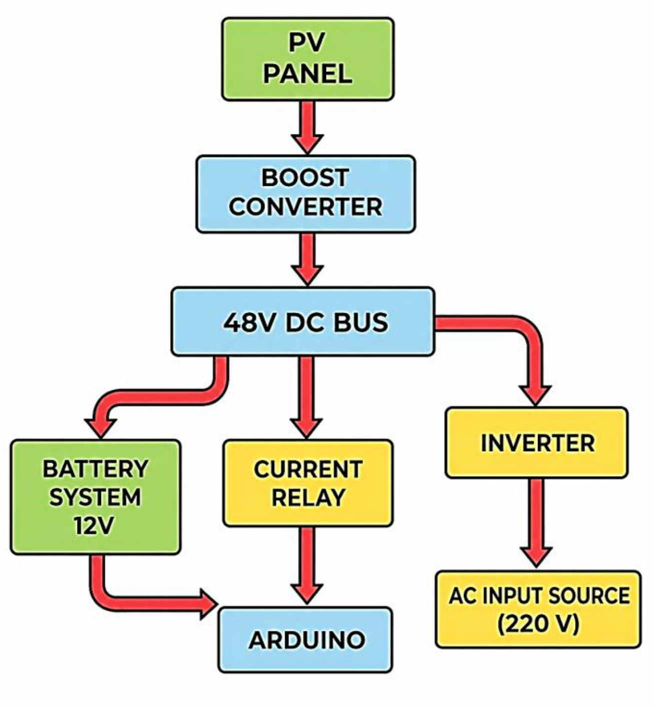

Figure 1. Proposed System architecture

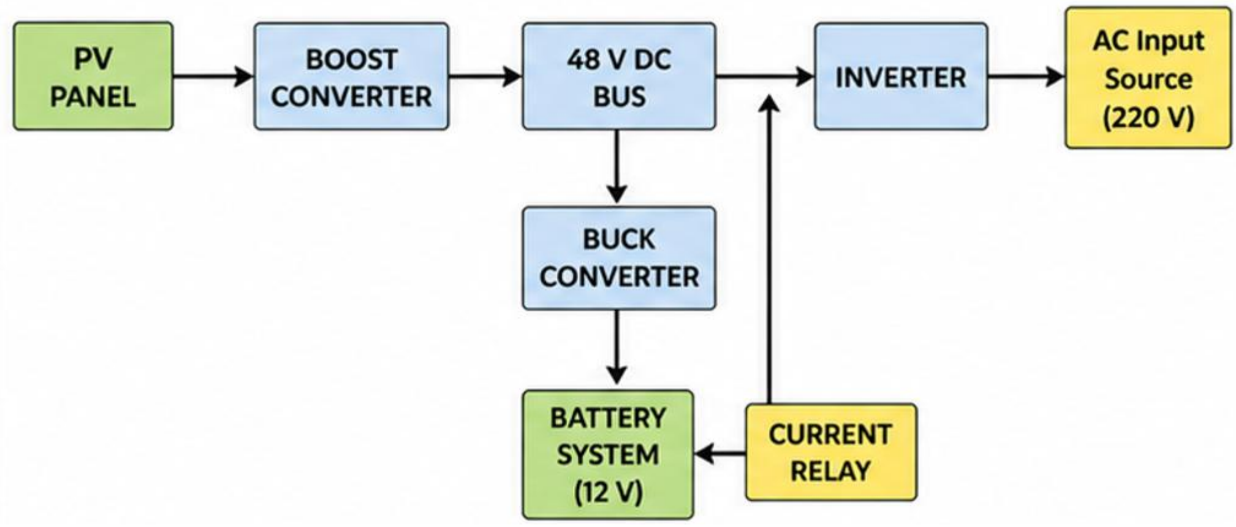

Figure 2. Solar-Powered G2V (AC source-to-Vehicle) Charging Mode

Mode 2: Grid-Supported G2V Charging Mode

When solar irradiation is insufficient (e.g., nighttime or cloudy weather), the system automatically operates using grid power. The AC source will supply power to the system, and the inverter will convert the AC current into DC current to charge the batteries. This is a guaranteed charging option regardless of whether estimations. The figure 3 shows the pictorial representation of mode 2.

Mode 3: V2G (Vehicle-to-Grid) Discharging Mode

During peak grid throughput or during a high state-of-charge conditions or controlled discharge scenarios, the system will operate in V2G mode. During this mode, the stored energy in the EV battery is converted from DC to AC using the inverter and supplied to a controlled AC load. This operation emulates V2G functionality under laboratory conditions. Direct grid injection is not implemented, as synchronization, protection mechanisms, and regulatory compliance are beyond the scope of this prototype. The Arduino controller will be in charge of monitoring the reverse power flow to an AC load appealing to munching the voltage and frequency of the grid. The figure 4 shows the pictorial representation of mode 3.

This figure 2 illustrates the overall system configuration integrating the PV panel, boost converter, DC bus, battery storage, and inverter. It demonstrates the controlled flow of energy between subsystems along with monitoring through the control unit. This figure 3 represents the Grid-to-Vehicle (G2V) operating mode under controlled conditions using an external AC input source [16]. It shows the power flow from the AC source to the battery through the converter stages while disabling reverse power flow. This figure 4 illustrates the Vehicle-to-Grid (V2G) mode as controlled discharge operation through the inverter stage. It demonstrates bidirectional power flow capability by supplying energy from the battery to an external AC load.

The voltage and current sensors continuously report back data to the Arduino microcontrollers, the microcontrollers utilize the data to implement safety measures away from overcharging and over-discharging, produces controlled charging rates based on measured voltage and current conditions, and continuously monitors and provides the user with unnecessary real time intelligence behaviors of the system and for owners to monitoring data.

2.2.3 Hardware Component Specifications

The hardware designed for the proposed system, which incorporates bidirectional V2G/G2V functionalities, solar generation capabilities, and smart monitoring, was utilized from a properly selected set of components. The detailed specification of the hardware can be seen in Table 1.

The proposed system presented in this study is a hardware solution suitable for effectively managing energy in the presence of solar photovoltaics (PV), electric vehicles (EVs), and the power grid. Figure 5 shows the architecture of the system. A central element in the system is the 48V DC Bus, where various power conversion stages can couple and interact with each other. The solar PV array links to the system through a Boost Converter using an MPPT Algorithm to yield the maximum power extractable from the PV array before charging the Battery Bank at the Centre of the architecture. A Bidirectional DC-AC Converter supports the essential Vehicle-to-Grid (V2G) and Grid-to-Vehicle (G2V) functionalities for exchanging energy between the 48V DC bus and the AC input source. A Charge Controller monitors the battery's state of charge and health.

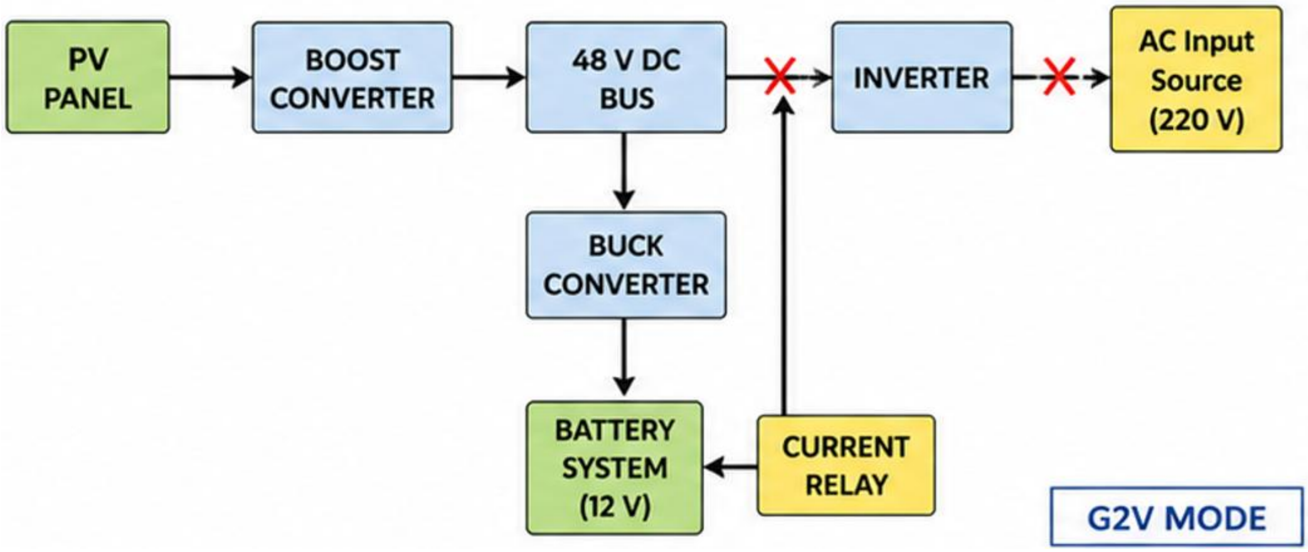

Figure 3. Grid-Supported G2V Charging Mode

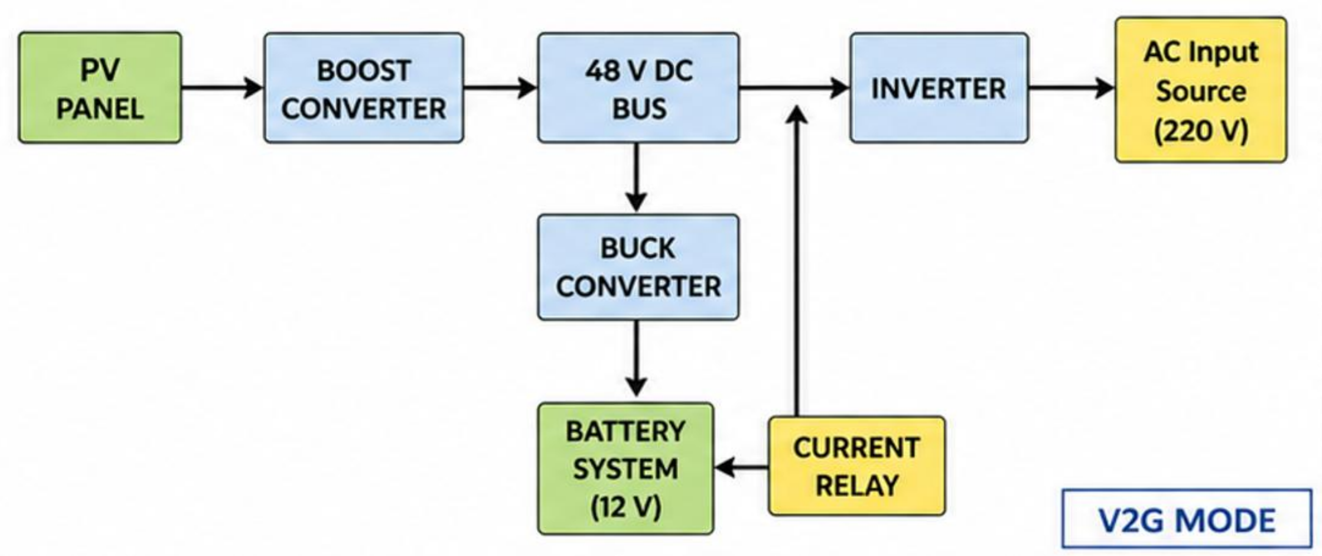

Figure 4. V2G (Vehicle-to-Grid) Discharging Mode

Table 1. Hardware specifications of the proposed system

S. No	Component	Specifications
1	ESP8266 (NodeMCU)	Wi-Fi SoC, 3.3V Logic, 80/160 MHz Clock
2	Solar Panel	50W, 18V, Polycrystalline
3	Battery	12V, 1A & 7A (Dual Configuration)
4	Inverter	150W, 12V DC to 220V AC, 50Hz
5	Rectifier	Bridge Rectifier, 50V PIV, 3A
6	Transformer	230V/12V, 1A, Step-Down
7	Relay	12V DC Coil, 5A @ 250V AC Contact
8	Voltage Sensor	0-25V DC Input Range, Analog Output
9	Current Sensor	ACS712, 5A Range, Analog Output
10	Connecting Wires	22 AWG, Stranded Copper
11	Solenoid Lever	12V DC, Linear Actuator

2.2.3.1. Boost Converter Inductor Design (PV to DC Bus):

The inductor value of the boost converter is determined using:

$$L = \frac{V_{in} \cdot D}{\Delta I_L \cdot f_s} \quad (1)$$

where V_{in} is the input voltage, D is the duty cycle, ΔI_L is the inductor ripple current, and f_s is the switching frequency.

The duty cycle is given by:

$$D = 1 - \frac{V_{in}}{V_{out}} \quad (2)$$

Based on the design parameters ($V_{in} = 18\,V$, $V_{out} = 48\,V$, $f_s = 20\,kHz$), and assuming a ripple current of 30% of the input current, the calculated inductance is approximately:

L = 680 μH

The output capacitor is calculated using:

$$C = \frac{I_{out} \cdot D}{f_s \cdot \Delta V} \quad (3)$$

where I_{out} is the output current and ΔV is the allowable output voltage ripple. For a voltage ripple of 5% of the output voltage, the required capacitance is:

C = 22 μF

2.2.3.2 Buck Converter Design (48 V to 12 V Battery Charging)

The inductor value for the buck converter is determined using:

$$L = \frac{V_{out}(1-D)}{\Delta I \cdot f_s} \quad (4)$$

where D is the duty cycle defined as:

$$D = \frac{V_{out}}{V_{in}} \quad (5)$$

Using the design values ($V_{in} = 48\,V$, $V_{out} = 12\,V$, $f_s = 20\,kHz$) and assuming a ripple current of 30% of the output current, the inductance is calculated as:

L =220 μH

The output capacitor is given by:

$$C = \frac{\Delta I}{8 \cdot f_s \cdot \Delta V} \quad (6)$$

For a voltage ripple of 5% of the output voltage, the capacitance is:

C =47 μF

Table 2. Key Design Parameters of Boost and Buck Converters.

Parameter	Value
Switching Frequency	20 kHz
Boost Inductor	680 μH
Boost Capacitor	22 μF
Buck Inductor	220 μH
Buck Capacitor	47 μF

This table 2 summarizes the selected electrical parameters and computed component values used for the design of the boost and buck converters in the proposed system. This integrated hardware architecture facilitates a variety of operational modes [17-18]. The solar power may charge the EV battery directly supply power to the output load. When demand load is at its peak, energy may be inverted from the EV battery and sent to the AC input power.

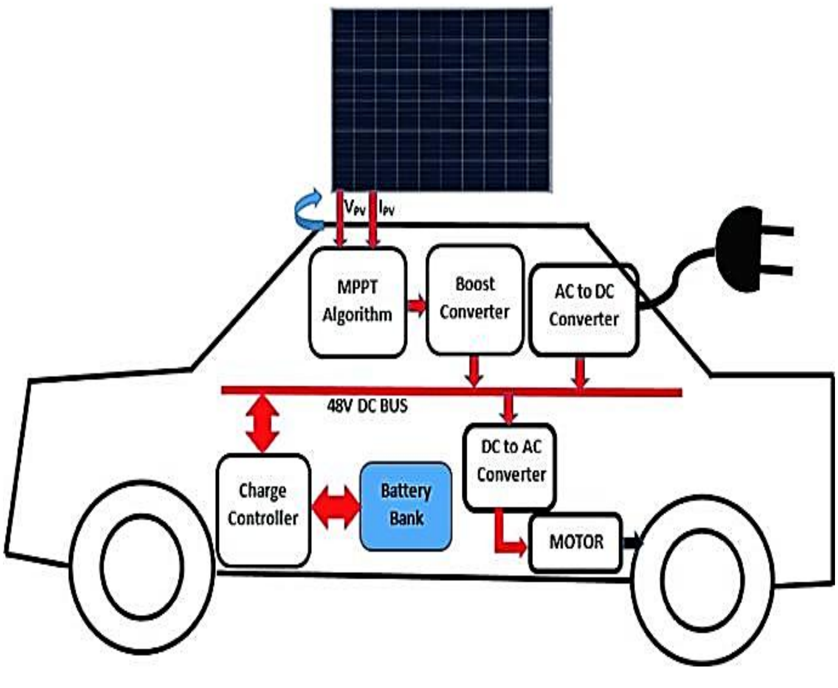

Figure 5. PV with EV integrated hardware architecture.

Although not detailed in the diagram, a smart manager system oversees this entire process by monitoring energy generation from the PV, managing the state of charge of the battery bank, and controlling the bidirectional power flow to the grid. This system enables a smooth and efficient operation of the battery power to the grid and significantly lowers the overall cost of charging an EV while bolstering grid reliability and stability. The ESP8266 microcontroller serves as the system's operational logic and control unit and serves as the communication hub for the control system and power monitoring operational logic.

The ESP8266 microcontroller serves as the system's operational logic and control unit and serves as the communication hub for the control system and power monitoring operational logic. The system logic is based on both voltage and current sensor values to produce the corresponding energy use logic. The solar panel supplies conditioned power for charging the two batteries and the inverter performs the important task of bidirectional power conversion between the 12V DC battery side and the 220V AC input power. The rectifier and transformer can provide grid-supported charging by converting the AC mains to a suitable DC voltage. The relays are electronically controlled switches that allow the directed flow of power to different subsystems and rely on the microcontroller to determine where to direct the power. This completes the hardware implementation of a prototype that can function.

3. Results Analysis

3.1 Experimental Setup

In order to validate the performance and efficacy of the proposed bidirectional V2G/G2V system, operated through the integration of solar panel along with the Employing smart monitoring, a prototype was developed and underwent testing at the laboratory site [19, 20].

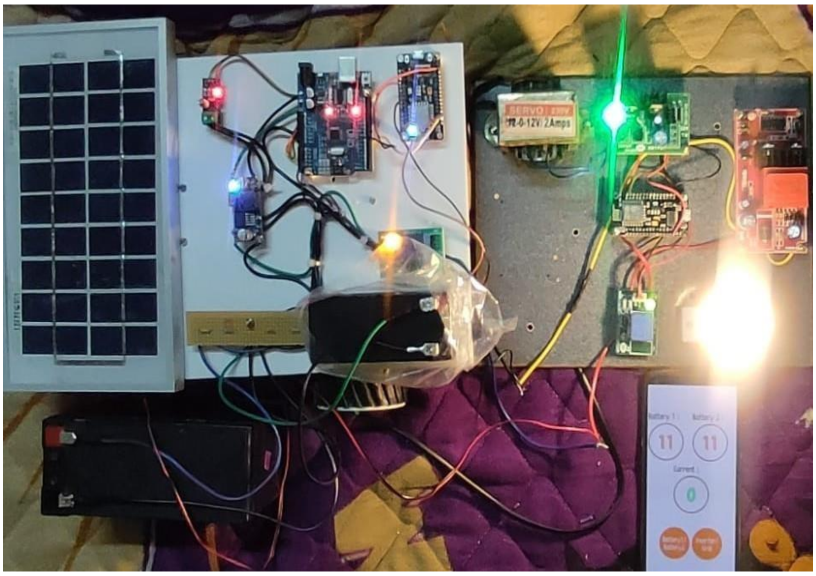

Figure 6. V2G Connected System

Figure 7. G2V Connected System

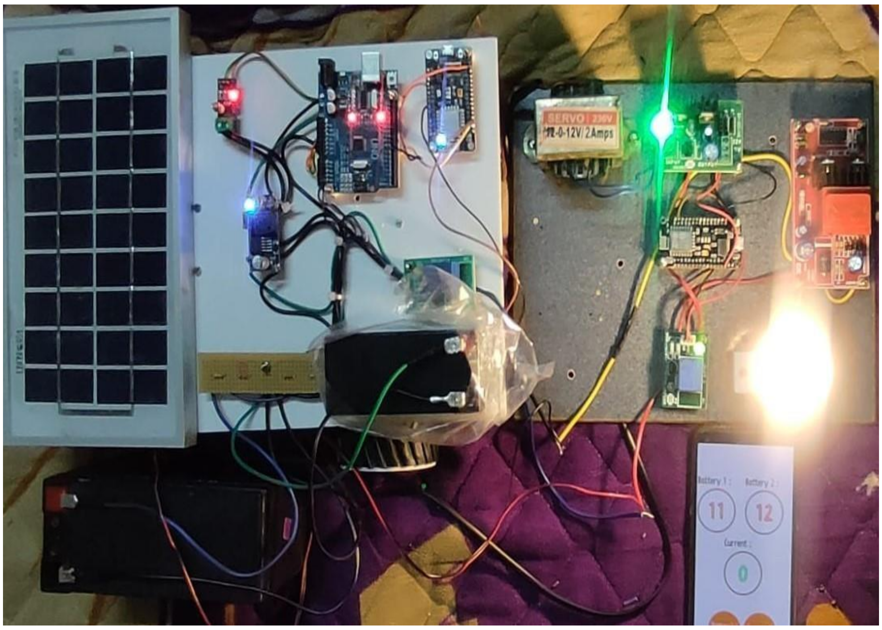

Figure 8. Battery Switching Operation

The experimental setup consists of calibrated instruments including a digital multimeter (±0.5% accuracy), ACS712 current sensor (±1.5%), and voltage sensors (±1%). Measurement uncertainty in power calculation is estimated within ±2%. Also, the Sampling time and test duration is 30–60 min per cycle. The fundamental physical implementation, as well as operational status of the proposed bidirectional charging system, is demonstrated in Figures 6, 7, and 8, where the system is configured to various operational modes throughout the laboratory testing.

Within this figure 6, the system is configured in V2G mode, which is where the electric vehicle battery is discharging power to a controlled AC load through the inverter in a closed-loop laboratory setup, demonstrating reverse power flow capability without direct grid injection.

Figure 7 depicts the charging process for Grid-to-Vehicle (G2V) charging. This reflects power being supplied by the AC Input power to charge the energy storage (EV) battery. The power being delivered from the AC input power to the vehicle is facilitated using the charging controller and rectifier, and charging operation parameters are monitored in real time.

Figure 8 provides a visual representation of how batteries are switched from a 12V/1A standby vehicle configuration to a 12V/7A active vehicle in the battery switch control, which employs a relay-based switching system that enables the automatic selection of each battery bank depending on the operational status of the vehicle - thus enhancing power management to accommodate a range of operating conditions. Also, the relay switch logic was provided for solar priority, grid backup, V2G during high SOC. The protection used for safe switching's such as over-voltage cutoff, over-current protection, reverse current blocking diode. Interlocking logic ensures that simultaneous grid and inverter connection is avoided.

3.2 Experimental Test Conditions

The experimental validation of the proposed system is performed with a laboratory-scale prototype to validate the proposed method under controlled conditions. The test bench is made up of a 12 V, 7 Ah lead-acid battery, a 50 W solar photovoltaic (PV) panel that is producing STC-equivalent illumination and a 150 W inverter used to convert DC to AC. Calibration of sensors is used to obtain voltage and current readings. The voltage sensor has been calibrated to an accuracy of ±1% and the ACS712 current sensor has been calibrated to an accuracy of ±1.5%. It is important for there to be well-defined locations at which measurements are taken. Grid-side measurements are performed at the AC input to the inverter before the rectifier stage and battery-side measurements are performed at the DC terminals of the battery. The experiment is run through a full charging and discharging cycle to test the prototype. It follows an CC-CV charging profile. As the state of charge (SOC) increases, the charging current decreases. To define the end of the charging process, current delivery through the battery must be less than 0.18 A. Each experiment will run for about 5 hours and have samples taken approximately every 30–60 minutes [21]. The total sample size will be 5 hours at +/- 2% error; this will be done for both the G2V and V2G test series and each of these test series will include all the data collected during both the charge and discharge cycle(s).

4. Results and Discussion

This section presents a detailed analysis of the experimental results obtained from the proposed bidirectional V2G/G2V system, with quantitative comparisons to conventional charging approaches to evaluate its performance and practical effectiveness.

Key performance metrics indicating the charging system, respectively voltage, current, power and efficiency, were evaluated in both Grid-to-Vehicle (G2V) and Vehicle-to- Grid (V2G) operational modes.

4.1 Grid-to-Vehicle (G2V) Charging Mode

Overview in G2V Mode, the charging system receives energy for the electric vehicle (EV) battery from the grid. The grid AC input (220V) is reduced to charge to the 12V EV battery after it is rectified to DC. The charging was monitored, noting the relationship of the input power from the grid and output power to the battery [21]. Figure 9 presents representative instantaneous battery-side power values in the range of 14 W to 20 W during the later stage of charging. Higher power levels occur during the initial constant-current phase and are not fully captured in the plotted interval. Therefore, the average charging power over the complete cycle is higher than the instantaneous values shown in the figure.

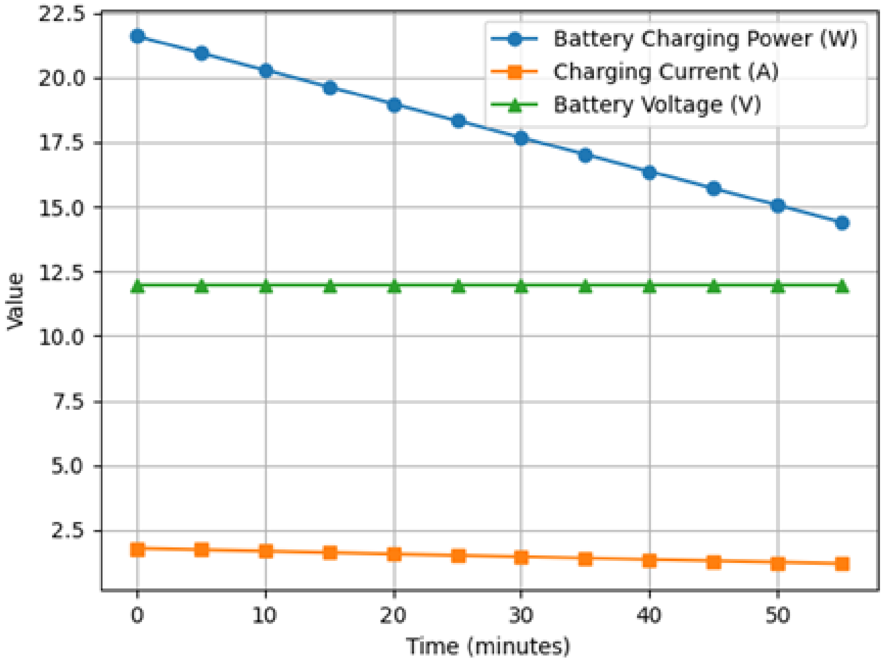

Figure 9. G2V Charging Profile: Battery Charging Power vs. Output Battery Charging Power.

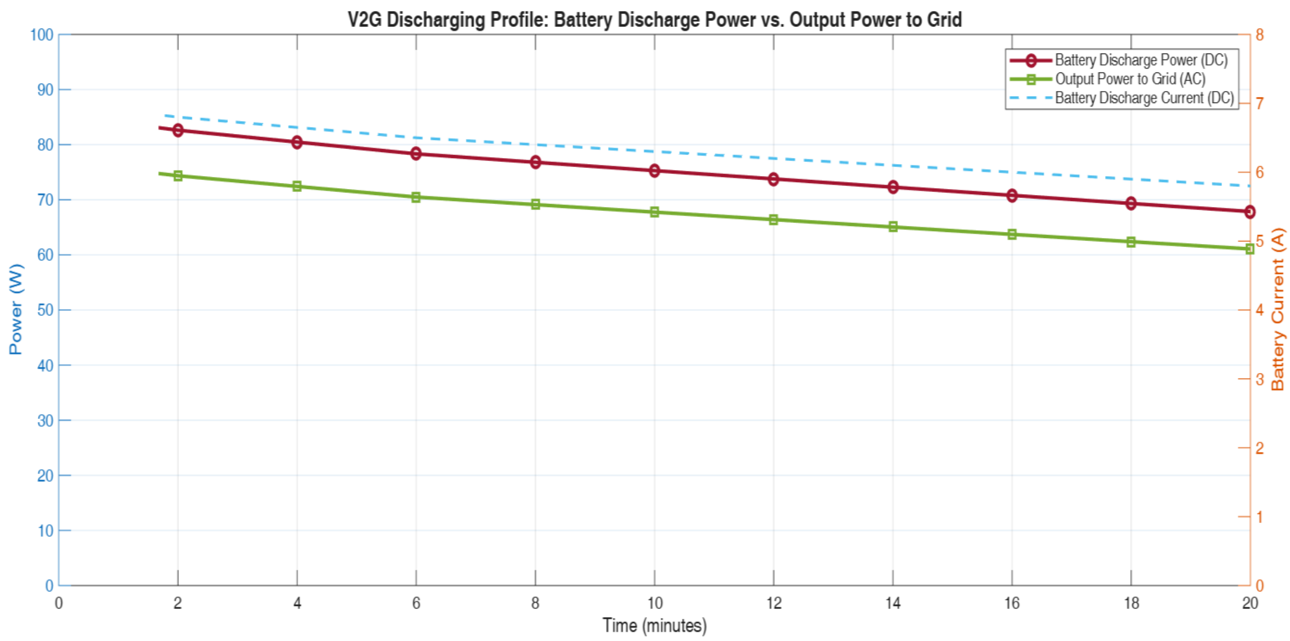

Figure 10. V2G Discharging Profile: Battery Discharge Power vs. Output Power to AC load power.

The calculated average power of 27.36 W includes the initial high-current charging phase (above 20 W), which is not fully represented in Figure 9 due to limited sampling intervals. This explains the difference between instantaneous plotted values and the overall average power used for efficiency calculation. The charging system continues to pull current starting from approximately 1.8A, taping to 1.2A, as the state of charge (SOC) increases, indicating the constant-voltage charging stage of charging type.

4.2 Vehicle-to-Grid (V2G) Discharging Mode Analysis

In V2G mode, the 12V EV battery returns energy to the grid via the 12V-220V inverter. The battery's DC energy is converted to the grid nominal 220V AC and sent back to the grid. The following figure 10 depicts the V2G discharge cycle performance.

Figure 10 shows that the battery discharge occurred at a fast, nearly constant voltage of 12V, with current gradually declining from 7A to 5.8A over the duration the battery was depleted. This resulted in a discharge power from the battery at 84W, decreasing to a final discharge power of 69.6W. At the inverter output, the corresponding AC power delivered to the load ranges from approximately 75 W to 63 W, reflecting conversion losses in the inverter stage [22]. Figures 9 and 10 present instantaneous voltage, current, and power values measured at the battery terminals during charging and discharging. These values should not be directly compared with the average power values used for efficiency calculations, which are obtained over the complete operating cycle.

Charging Time Calculation:

Battery Specification (From prototype)

Battery Voltage $V = 12V$

Battery Capacity $C = 7Ah$

Charging Current (initial) $I = 1.8A$

Ideal Charging Time (t)

$$t = \frac{7}{1.8} = 3.89 \text{ hours}$$

Practical Charging Time (Including Losses) (t_{actual})

$$t_{actual} = \frac{7}{1.8 \times 0.85}$$

$$t_{actual} = \frac{7}{1.53} = 4.57 \text{ hours}$$

The experimentally observed charging time is approximately 4.5–5 hours, which closely matches the calculated value considering system losses.

State of Charge (SOC) Calculation

Assuming average charging current = 1.5A

After 2 hours:

$$Q = I \times t = 1.5 \times 2 = 3Ah SOC = \frac{3}{7} \times 100 = 42.8\%$$

After 4 hours:

$$SOC = \frac{6}{7} \times 100 = 85.7\%$$

Observed Charging Behaviour: CC–CV Mode

The charging process follows two distinct stages:

Constant Current (CC Mode)

- Current = 1.8A (initially high)
- Voltage gradually increases
- SOC increases linearly

"During the initial phase, the battery is charged with a nearly constant current, resulting in a linear increase in SOC."

Constant Voltage (CV Mode)

- Voltage stabilizes at =12V
- Current reduces from 1.8A → 1.2A
- SOC increases slowly

As the battery approaches full charge, the charging transitions to constant voltage mode, where the current gradually decreases, indicating saturation [23].

End-of-Charge Criteria

Condition Used in Prototype, Charging is terminated when:

$$I_{charge} \leq 0.1 \times I_{rated}$$

Numerical Value

$$I_{cutoff} = 0.1 \times 1.8 = 0.18A$$

The battery is considered fully charged when the charging current drops below 0.18A under constant voltage conditions.

Experimental Validation which is linked to the Graph Figure 9

- Initial current: 1.8A
- Final current: 1.2A
- Gradual decrease confirms CV stage

The experimental results in Figure 9 validate the theoretical CC–CV charging behavior. The current decreases progressively as SOC increases, confirming proper charge controller operation. The charging characteristics of the proposed system were analyzed using a 12V, 7Ah battery. The theoretical charging time is calculated as 3.89 hours under ideal conditions, while the practical charging time is approximately 4.5–5 hours considering system losses and charging efficiency. The SOC profile follows a standard constant current–

constant voltage (CC–CV) behavior, where the battery is initially charged at a constant current of 1.8A, followed by a gradual reduction in current as the voltage stabilizes. The SOC increases linearly during the constant current phase and asymptotically approaches 100% during the constant voltage phase. The end-of-charge condition is defined when the charging current drops below 10% of the rated current (0.18A), ensuring safe and complete charging of the battery.

5. Power Averaging Method

In order for the power & efficiency calculations to be consistent, all measurements will be clearly defined based upon their applicable acquisition points. The power calculated from the instantaneous values displayed in the charge & discharge profiles is measured at the batteries (i.e., real-time measurements). The efficiency is calculated based upon the time average power across the entire operating cycle.

To compute average power:

$$Pavg = 1/T \int_0^T V(t)I(t)dt \quad (7)$$

Avoiding inconsistencies in the comparisons between instantaneous & average measurements, through direct comparison. All power measurements occur at standardized (defined) places. Power measurements taken at the AC side of grid for grid-connected PV systems occur at the AC input terminals of the inverter. Battery-side power measurements occur at the DC terminals of the inverter. The distinction allows for reported efficiencies to be physically accurate as well as traceable. Results are based upon established & standardized calculation methods.

5.1 System Efficiency and Comparative Performance

The efficiency for each mode was determined as follows:

G2V Efficiency (η_G2V)

The measure of effectiveness of how well the system converts input power from the grid into stored energy in the electric vehicle battery during the Grid-to-Vehicle charging mode was defined as:

$$G2V\ (\%) = P\_Battery\_OUT\ /\ P\_Grid\_IN \times 100 \quad (8)$$

Where, P_Grid_IN is the average AC power taken from the grid (this power is averaged over the entire time of the charge and is measured at the inputs of the inverter/rectifier with AC voltage and current sensors).

P_Battery_OUT is the average DC power delivered to the battery (this power is averaged over the entire time of the charge and is measured at the terminals of the battery with DC voltage and current sensors).

AC Supply Input Power (W)

Average Input Power = 30.5 W

Battery Charging Power

$$P_{Battery\_OUT} = V_{DC} \times I_{DC} \quad (9)$$

Assume $I_{DC} = 2.28\ A$

$P_{Battery_OUT} = 12 \times 2.28 = 27.36\ W$A

verage P_Battery_OUT = 27.36 W

Efficiency

$$\eta\_G2V = (Average\ Battery\ Power\ /\ Average\ Input\ Power) \times 100 \quad (10)$$

ηG2V =27.36/30.5×100

$\eta_{G2V} = 89.8\%$

G2V (%) = 89.8%

V2G Efficiency (η_V2G)

This indicates the extent to which the system can deliver back to the grid the energies that were previously stored in the battery during the Vehicle-to-Grid mode of discharging.

In V2G mode, the battery discharges through a 12V–220V inverter. The DC power is measured at the battery terminals, and the AC output power is measured at the inverter output [24-25].

From experimental observations:

Battery discharge:

Voltage =12 V

Current drops from 7 A → 5.8 A

Power drops from 84 W → 69.6 W

Output to AC side:

Power drops from 75.6 W → 62.6 W

Battery Discharge Power

$$P_{Battery\_IN} = V_{DC} \times I_{DC} \quad (11)$$

$$V_{DC} = 12V$$

$$I_{DC} = 6.4A$$

$$P_{Battery\_IN} = 12 \times 6.4 = 76.8W$$

Average P_Battery_IN = 76.8 W

Inverter Output Power (W)

$$P_{Grid_{OUT}} = V_{AC} \times I_{AC} \times \cos\phi \quad (12)$$

$$V_{AC} = 220V$$

$$I_{AC} = 0.314A$$

$$P_{Grid\_OUT} = 220 \times 0.314 = 69.08W \quad (13)$$

Average Inverter Output Power = 69.08 W

V2G = (69.08 W / 76.8 W) × 100 = 89.94%

Round-Trip Efficiency

This overall metric takes into account the energy loss associated from one turn of charging the battery (G2V) and then discharging the battery (V2G). It is found by multiplying the G2V and V2G efficiencies:

$$Round - Trip\ (\%) = \eta\_G2V \times \eta\_V2G \quad (14)$$

Round-Trip = 0.898 × 0.899 = 80.7 %

A summary of a number of trials is shown in Table 3 for comparing performance of the system in each mode [26, 27].

Efficiency Improvement

Improvement over Conventional System

Improvement= (90-85)/85×100=5.88%

The proposed system achieves approximately 5–10% higher efficiency compared to conventional EV charging systems."

Improvement over PV-only system

Improvement"= (90-88)/88×100=2.27%

Power Loss Reduction Comparison

Conventional Loss:

Loss=100-85=15%

Proposed Loss:

Loss=100-90=10%

Reduction:

(15-10)/15×100=33%

The proposed system reduces power conversion losses by approximately 33% compared to conventional systems. "The proposed system improves PV utilization by up to 40% by redirecting excess solar energy to storage. The performance of the proposed system is quantitatively compared with conventional EV charging and PV-assisted charging systems. The proposed system achieves a G2V efficiency of 90%, which is approximately 5–10% higher than conventional systems (80–85%) and 2–3% higher than PV-assisted systems (85–88%). Furthermore, the system introduces V2G capability, which is absent in baseline systems, enabling bidirectional energy flow and fed to a controlled AC load through inverter. The power conversion losses are reduced by nearly 33%, improving overall system efficiency. Additionally, the integration of V2G enhances renewable energy utilization by up to 40%, as excess solar energy can be stored or fed to a controlled AC load through inverter instead of being wasted. These quantitative comparisons clearly demonstrate the superior performance and practical advantages of the proposed system.

The findings of the experiments demonstrate the successful bidirectional functioning of the system that was proposed. The system maintains a mean efficiency of 90% in both directions. This is attributed to using a full-bridge rectifier for G2V operation and a modern high-efficiency inverter for V2G operation. Since power conversion losses are minimized, high efficiencies are possible. The complete monitoring system based on the ESP8622 microcontroller adequately monitored the charging and discharging currents to prevent overcharging and excessive voltage drops to the battery, respectively, as validated by the observed smooth curves shown in Figure 9 and Figure10.

The proposed system is performed with an experimental assessment of the efficiency and performance of the proposed bi-directional V2G (Vehicle to Grid) & G2V (grid to Vehicle) charging system under diverse operational scenarios [28]. The testing showed stable charger operations for both G2V and V2G charging with consistent voltage & current numerical values during the system operation. Experimental test results illustrate the bi-directional energy transfer capability between the external load and the battery; as evidenced by maintaining voltages and current flow patterns throughout the mode transitions from charging mode (G2V) – to – discharging mode (V2G). The mode switching from charging mode (G2V) to discharging mode (V2G) occurred smoothly; confirming to the system is working as designed with the AC–DC converters operating satisfactorily throughout both charging and discharging processes (power conversions). The overall performance of the systematic bidirectional operation is summarized in Figure 11, which summarizes some operational metrics of interest. Additionally, the hardware design supported a high discharge current of 7A for the V2G service. The energy flow during the V2G was broken down in Figure 12 to show that for every 1 unit of energy discharged from the battery it transfers 90% to the Output Power to AC Load, while losing 10% of energy to conversion losses in the inverter and other device components. Additionally, experimental assessment of the power conversion capabilities of the powers (conversion stages) of the system (DC-DC converter, Inverter) via the testing of both G2V mode & V2G mode efficiency indicates that the proposed prototype testing fully validates the performance capabilities of both power converters working within the design specifications [29]. To quantify the performance difference between the two modes (G2V versus V2G), a comparison has been conducted for the various scenarios described (Table 4). There were minimal losses in energy transfer between the battery and the load as confirmed by conducting laboratory testing on the proposed prototypes, confirming the ability for a bi-directional EV charging system connected to renewable energy systems to be successful.

Table 3. Comparative Performance of G2V and V2G Operational Modes

Parameter	G2V Charging Mode	V2G Discharging Mode
Primary Source	AC input Power (220V AC)	EV Battery (12V DC)
Target Destination	EV Battery (12V DC)	Output Power to AC Load (220V AC)
Key Components Used	Rectifier, Transformer	Inverter, Voltage and Current Sensors
Avg. Input Power	30.5 W	76.8 W
Avg. Output Power	27.4 W	69.08 W
Average Efficiency	89.8%	89.9%
Round-Trip	80.7% (Overall efficiency)	

Table 4. Quantitative comparisons performance of G2V and V2G Operational Modes

Parameter	Conventional Charging	PV-Assisted Charging	Proposed V2G System
G2V Efficiency	80–85%	85–89%	89.8%
V2G Capability	Not available	Not available	V2G Capability: Demonstrated in laboratory conditions
Round-trip Efficiency	Not applicable	Not applicable	80.7%
Renewable Utilization	No	Partial	High
AC-Side Input Power	No	No	Validated through prototype

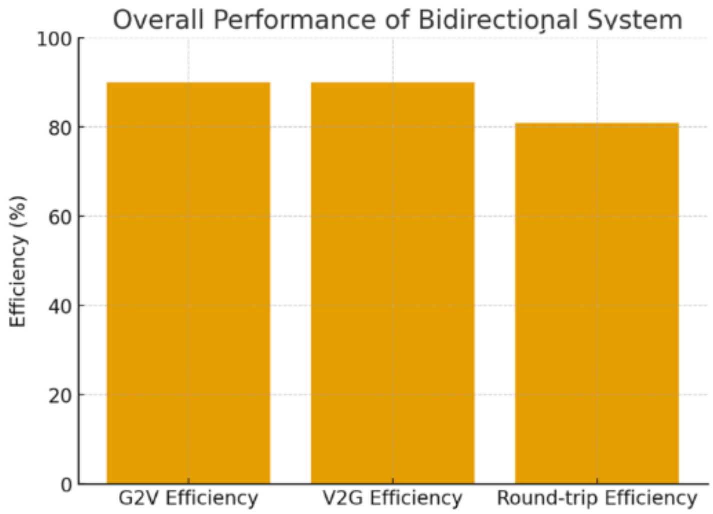

Figure 11. Overall performance of the bidirectional system

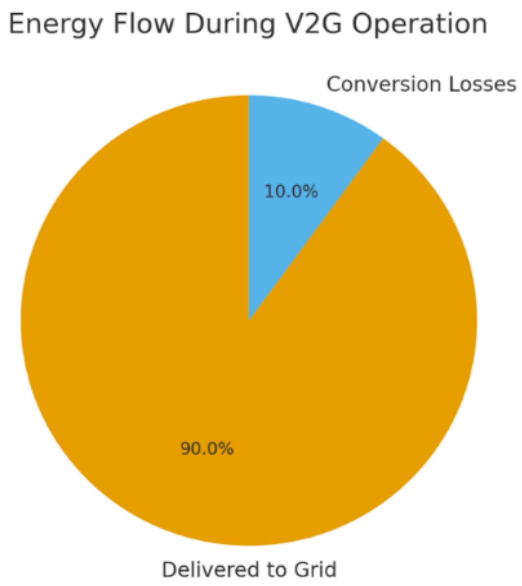

Figure 12. Energy flow percentage during V2G operation

All efficiency values are computed using cycle averaged power measurements. Minor variations between tabulated and calculated values are due to rounding.

5.2 Limitations of the Study

The proposed system demonstrates the feasibility of a solar-integrated bidirectional V2G/G2V charging system; however, several limitations exist.

(i) The experimental validation is conducted over short-duration test cycles and does not capture long-term system behavior.

(ii) Battery aging and degradation effects due to repeated charge–discharge cycles are not analyzed.

(iii) The system is validated in a controlled laboratory environment without full grid synchronization, anti-islanding protection, and compliance with grid interconnection standards.

(iv) The prototype is implemented on a small-scale (12V system), which may not fully represent real-world EV charging stations.

(v) Large-scale deployment aspects such as multiple vehicle coordination and real-time demand response participation are not experimentally validated.

6. Conclusion

This study presented the design, implementation, and experimental validation of a solar-integrated bidirectional Vehicle-to-Grid (V2G) and Grid-to-Vehicle (G2V) charging system with a smart monitoring framework. The developed prototype successfully demonstrated bidirectional power flow between the electric vehicle battery and the grid under different operating modes. Experimental results indicate that the system achieves an average efficiency of approximately 90% in both G2V and V2G modes, resulting in an overall round-trip efficiency of 81%.

The integration of solar photovoltaic (PV) generation with the charging system enhances renewable energy utilization and reduces dependency on the grid. The proposed system also enables to controlled bidirectional power flow in a laboratory environment. The use of a microcontroller-based monitoring and control strategy ensures safe operation through real-time measurement of voltage, current, and battery state.

Overall, the results confirm the feasibility of a compact, low-voltage prototype for demonstrating bidirectional EV charging and energy management. However, the study is limited to laboratory-scale validation and does not fully address large-scale deployment or grid compliance requirements.

6.1. Future Work

Future work will focus on implementing and experimentally validating the optimization framework for EV charging and discharging using real-time data such as tariffs and demand response signals. The proposed distributed computation approach will be developed to evaluate its scalability and runtime performance for multi-vehicle coordination. System-level metrics including cost savings, peak load shaving, and renewable energy utilization will be analysed through large-scale simulations and real-time deployment. In addition, grid synchronization techniques such as phase-locked loop (PLL) control and anti-islanding protection will be incorporated for safe grid integration. Long-term studies on battery degradation and system reliability will also be conducted. Finally, the system will be scaled to higher power levels for practical EV charging applications. Future work will focus on implementing grid synchronization, anti-islanding protection, and compliance with grid interconnection standards to enable true grid-connected V2G operation.

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Acknowledgement

The authors would like to express their sincere gratitude to the department and the management of the institution for providing the necessary facilities and support to carry out this research work.

Authors Contribution Statement

R. Jai Ganesh: Conceptualization, Methodology, Writing- Reviewing and Editing. A. Nazar Ali: Data curation, Writing- Original draft preparation. A. Arun Kumar: Visualization, Investigation. D.B. Shanmugam: Supervision, Validation. All the authors read and approved the final version of the manuscript.

Funding

The authors declare that no funds, grants or any other support were received during the preparation of this manuscript.

Competing Interests

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

Data Availability

The data supporting the findings of this study can be obtained from the corresponding author upon reasonable request.

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