A Three-Port Bidirectional DC-DC Converter with G2V and V2G Power Flow Capabilities

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***Abstract*— The rapid adoption of electric vehicles (EVs) and renewable energy sources has increased the need for compact and efficient power electronic interfaces capable of managing multiple energy sources with bidirectional power flow. Conventional EV charging systems use separate converters for PV generation, battery storage, and grid interfacing, leading to higher cost, losses, and complexity. This work presents a battery-integrated three-port bidirectional DC–DC converter for light electric vehicles with grid-to-vehicle (G2V) and vehicle-to-grid (V2G) capability. The proposed non-isolated topology integrates PV, battery, and a low-voltage DC grid in a single converter. MATLAB/Simulink simulations validate multiple operating modes, stable DC bus regulation, and seamless bidirectional power transfer, offering an efficient solution for PV-assisted EV charging applications.**

***Index Terms*— Three-port converter, Bidirectional DC–DC converter, EV charging, PV integration, MPPT, SOC-based mode selection, V2G, G2V, LVDDS**

I. INTRODUCTION

Global efforts to reduce carbon emissions and improve energy efficiency are accelerating the transition toward electric vehicles (EVs). As EV adoption increases, the demand for reliable and efficient charging infrastructure is also growing. Conventional EV chargers are mainly unidirectional, transferring energy only from the grid to the battery, which can increase grid stress during peak demand. To address this, bidirectional charging concepts such as grid-to-vehicle (G2V) and vehicle-to-grid (V2G) have gained attention, enabling EV batteries to support the grid as distributed energy storage. In addition, integrating photovoltaic (PV) systems with EV charging allows direct utilization of renewable energy and reduces dependence on the conventional grid. However, the intermittent nature of PV generation requires energy storage and coordinated control to ensure continuous operation. Traditional PV-assisted charging architectures often use multiple independent converters for PV, battery storage, and grid interfacing, increasing system complexity, cost, and losses. Multi-port DC–DC converters provide a compact alternative by integrating multiple energy ports within a single conversion stage, reducing component count and improving efficiency.

Battery-integrated three-port bidirectional DC–DC converters are particularly suitable for light electric vehicle applications in low-voltage DC systems, as they enable coordinated power exchange among PV, battery, and DC grid while supporting both G2V and V2G operation.

Hannan et al. reviewed hybrid electric vehicle technologies and highlighted major challenges such as battery degradation, low energy density, system complexity, and inefficient power conversion. The study emphasized the need for compact and flexible converters capable of coordinating bidirectional power flow[1]. Yilmaz and Krein surveyed EV battery charger topologies and showed that many existing systems rely on cascaded converter stages, increasing losses, component count, and control complexity, particularly for bidirectional charging[2].

Jiang et al. presented a bidirectional DC–DC converter for grid-to-vehicle (G2V) and vehicle-to-grid (V2G) operation, validated through simulation and experiments, but the work was limited to two-port energy exchange without renewable integration[3]. Bhattacharya et al. proposed an isolated multiphase bidirectional flyback converter, achieving bidirectional operation but suffering from higher switching losses and transformer stress, limiting scalability[4]. Zhu et al. introduced a non-isolated three-port converter integrating PV, battery, and load with independent power regulation, demonstrating reduced conversion stages but lacking galvanic isolation[5]. Zhang et al. developed variable-structure non-isolated three-port converters with wide operating range, but with increased control complexity[6].

Iram et al. presented a comprehensive review of three-port DC–DC converters (TPCs), classifying topologies into non-isolated, isolated, hybrid, and application-specific structures while analyzing associated control strategies such as MPPT, droop, predictive, and AI-based methods. The study identified key research gaps in scalability, battery health integration, lightweight control implementation, and grid-standard compliance for EV and LVDC applications[7]. Al-Soeidat et al. proposed a compact three-port converter for PV–battery integration, though validated only at low power[8]. Deihimi and Mahmoodieh analyzed battery-integrated DC–DC converters and highlighted stability challenges due to strong port coupling, stressing the importance of coordinated control[9].

From existing studies, it is observed that many works focus either on two-port bidirectional converters or specific three-port configurations without addressing a scalable and coordinated solution for EV charging with renewable integration. Cascaded architectures increase losses and complexity, while non-isolated three-port converters offer compactness but raise safety concerns due to lack of isolation. Additionally, many control approaches increase computational burden, and comprehensive coordinated control under dynamic conditions remains limited. Experimental validation at higher power levels is also insufficient. These gaps motivate the development of a compact three-port bidirectional converter with simplified coordinated control suitable for practical PV-assisted EV charging with G2V and V2G operation.

II. SYSTEM ARCHITECTURE

LOW VOLTAGE DC DISTRIBUTION SYSTEM

Traditional power distribution systems are predominantly based on AC networks. However, in applications involving photovoltaic (PV) sources, batteries, and electric vehicles (EVs), most sources and loads inherently operate in the DC domain. Employing AC distribution in such systems introduces multiple AC–DC and DC–AC conversion stages, resulting in increased power losses, higher system complexity, and reduced efficiency. A Low Voltage DC Distribution System (LVDDS) is a power distribution architecture in which electrical energy is generated, distributed, and utilized in DC form at voltage levels typically below 100 V. LVDDS eliminates unnecessary power conversion stages, making it well suited for renewable energy sources, energy storage systems, and EV charging applications. As shown in Fig. 1, the LVDDS acts as a common DC power backbone interconnecting PV sources, battery storage, DC loads, and EV charging interfaces through DC–DC converters. Multiple PV sources are connected to the LVDDS via individual DC–DC converters that regulate the PV output and inject power into the DC bus while allowing independent PV operation. The low-voltage DC grid consists of positive and negative rails, with a DC bus capacitor connected across the grid to stabilize the bus voltage and absorb transient power fluctuations. DC loads are supplied through dedicated DC–DC converters to ensure regulated voltage and power delivery irrespective of DC bus variations.

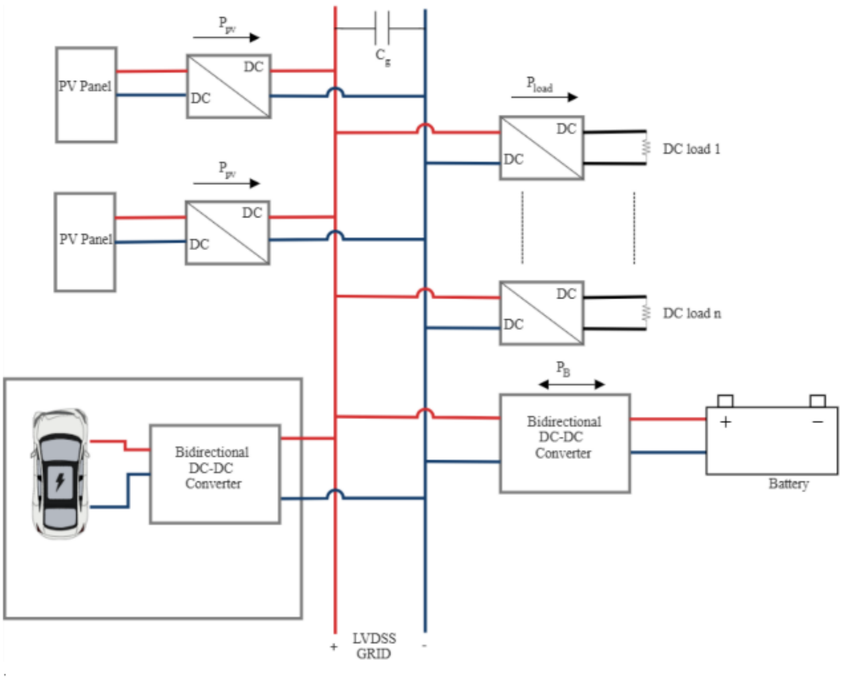


Fig. 1 Typical Architecture of LVDDS with multiple sources

Battery energy storage is interfaced with the LVDDS through a bidirectional DC–DC converter, enabling controlled charging and discharging. This allows excess PV energy to be stored or battery energy to be supplied back to the DC grid when required. Similarly, the electric vehicle is connected to the LVDDS via a bidirectional DC–DC converter, supporting grid-to-vehicle (G2V) operation during charging and vehicle-to-grid (V2G) operation during discharge. In this work, the LVDDS is modeled as a low-voltage DC grid connected across a DC bus capacitor, with the DC bus voltage maintained at 48 V through coordinated operation of the PV and battery ports using the proposed three-port converter. The LVDDS operates as the load during PV-to-grid and battery-to-grid modes, as the source during grid-to-battery (G2V) operation, and as a stable DC voltage reference for power flow control.

BLOCK DIAGRAM OF BATTERY INTEGRATED THREE-PORT BIDIRECTIONAL DC-DC CONVERTER

The proposed system consists of a battery-integrated three-port bidirectional DC–DC converter interfacing a photovoltaic (PV) source, a battery energy storage system, and a low-voltage DC distribution system (DC grid). Fig. 2 illustrates the functional interconnection of these subsystems along with the associated control unit. The PV panel acts as the primary renewable energy source supplying DC power to the converter, while the battery provides energy storage and enables bidirectional operation, supporting both grid-to-vehicle (G2V) charging and vehicle-to-grid (V2G) discharging. The DC grid represents the low-voltage DC distribution system supplying power to connected DC loads or charging infrastructure.

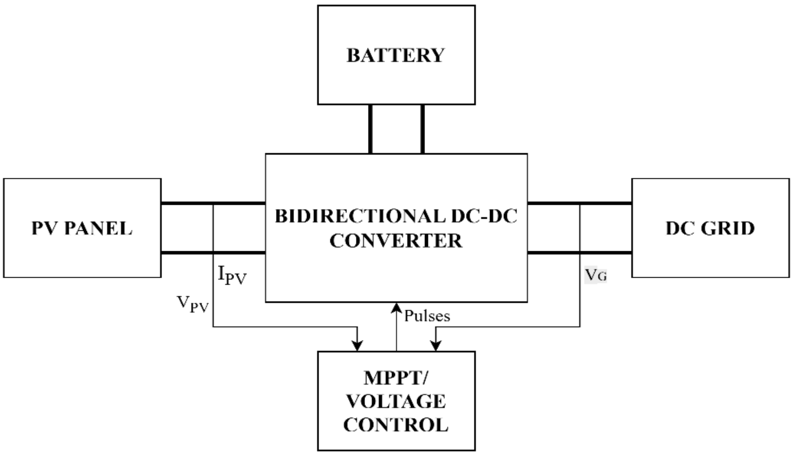


Fig. 2 Block diagram of Battery Integrated Bidirectional Three-Port DC-DC Converter(BIBTPC)

The bidirectional DC–DC converter serves as the core power processing unit, enabling controlled energy exchange among the PV source, battery, and DC grid. An MPPT and voltage control block generates the required control signals for the converter switches. During PV-dominant operation, the MPPT algorithm ensures maximum power extraction from the PV source, while the voltage control loop regulates the DC bus voltage to a predefined reference, ensuring stable DC grid operation. Based on system operating conditions, the controller coordinates power flow between the PV source and the battery to maintain power balance. The block diagram highlights the compact and integrated nature of the proposed architecture, in which multiple energy sources and storage elements are interfaced through a single power conversion stage. This integrated approach reduces component count, improves efficiency, and enables bidirectional energy transfer, making the system suitable for PV-assisted electric vehicle charging applications.

III. CIRCUIT CONFIGURATION

The proposed system employs a three-port bidirectional DC–DC converter to interface a photovoltaic (PV) source, a battery energy storage system, and a low-voltage DC grid or load using a single power conversion stage as shown in Fig. 3. This integrated converter topology enables efficient power exchange among the three ports while reducing component count and system complexity.

The PV port is connected to the converter through an inductor L_1, which operates in continuous conduction mode (CCM). This configuration allows voltage boosting from the PV source to the DC bus and facilitates effective maximum power point tracking (MPPT) for optimal utilization of solar energy. The DC grid or load is connected across a common DC bus capacitor, which is responsible for maintaining a stable DC bus voltage. The capacitor absorbs transient power imbalances and ensures smooth power delivery to the connected load. The battery port is interfaced through a low-value inductor L_2 that operates in discontinuous conduction mode (DCM). This operating mode enables pulse-based energy transfer and supports bidirectional power flow, allowing controlled charging and discharging of the battery.

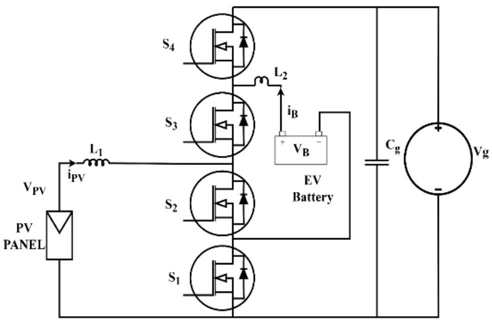


Fig. 3 Circuit Diagram of Three-port bidirectional DC–DC converter

Power flow among the PV source, battery, and DC grid is regulated using four controlled switches (S_1-S_4). By appropriately controlling the duty cycles of these switches, the converter can operate in grid-to-vehicle (G2V), vehicle-to-grid (V2G), and PV-assisted operating modes, ensuring flexible and efficient energy management.

POWER FLOW SCENARIOS OF BIBTPC

The proposed three-port bidirectional DC–DC converter is capable of operating in multiple power flow scenarios depending on the availability of photovoltaic power, battery state, and the power demand of the low-voltage DC distribution system (LVDDS). By appropriately controlling the duty ratios of the converter switches, the system transitions between different input–output configurations such as single-input single-output (SISO), dual-input (DI), and dual-output (DO) modes.

Power flow is governed by duty cycles D_1–D_4 of switches S_1–S_4. Different power flow paths are enabled by duty-cycle combinations. Table 1 shows different duty cycle combinations. The detailed operating scenarios are described as follows. The symbols x_1, x_2 and x_3 used in Table 2 denote control signals applied to the converter switches during different operating modes. These signals correspond to the outputs of three independent regulators employed in the proposed system. Specifically, x_1 represents the output of the PV-side current regulator used for maximum power point tracking, x_2 represents the output of the DC bus voltage regulator, and x_3 represents the output of the battery voltage regulator.

Table 1 Duty Cycle Combinations

Mode	Duty Cycle Condition
PV2G	$D_1 < D_2, D_3 = 0, D_4 = 0$
P2VG	$D_1 > D_2, D_3 = 0, D_4 = 0$
P2G	$D_1 = D_2, D_3 = 0, D_4 = 0$
V2G	$D_1 = 0, D_2 = D_3, D_4 = 0$
G2V	$D_1 = D_4, D_2 = 0, D_3 = 0$

Table 2 Control Signal Assignment for Different Power Flow Modes

Operating Mode	S_1	S_2	S_3	S_4
PV2G	x_1	x_2	0	0
P2VG	x_1	x_2	0	0
P2G	x_2	x_2	0	0
V2G	0	x_2	x_2	0
G2V	x_3	0	0	x_3

These control outputs define the effective duty-cycle applied to the corresponding switches during each operating mode. Depending on the selected operating condition, the appropriate control signal is routed to one or more switches, while the remaining switches are maintained in the OFF state to prevent undesired power circulation. At this stage, the signals are treated as generic control inputs, and the detailed design of the control algorithms used to generate these signals is discussed in a subsequent section. This definition is provided here to facilitate understanding of the switch activation patterns and current flow paths described in the following mode-wise analysis.

1. PV PANEL AND BATTERY TO GRID(PV2G)

This operating scenario occurs when the power generated by the PV panel (P_{PV}) is insufficient to meet the LVDDS grid demand (P_G). In such a condition, the battery assists the PV source in supplying power to the grid, and the converter operates in a dual-input (DI) state. The duty cycle conditions for this mode are: $D_1 < D_2$, $D_3 = 0$, $D_4 = 0$

This scenario ensures uninterrupted power supply to the LVDDS even during reduced solar generation.

2. PV PANEL TO BATTERY AND GRID (P2VG)

When the PV power (P_{PV}) exceeds the grid demand (P_G) the excess energy is utilized to charge the battery while simultaneously supplying the grid. In this case, the converter operates in a dual-output (DO) state. The PV panel acts as the sole input source, and power is split between the DC grid and the battery. This operating mode improves renewable energy utilization by storing surplus solar energy rather than curtailing it. The converter exhibits multiple operating intervals within a switching cycle, and the duty cycle conditions are: $D_1 > D_2$, $D_3 = 0$, $D_4 = 0$.

This mode is particularly useful during periods of high solar irradiance and low grid demand.

3. PV PANEL TO GRID (P2G)

In this scenario, the PV panel alone is capable of meeting the LVDDS grid power demand, and the battery does not participate in power transfer. The converter therefore operates in a single-input single-output (SISO) configuration. Under this condition, the converter behaves as a conventional second-order boost converter, transferring power solely from the PV source to the DC grid. Only two operating modes occur within a switching cycle. The duty cycle conditions are: $D_1 = D_2$, $D_3= 0$, $D_4 = 0$

This mode represents the simplest operating condition with minimal switching activity.

4. BATTERY TO GRID(G2V)

When solar power is unavailable or insufficient, the battery supplies energy to the LVDDS grid, enabling vehicle-to-grid (V2G) operation. In this mode, the converter functions as a boost converter operating in discontinuous conduction mode (DCM) on the battery side. Energy is transferred from the battery to the DC grid in controlled pulses, and three operating modes occur within a switching cycle. The duty cycle conditions for this scenario are: $D_1 = 0$, $D_2 = D_3$, $D_4 = 0$

This operating mode allows the battery to support the grid during peak demand or absence of renewable energy.

5. VEHICLE TO GRID(V2G)

In the grid-to-vehicle (G2V) mode, power is drawn from the LVDDS grid to charge the battery when sufficient grid power is available or when the battery state of charge is low. The converter operates as a buck converter in discontinuous conduction mode, stepping down the DC bus voltage to the battery voltage level.

Power transfer occurs through controlled switching of S_1 and S_4, and the duty cycle conditions are: $D_1 = D_4$, $D_2 = 0$, $D_3 = 0$

Table 3 summarizes the output voltage equations of different power flow paths

Table 3 Output Voltage Equations

Mode	Duty Cycle Condition	Output Voltage Equation
P2G	$D_1 = D_2$	$V_G = \frac{V_{PV}}{1 - D_2}$
P2VG	$D_1 > D_2$	$V_G = \frac{V_{PV}}{1 - D_2}$
PV2G	$D_1 < D_2$	$V_G = \frac{V_{PV} + V_B}{1 - D_2} = 48V$
V2G	$D_2 = D_3$	$V_G = \frac{V_B}{1 - D_2}$
G2V	$D_1 = D_4$	$V_B = D.V_G$

DESIGN SPECIFICATIONS AND ASSUMPTIONS

The design of the passive components of the proposed battery-integrated three-port bidirectional DC–DC converter is carried out based on the system ratings, operating conditions, and control requirements. The photovoltaic (PV) source operates at a nominal voltage of 30 V, while the DC grid voltage is regulated at 48 V. The battery nominal voltage is selected as 36 V to represent a typical light electric vehicle (LEV) battery. The converter is designed for a rated power of 2 kW and operates at a switching frequency of 50 kHz. The PV-side inductor is designed to operate in continuous conduction mode (CCM) to ensure smooth power transfer and stable MPPT operation, whereas the battery-side inductor is intentionally designed to operate in discontinuous conduction mode (DCM) to enable pulse charging and discharging of the battery. These specifications form the basis for the selection and design of the passive components.

DESIGN OF PV-SIDE INDUCTOR L_1

Inductor L_1 is connected to the photovoltaic (PV) port and primarily operates in continuous conduction mode (CCM) when power is transferred from the PV panel to the DC grid or battery. Its main function is to boost the PV voltage to the regulated DC bus voltage while maintaining low current ripple.

The duty cycle of the boost operation is given by:

$$D = 1 - \frac{V_{PV}}{V_{DC}}$$

The inductor value is selected based on the allowable inductor current ripple ΔI_L, which is typically chosen as 20–40% of the average inductor current. The inductor value for a boost converter operating in CCM is given by:

$$L_1 = \frac{V_{PV}.D}{\Delta I_L.f_s}$$

DESIGN OF BATTERY-SIDE INDUCTOR L_2

Inductor L_2 is associated with the battery port and is intentionally designed to operate in discontinuous conduction mode (DCM). This inductor facilitates pulse charging and pulse discharging of the battery, which helps in improving the battery charging efficiency and lifetime. To ensure DCM operation, the value of L_2 is chosen significantly smaller than L_1, i.e.,

$L_2 << L_1$. This small inductance value ensures that the inductor current reaches zero before the next switching cycle, thereby confirming DCM operation. The DCM behaviour of L_2 also simplifies control, prevents circulating currents, and naturally limits the battery current, contributing to safer and more efficient battery charging and discharging.

DESIGN OF OUTPUT CAPACITOR C_G

The output capacitor is connected across the DC bus and is responsible for maintaining a stable DC voltage by filtering the voltage ripple caused by switching action and load variations. The capacitor value is selected based on the allowable DC bus voltage ripple. The output capacitor for a boost-type converter is designed using:

$$C_g = \frac{I_o.D}{\Delta V_{dc}.f_s}$$

This capacitor value ensures effective voltage regulation, reduced ripple, and smooth power delivery to the DC grid and battery.

IV. CONTROL STRATEGY

During daytime, photovoltaic (PV) systems typically generate maximum power, while electric vehicle (EV) charging demand is often higher at night. When excess PV power is available, it can supply the low-voltage DC distribution system (LVDDS) loads or charge the battery. During low PV generation, power is drawn from the LVDDS to supply the load and charge the light electric vehicle (LEV) battery. Hence, an effective control strategy is required to manage power flow among the system ports.

For the proposed battery-integrated three-port bidirectional DC–DC converter (BIBTPC), a dedicated control strategy coordinates power exchange among the PV source, LEV battery, and LVDDS grid. The objective is to maintain stable DC bus voltage, maximize PV utilization, and ensure safe battery charging and discharging under varying conditions.

The control scheme employs three PI-based regulators. A current regulator (IR) at the PV port implements maximum power point tracking (MPPT) to extract maximum PV power. A voltage regulator (VR) maintains DC grid voltage stability. A battery voltage regulator (BVR) controls battery charging through constant-voltage (CV) regulation to protect battery life. Coordinated operation of these regulators enables smooth transitions between PV-assisted, grid-to-vehicle (G2V), and vehicle-to-grid (V2G) modes, ensuring reliable and stable system performance.

The Perturb and Observe (P&O) technique is used to extract maximum power from the photovoltaic (PV) system by continuously adjusting its operating voltage. In this method, the PV voltage is slightly perturbed and the resulting change in output power is observed. If an increase in voltage causes the power to increase, the perturbation continues in the same direction, indicating movement toward the maximum power point (MPP). If the power decreases, the perturbation direction is reversed. By repeatedly applying this process, the operating point converges near the MPP. The P&O method is widely used due to its simple control logic and ease of implementation. Fig. 4 shows the Flowchart of P&O method.

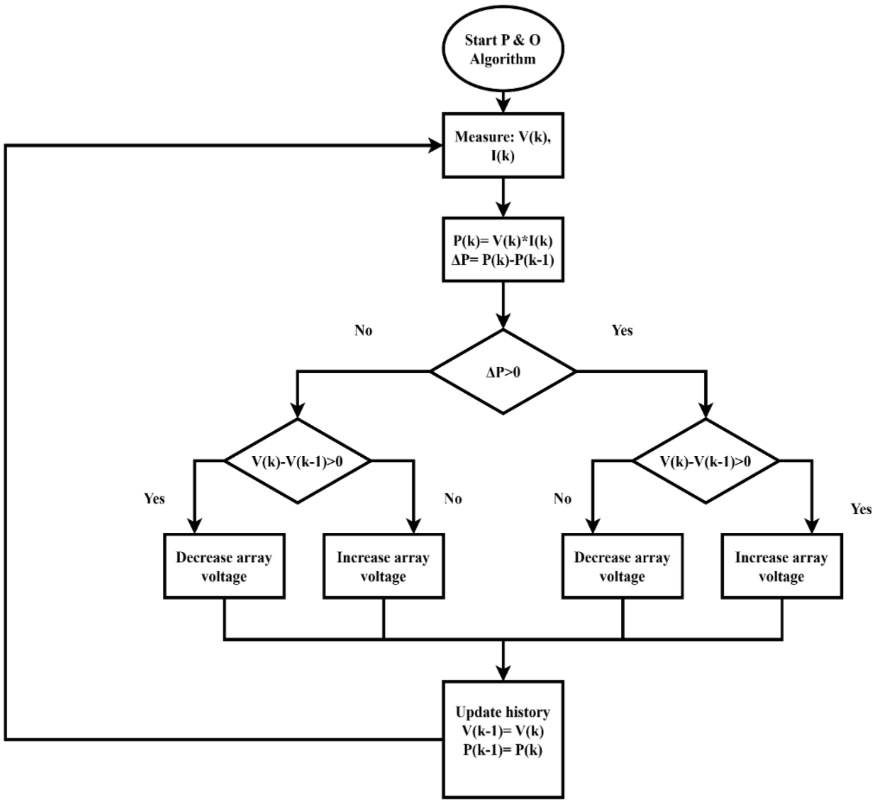


Fig. 4 Flowchart of Perturb and Observe Method

A Proportional–Integral (PI) controller is widely used in power electronic systems due to its simple structure, reliable performance, and ability to eliminate steady-state error. In PV-based DC–DC converters, PI controllers regulate variables such as PV current, DC bus voltage, and battery voltage to ensure stable operation under varying conditions. The integral action removes steady-state error, making the controller suitable for voltage and current regulation. In the proposed system, the PI controller maintains DC bus voltage and ensures smooth power flow among the ports. Proper tuning of the gains provides fast response, minimal overshoot, and stable operation.

In the proposed three-port bidirectional DC–DC converter, battery state of charge (SOC) plays a key role in determining the operating mode and direction of power flow. Since the battery functions as both an energy storage element and a support source for the low-voltage DC distribution system (LVDDS), its operating limits must be maintained to prevent overcharging, deep discharge, and excessive stress. Therefore, SOC-based decision logic is incorporated into the control strategy.

During high photovoltaic (PV) generation, the controller first compares PV power P_{PV} with load demand P_{LOAD}. If excess PV power is available, the battery SOC is evaluated. When SOC is below the upper threshold, the converter operates in PV-to-battery and grid (P2VG) mode to store surplus energy. If SOC exceeds the limit, the system switches to PV to grid (P2G) mode.

During low or zero PV generation, SOC determines whether the battery can support the grid. If SOC is above the minimum threshold, the converter operates in battery-to-grid (V2G) mode. If SOC falls below the lower limit, discharging is restricted and the system enters grid-to-vehicle (G2V) mode to recharge the battery.

The control flow (Fig. 5) follows three main steps:

Step1: Initial Power Comparison: The controller compares P_{PV} and P_{LOAD}. If $P_{PV} > P_{LOAD}$, the system enters the excess power branch; otherwise, it enters the deficient power branch.

Step 2: Excess PV Power

- SOC > 80%: Operates in P2G mode.
- 50% < SOC < 80%: Operates in PV2G mode.
- SOC < 50%: Operates in P2VG mode to prioritize charging.

Step 3: Deficient PV Power

- Partial PV available: Operates in PV2G mode.
- No/low PV and SOC > 50%: Operates in V2G mode.
- No/low PV and SOC < 50%: Operates in G2V mode to prevent deep discharge.

By incorporating SOC thresholds into the control logic, the converter achieves intelligent mode selection (P2G, P2VG, PV2G, V2G, and G2V), ensuring optimal renewable utilization, DC bus stability, and battery protection.

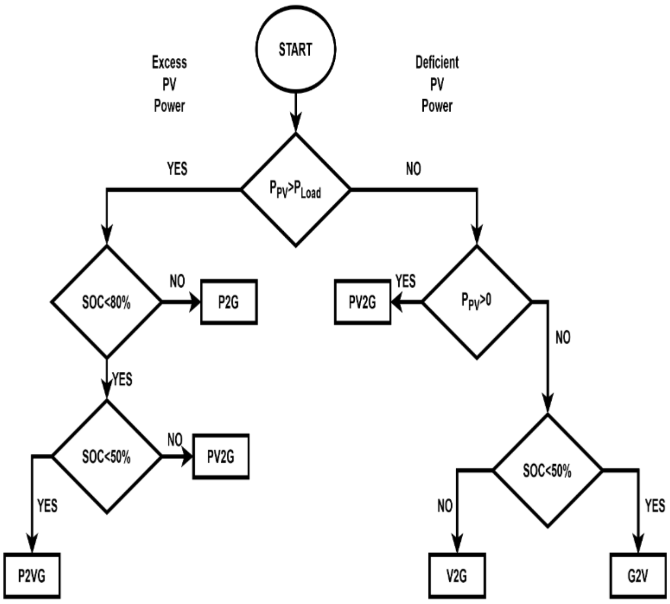


Fig. 5 Control Flowchart

V. RESULTS AND DISCUSSIONS

SIMULATION PARAMETERS AND INPUT PROFILES

Irradiance Profile: The solar irradiance was varied to simulate different weather conditions and their impact on photovoltaic power generation P_{PV}. Fig. 6 shows Irradiance at different time intervals.

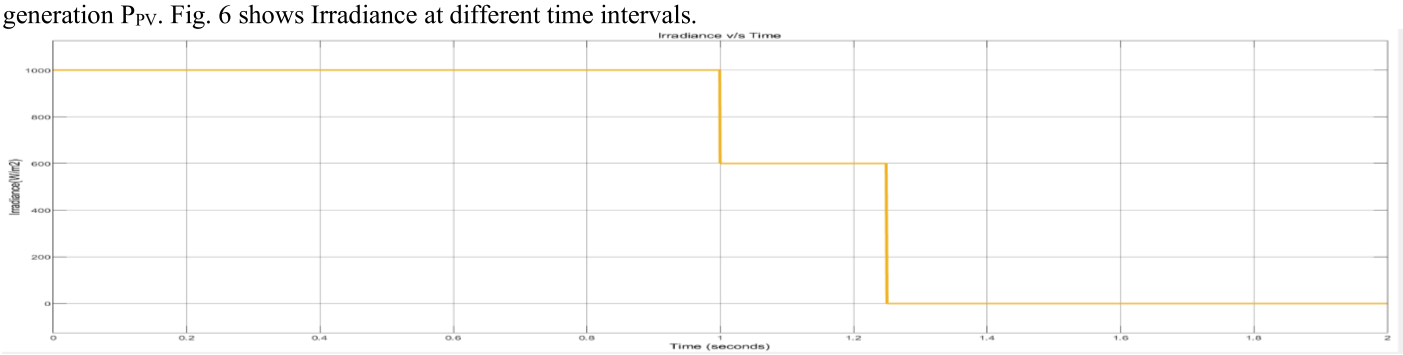


Fig. 6 Irradiance in different time intervals

- 0.00s – 1.00s (High Irradiance): Irradiance is maintained at 1000 W/m^2, representing peak sunlight conditions where P_{PV} is at its maximum.
- 1.00s – 1.25s (Medium Irradiance): A step-change occurs, dropping the irradiance to 600 W/m^2 to simulate partial cloud cover or late-afternoon sun.
- 1.25s – 2.00s (Zero Irradiance): Irradiance is reduced to 0 W/m^{2}simulating nighttime or complete shading where the PV source provides no power (P_{PV}=0).

System State: Battery State of Charge (SOC) Cycle

The battery SOC was cycled through three distinct thresholds to test the controller's ability to protect the battery and manage energy storage effectively. This cycle repeats after 1.0s. Fig. 7 shows %SOC of Battery at different time intervals.

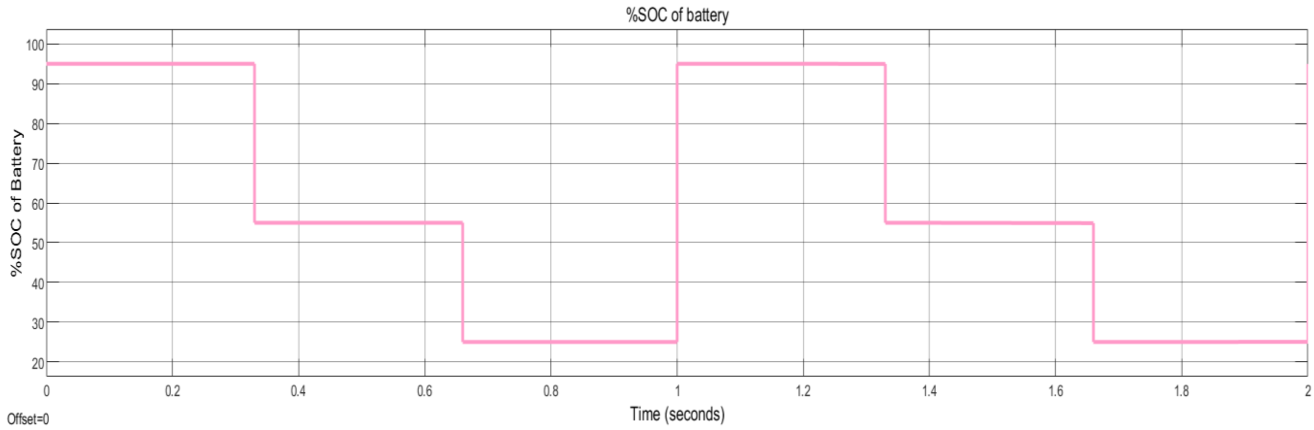


Fig. 7 %SOC of Battery at different time intervals

- Interval 1 (0.00s – 0.33s & 1.00s – 1.33s): The SOC is at 95%, representing a nearly full battery where further charging must be restricted to prevent overcharging.
- Interval 2 (0.33s – 0.66s & 1.33s – 1.66s): The SOC is at 55%, representing a healthy, mid-level charge where the battery can either remain idle or discharge to support the load.
- Interval 3 (0.66s – 1.00s & 1.66s – 2.00s): The SOC is at 25%, which is below the minimum allowable safety limit (50% threshold). At this level, discharging is restricted, and the battery requires recharging to prevent deep discharge.Fixed Voltage Parameters:
- PV Source Voltage: 30 V
- Battery Nominal Voltage: 36 V
- Load/DC Bus Voltage V_G: Regulated at 48 V

ANALYSIS OF POWER FLOW MODES BASED ON BATTERY SOC AND PV AVAILABILITY

The simulation waveforms illustrate the autonomous transition between different power flow paths based on environmental inputs and the battery's state of charge (SOC). By monitoring the inductor currents and the battery SOC, the bidirectional nature of the converter is evidenced: energy flows into the battery during surplus generation and out of the battery when solar power is deficient. These waveforms confirm that the control algorithm successfully regulates the 48V DC bus voltage while alternating between single-input, dual-input, and dual-output configurations.

Interval 1: 0 – 0.33 s (P2G Mode)

During this interval, the solar irradiance is high (1000 W/m²), resulting in photovoltaic power exceeding the load demand. At the same time, the battery state of charge is high (approximately 95%), and therefore battery charging is restricted to avoid overcharging. Under these conditions, the system operates in the P2G mode, where the PV source alone supplies the load and the DC grid, while the battery remains isolated from power exchange.

Fig. 8(a) shows P2G mode is active in this interval. Fig. 8(b) shows the %SOC of the battery showing how battery is idle in this interval.

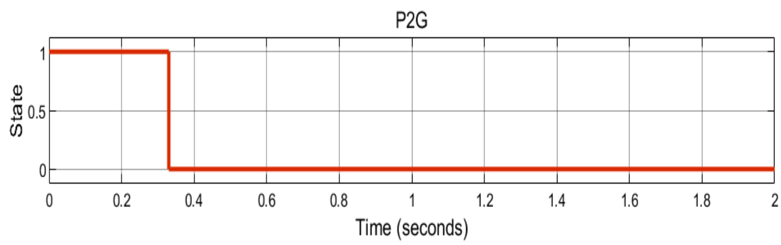


Fig. 8(a) P2G

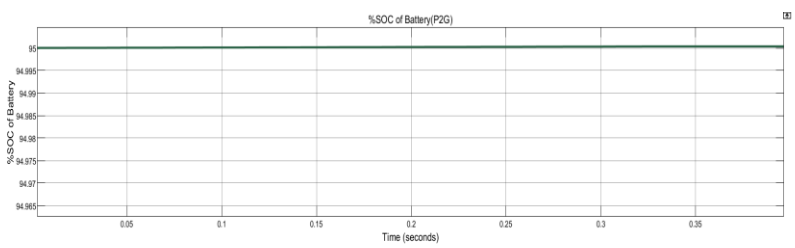


Fig. 8(b) %SOC of Battery during P2G

Interval 2: 0.33 – 0.66 s (PV2G Mode)

During this interval, the solar irradiance is high (1000 W/m²), resulting in photovoltaic power exceeding the load demand. At the same time, the battery state of charge is medium(approximately 55%). Under these conditions, the system operates in the PV2G mode, where the PV source supplies the load and the DC grid, along with the battery.

Fig. 9(a) shows the active state of PV2G mode in the time interval. Fig. 9(b) shows the %SOC of battery in this interval, that is discharging depicting that the battery is assisting the PV panel in supplying power.

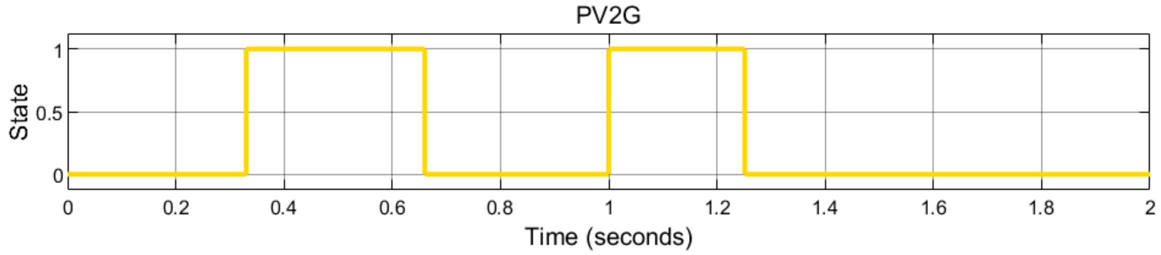


Fig. 9(a) PV2G

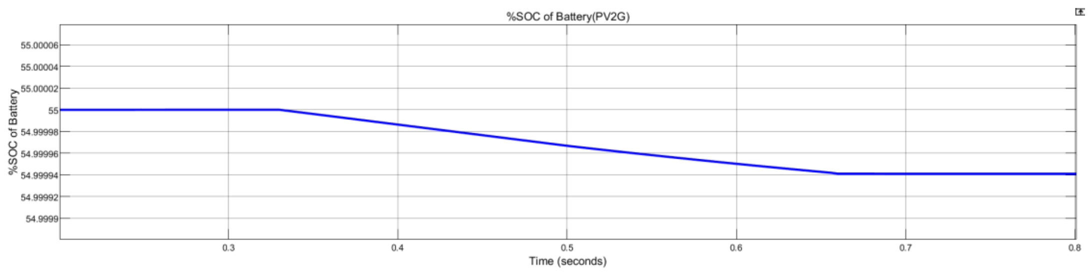


Fig. 9(b) %SOC of Battery during PV2G

Interval 3: 0.66 – 1.00 s (P2VG Mode)

In this interval, the PV power is still higher than the load demand, but the battery SOC has dropped further to a low level (approximately 25%). To prevent deep discharge and restore battery energy, the controller prioritizes battery charging. Therefore, the system continues operating in P2VG mode, with the PV source charging the battery while maintaining load support.

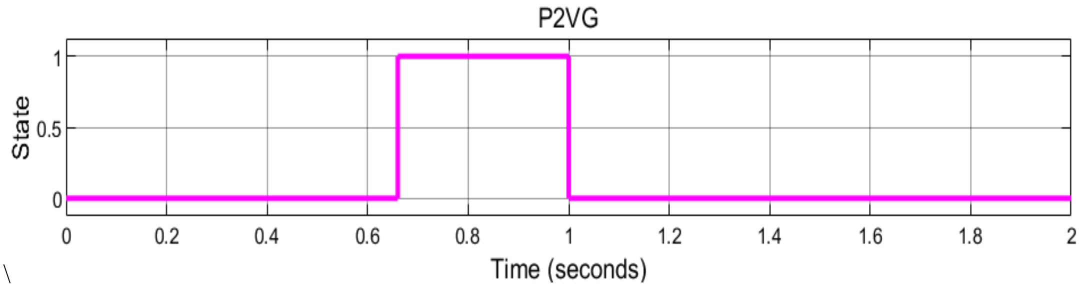


Fig. 10(a) P2VG

Fig. 10(a) shows the active state of P2VG mode between the time interval. Fig. 10(b) shows the %SOC of the Battery in this interval. It can be seen that the battery is being charged from 0.66-1s confirming the state of this mode.

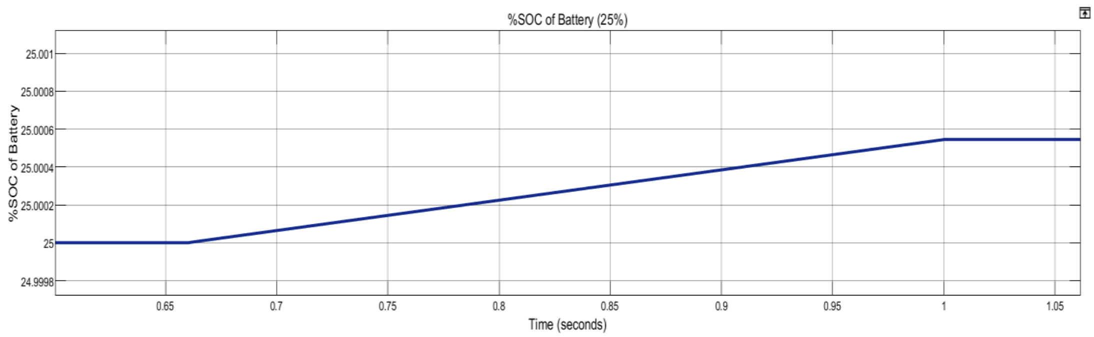


Fig. 10(b) %SOC of Battery during P2VG

Interval 4: 1.00 – 1.25 s (PV2G Mode)

As the irradiance reduces to a medium level (600 W/m²), the PV power becomes insufficient to meet the load demand. Since the battery SOC is high, the battery is permitted to discharge and support the PV source. Consequently, the system operates in PV2G mode, where both the PV and battery jointly supply the load to maintain the regulated DC bus voltage.

Fig. 11(a)shows the active state of PV2G in this interval. Fig. 11(b) shows the %SOC of battery and how battery is discharging to grid along PV.

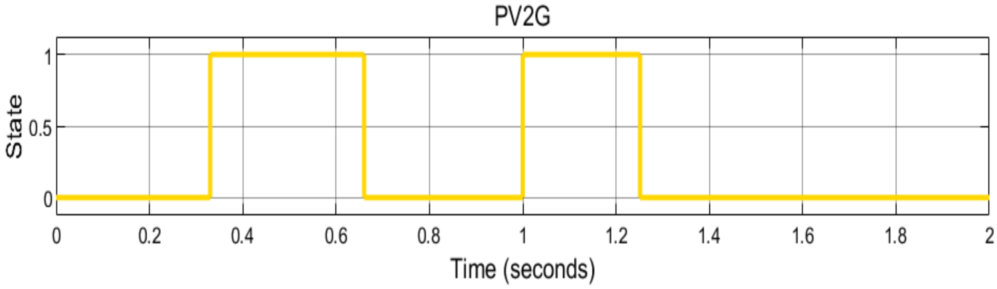


Fig. 11(a) PV2G

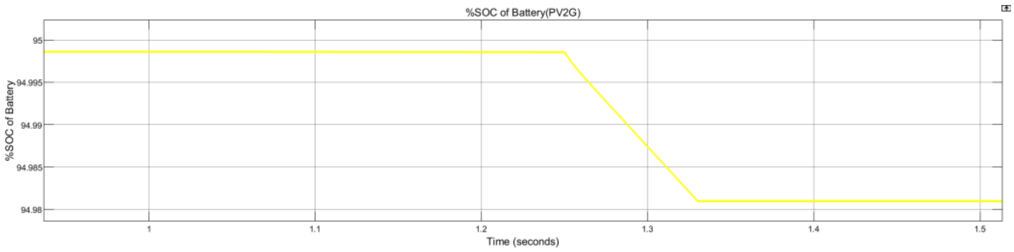
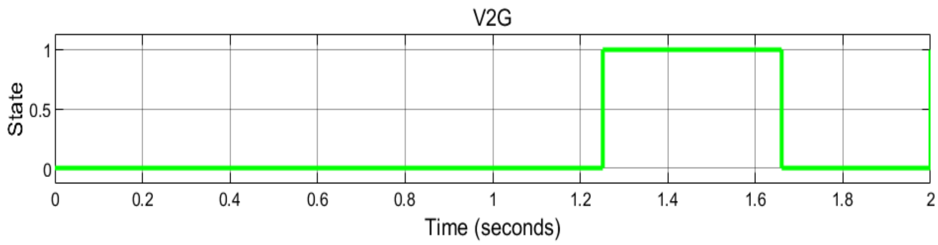


Fig. 11(b) %SOC of Battery during PV2G

Interval 5: 1.25 – 1.66 s (V2G Mode**)**

During this interval, PV power remains unavailable, and the battery SOC has reduced from high level to a medium level. The battery continues to discharge and supply the load in V2G mode until the lower SOC threshold is reached. This ensures uninterrupted power delivery while maintaining safe battery operation.

Fig. 12(a) shows the active state of V2G mode. Fig. 12(b) shows the %SOC of the battery in the interval 1.25-1.33 s that is 95% and Fig. 12(c) that shows %SOC of battery in the interval 1.33-1-66 s and it can be observed that during this interval, the battery is discharging to the grid.



Fig, 12(a) V2G

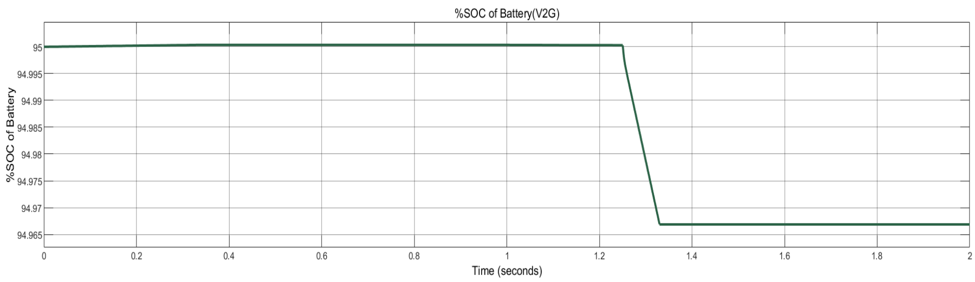


Fig. 12(b) %SOC of Battery during V2G(1.25-1.33 s)

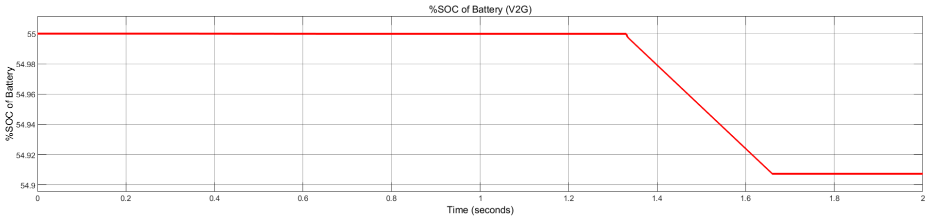


Fig. 12(c) %SOC of Battery during V2G(1.33-1.66 s)

Interval 6: 1.66 – 2.00 s (G2V Mode)

In the final interval, the battery SOC drops to a low level (around 25%), and PV power remains zero. To prevent deep discharge and protect battery health, the system transitions to G2V mode. In this mode, power flows from the DC grid to the battery, enabling controlled battery charging and restoring the SOC to a safe level. Fig. 13(a) shows the active state of G2V mode. Fig. 13(b) shows the %SOC of battery in this interval where battery is charging.

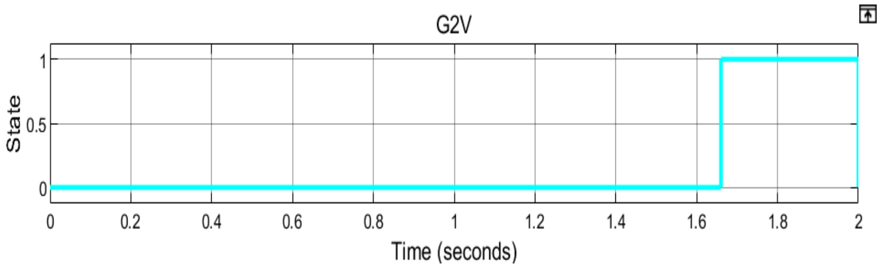


Fig. 13(a) G2V

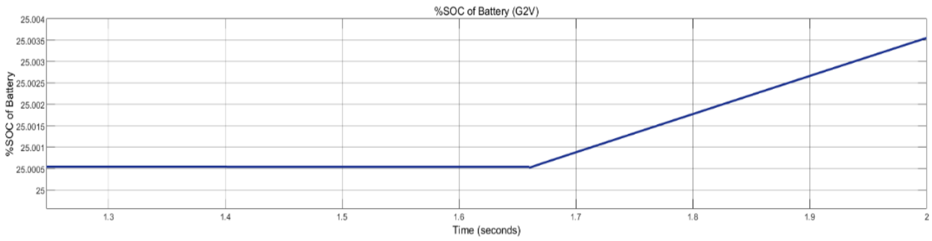


Fig. 13(b) %SOC of Battery during G2V

From the above time-based analysis, it is evident that the proposed control strategy enables seamless transition between different power flow modes based on photovoltaic power availability and battery state-of-charge conditions. The operating modes are selected in real time to ensure maximum utilization of solar energy, uninterrupted load support, and protection of the battery from overcharging and deep discharge. The observed transitions among P2G, P2VG, PV2G, V2G, and G2V modes validate the autonomous nature of the control algorithm and confirm its capability to coordinate power flow among multiple ports and also bidirectional power flow. Table 4 summarizes results.

VI. CONCLUSION AND FUTURE SCOPE

This project presented the design, simulation, and evaluation of a battery-integrated three-port bidirectional DC–DC converter for light electric vehicle (LEV) charging integrated with a low-voltage DC distribution system (LVDDS). The proposed converter interfaces a photovoltaic (PV) source, battery energy storage system, and DC grid using a single conversion stage, reducing component count and improving flexibility. The system design included circuit analysis, operating mode identification, passive component selection, and SOC-based control development. MATLAB/Simulink results validate operation under P2G, PV2G, P2VG, V2G, and G2V modes, demonstrating stable 48 V DC bus regulation, effective bidirectional power flow, efficient PV utilization through CCM operation, controlled battery charging/discharging via DCM, and smooth mode transitions. Although simulation results confirm satisfactory performance, further enhancements can extend system applicability. Future work includes hardware prototype development, implementation of advanced control techniques for improved dynamic response, integration of an AC grid interface, scaling to higher power levels for fast charging, incorporation of battery health and thermal management, and integration with higher-level energy management systems for coordinated operation in DC microgrids and smart charging infrastructure.

Table 4 Mode Selection Based on Irradiance, Power Balance, and SOC

Time Interval (s)	Irradiance (W/m²)	Power Condition	%SOC of Battery	Selected Mode	System Behaviour
0 – .33	1000 (High)	($P_{PV} > P_{LOAD}$)	95% (High)	**PV2G**	PV supplies the load and excess power is exported; Battery participation is less.
0.33 – 0.66	1000 (High)	($P_{PV} > P_{LOAD}$)	55% (Mid)	**P2G**	PV supplies the load. Battery is isolated
0.66 – 1.00	1000 (High)	($P_{PV} > P_{LOAD}$)	25% (Low)	**P2VG**	PV prioritizes charging the low-SOC battery while supporting the load.
1.00 – 1.33	600 (Mid)	($P_{PV} < P_{LOAD}$)	95% (High)	**PV2G**	PV power is discharged to meet the load demand. Battery assists PV panel in supplying the grid
1.33 – 1.66	0 (None)	($P_{PV} = 0$)	95%-55%	**V2G**	Battery continues to supply the load until the SOC threshold is reached.
1.66 – 2.00	0 (None)	($P_{PV} = 0$)	25% (Low)	**G2V**	Grid charges the battery to prevent deep discharge.

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