

RESEARCH ARTICLE

Solar-PV-Powered Two-Quadrant DC–DC Converter for Bidirectional Battery Energy Management System

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Abstract

The intermittent output of solar photovoltaic (PV) sources requires an efficient power-electronic interface to coordinate energy exchange with battery storage while maintaining regulated DC-side operation. This paper presents the design and MATLAB/Simulink evaluation of a non-isolated, two-quadrant bidirectional buck–boost converter for solar-PV-powered battery energy management. The converter operates in buck mode to transfer energy from the PV-fed DC bus to the battery and in boost mode to return stored energy from the battery to the load when solar generation is unavailable. The power stage, operating principles, duty-ratio relations, and passive-component design considerations are described for both modes. Converter performance is assessed using battery state of charge (SoC), current, and voltage responses. The simulated results exhibit a smooth increase in SoC and a well-settled charging current in buck operation, whereas boost operation produces a monotonic SoC reduction, appropriately directed discharge current, and stable voltage response after the initial transient. These findings verify the intended bidirectional power-flow sequence under the investigated simulation conditions and establish a basis for experimental implementation, mode-transition testing, and the subsequent integration of adaptive energy-management and maximum-power-point-tracking strategies.

Keywords: Bidirectional DC-DC converter, Solar photovoltaic system, Battery energy storage, Buck-boost conversion, State of charge, MATLAB/Simulink.

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1. Introduction

The transition towards low-carbon electricity has intensified the deployment of solar PV generation in stand-alone systems, DC microgrids, electric-mobility infrastructure, and remote-area electrification [1]. Although PV technology offers clean and modular power generation, its output is inherently intermittent and nonlinear because it varies with irradiance, temperature, shading, and the electrical operating point. Battery energy storage can mitigate this variability by absorbing surplus PV energy and supplying the load during generation deficits. Effective coordination

between the PV source, DC bus, battery, and load is therefore essential for maintaining power balance, preserving battery operating limits, and ensuring continuity of supply.

A DC–DC converter forms the principal power-electronic interface between the PV-fed DC bus and the battery. Beyond matching unequal terminal voltages, the converter regulates charging and discharging currents, controls the direction of power flow, and supports stable DC-bus operation. When coordinated with a MPPT algorithm, it can also facilitate improved utilization of the available PV power [2]. Converter topology and control design consequently have a direct influence on conversion losses, current ripple, transient response, semiconductor stress, system complexity, and overall reliability.

Conventional buck, boost, and buck–boost converters remain attractive because of their simple structures and established design procedures. However, a unidirectional converter cannot return stored battery energy to the DC bus, while separate charging and discharging stages in-

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Acronyms and mathematical notations.

Term/Symbol	Expanded form	Description	Unit
Acronyms			
BDC	Bidirectional DC–DC Converter	Power-electronic converter that supports energy transfer in both directions between the DC bus and battery.	–
CCM	Continuous Conduction Mode	Operating condition in which the inductor current does not fall to zero during a switching cycle.	–
DC	Direct Current	Unidirectional electrical current employed on the converter input and output sides.	–
ESR	Equivalent Series Resistance	Internal effective resistance of a capacitor that influences power loss and voltage ripple.	Ω
IGBT	Insulated-Gate Bipolar Transistor	Controlled power-semiconductor device employed in the converter switching stage.	–
MOSFET	Metal-Oxide-Semiconductor Field-Effect Transistor	High-frequency controlled switching device used in DC–DC converters.	–
MPPT	Maximum Power Point Tracking	Control process used to extract the maximum available power from the PV array.	–
PI	Proportional–Integral	Feedback controller used to regulate the converter voltage or current response.	–
PV	Photovoltaic	Solar-energy conversion technology used as the primary power source.	–
PWM	Pulse-Width Modulation	Switch-control technique used to regulate the converter duty ratio.	–
SoC	State of Charge	Available battery capacity expressed as a percentage of its rated capacity.	%
Mathematical notation			
C_{out}	Output capacitance	Capacitance required to limit switching-induced output-voltage ripple.	μF
D	Duty ratio	Ratio of the semiconductor-switch on-time to the total switching period.	–
E_{in}	Input voltage	Voltage applied to the input terminal of the converter.	V
E_{out}	Output voltage	Regulated voltage obtained at the output terminal of the converter.	V
f_s	Switching frequency	Frequency at which the controlled semiconductor switch is operated.	Hz
I_{in}	Input current	Current drawn from the source during converter operation.	A
I_{out}	Output current	Current supplied by the converter to the battery or DC load.	A
L	Inductance	Energy-storage inductance used to limit converter-current ripple.	mH
S_1	Upper controlled switch	Power-semiconductor switch primarily controlled during buck-mode operation.	–
S_2	Lower controlled switch	Power-semiconductor switch primarily controlled during boost-mode operation.	–
ΔE_{out}	Output-voltage ripple	Allowable peak-to-peak variation in the converter output voltage.	V
ΔI_L	Inductor-current ripple	Allowable peak-to-peak variation in the inductor current.	A
η	Converter efficiency	Ratio of converter output power to input power under a specified operating condition.	%

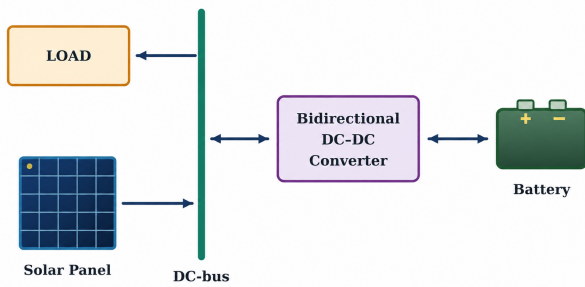


Figure 1: A basic configuration of the bidirectional DC-DC converter system.

crease the component count and conduction path. Bidirectional DC–DC converters address these limitations by realizing both power-flow directions through a common power stage. Depending on voltage ratio, isolation requirement, power rating, and safety constraints, the converter may employ an isolated or non-isolated structure. For low- and medium-power applications in which galvanic isolation is not mandatory, a non-isolated two-switch buck–boost configuration offers compactness, relatively low implementation complexity, and straightforward control [18].

Despite the extensive literature on bidirectional conversion, the operating evidence presented for a specific PV–battery interface must remain consistent with its design equations and reported waveforms. In particular, charging and discharging claims should be supported collectively by SoC, current-direction, and voltage responses rather than by a single signal. The present study therefore develops a mode-specific description and simulation assessment of a non-isolated two-quadrant converter, with attention to the physical interpretation of its measured battery variables.

A basic bidirectional DC-DC converter configuration is shown in Figure 1. It illustrates the bidirectional power interface between the DC-bus and the battery, with the PV source and load connected on the DC-bus side.

The principal contribution of this work is a unified design and simulation analysis of the converter in its two complementary operating modes. The study: (i) explains the semiconductor switching paths governing PV-to-battery and battery-to-load power transfer; (ii) presents duty-ratio and passive-component design considerations for both modes; and (iii) evaluates the resulting SoC, battery-current, and battery-voltage responses in MATLAB/Simulink. The results are interpreted conservatively within the simulated operating conditions, thereby providing a reproducible foundation for controller refinement and experimental validation.

2. Literature survey

Bidirectional power conversion is widely employed to coordinate energy exchange among electrical sources, storage units, and DC loads. Khaligh and Li [8] reviewed battery, ultracapacitor, fuel-cell, and hybrid storage systems for electrified transportation, highlighting the importance of the power interface in meeting different energy and power demands. Du et al. [16] surveyed non-isolated bidirectional DC–DC converters for charging stations and

discussed their structural and operational trade-offs. At the distributed-generation level, Blaabjerg et al. [17] established the broader role of power-electronic interfaces in conditioning and controlling renewable power. Collectively, these studies demonstrate that converter selection cannot be separated from the voltage levels, storage characteristics, direction of energy flow, and intended system service.

For PV systems, MPPT is required because the power-producing operating point varies with environmental and loading conditions [1]. Femia et al. [9] examined the optimization of the perturb-and-observe method, whereas Esmar and Chapman [10] compared established MPPT techniques and their implementation characteristics. Patel and Agarwal [11] addressed operation under partial shading, where multiple local maxima complicate tracking. High-efficiency solar energy harvesting with MPPT was investigated in [12], and converter-level MPPT control was demonstrated in [13]. These contributions show that source-side operating-point tracking and storage-side current regulation are distinct but coordinated control objectives in a PV–battery system.

Grid-connected and distributed renewable-energy interfaces have also received substantial attention. Kjaer et al. [14] reviewed single-phase grid-connected inverter topologies for PV modules, and Carrasco et al. [15] surveyed power-electronic systems for renewable-source integration. Although their primary focus extends beyond the battery-side converter considered here, both studies emphasize reliable interfacing, appropriate control hierarchy, and stable interaction among renewable sources, storage devices, converters, and loads.

Complementary system-level studies have examined proportional power sharing among parallel inverters [1], fault recovery in islanded microgrids under different loading conditions [2], deployment of renewable-energy-based permanent-magnet synchronous generators [3], and power balancing using battery storage and electronic load control [4]. Comparisons of centralized and parallel-inverter hybrid microgrids [5], techno-economic selection of hybrid resources for rural communities [6], and programmable low-cost protection [7] further illustrate the close coupling among conversion, control, protection, and energy management. These works motivate converter designs that can accommodate reversible energy flow without compromising system-level coordination.

The literature establishes mature foundations for PV tracking, bidirectional conversion, and renewable-system integration. Nevertheless, sophisticated control cannot compensate for an inadequately characterized power stage. Accordingly, the present work focuses on the fundamental operating behaviour of a non-isolated bidirectional buck–boost converter under controlled charging and discharging conditions. This scope enables the converter’s two-quadrant functionality to be assessed transparently before more advanced MPPT, adaptive, or data-driven control strategies are introduced.

3. Methodology

The bidirectional converter was modelled in MATLAB and Simulink to examine its switching and battery-side

dynamics under controlled operating conditions. The simulation contains a PV source, DC link, non-isolated bidirectional converter, lithium-ion battery, variable DC load, and mode-dependent control system. This component-level arrangement permits direct observation of the electrical response during both directions of energy transfer.

Two operating cases were investigated. When PV power is available and charging is commanded, the converter operates as a step-down stage and transfers energy from the higher-voltage DC bus to the battery. When PV input is unavailable and load support is required, the switching sequence is reversed and the converter operates as a step-up stage, transferring stored battery energy to the load. Complementary gating is required to prevent simultaneous conduction of the two controlled devices; in a practical implementation, an appropriate dead time must also be introduced.

The monitored variables are battery SoC, battery current, and battery terminal voltage. SoC identifies the direction of net stored-energy change, the current waveform captures the transient and steady-state power-flow direction under the adopted sign convention, and the voltage waveform indicates the quality of regulation. Their combined interpretation is used to verify charging and discharging operation. Because the reported study is simulation based, the assessment is limited to the model parameters and operating scenarios represented in the simulation.

3.1. Design of bidirectional converter

A bidirectional DC-DC converter enables controlled energy transfer between two DC terminals, typically a source-side DC bus and a battery. Its design requires appropriately rated semiconductor switches, an energy-transfer inductor, filtering capacitors, gate-drive circuitry, and supervisory logic. The semiconductor voltage and current ratings must include adequate margins for switching transients, while the passive components must satisfy ripple and thermal constraints in both power-flow directions.

Bidirectional topologies are generally classified as isolated or non-isolated. Isolated configurations employ a high-frequency transformer to provide galvanic isolation and an additional voltage-conversion degree of freedom, but require more devices and a more complex modulation strategy. Non-isolated configurations transfer energy directly between the terminals and are advantageous when compactness, reduced component count, and lower control complexity are priorities. The present study adopts the non-isolated bidirectional buck-boost circuit shown in Figure 2 for a low- to medium-power PV-battery interface.

3.1.1. Buck mode (step-down operation)

In buck mode, the converter reduces the higher DC-bus voltage to the level required for battery charging. Switch S_1 is pulse-width modulated and S_2 provides the complementary freewheeling path, subject to the device implementation and gating strategy shown in Figure 3. During the energizing interval, the DC bus supplies the inductor and battery; during the freewheeling interval, the inductor maintains battery current by releasing stored magnetic energy. The duty ratio consequently determines the average conversion ratio and charging-current operating point.

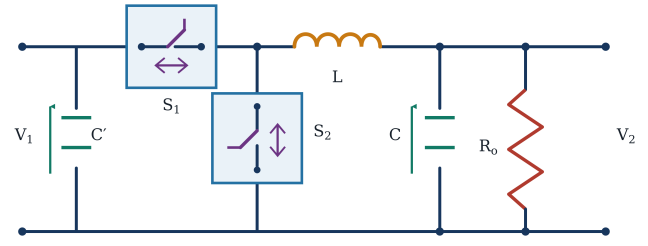


Figure 2: Bidirectional DC-DC converter circuit.

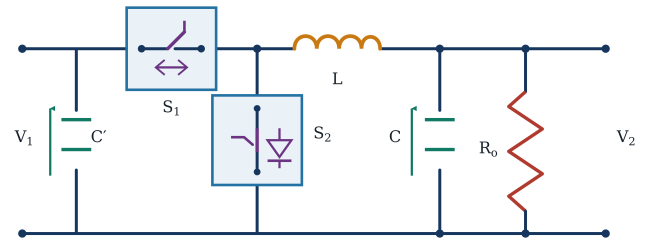


Figure 3: Bidirectional converter circuit in buck mode.

Duty cycle: The duty ratio D is defined as the ratio of switch on-time to the switching period. Including the assumed converter efficiency η , the design relation is given by (1).

$$D = \frac{E_{out}}{E_{in}\eta}. \quad (1)$$

For the stated design values, D is considered as in (2).

$$D = \frac{24}{48 \times 0.9} = 0.556. \quad (2)$$

An efficiency range of 90–95% is assumed for preliminary design; this value should be verified experimentally because it varies with load, switching frequency, and device losses.

Inductor selection: The inductor is selected to restrict the peak-to-peak current ripple to approximately 10–20% of the rated output current I_{out} is expressed as (3).

$$\Delta I_L = (0.1 \text{ to } 0.2) I_{out}, \quad (3)$$

with the stated numerical value is calculated in (4).

$$\Delta I_L = 0.1 \times 10 = 1 \text{ A}. \quad (4)$$

For continuous-conduction buck operation, the corresponding design relation is

$$L = \frac{(E_{in} - E_{out})D}{f_s \Delta I_L}, \quad (5)$$

which, for $f_s = 25 \text{ kHz}$ and the stated values, gives

$$L = \frac{(48 - 24) \times 0.556}{25 \times 10^3 \times 1} = 0. \text{ mH}. \quad (6)$$

In (6), f_s denotes the switching frequency. Increasing L reduces current ripple but increases component volume, stored energy, and cost.

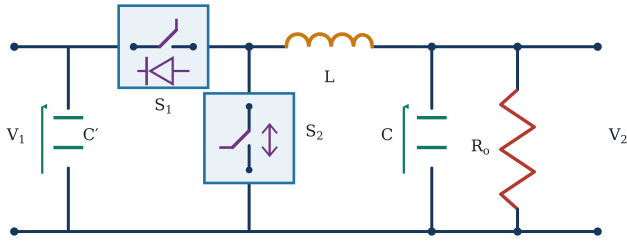


Figure 4: Bidirectional converter circuit in boost mode.

Selection of output capacitor. A low-equivalent-series-resistance (ESR) capacitor is used to reduce output-voltage ripple. For an allowable ripple ΔE_{out} , the preliminary buck-mode capacitance may be estimated as

$$C_{\text{out}} \geq \frac{\Delta I_L}{8f_s \Delta E_{\text{out}}}. \quad (7)$$

For $\Delta I_L = 1$ A, $f_s = 25$ kHz, and $\Delta E_{\text{out}} = 0.24$ V, this yields

$$C_{\text{out}} \geq \frac{1}{8 \times 25 \times 10^3 \times 0.24} = 20.83 \mu\text{F}. \quad (8)$$

The final component rating must additionally account for capacitance tolerance, ESR heating, ripple-current rating, and closed-loop stability.

3.1.2. Boost mode (step-up operation)

In boost mode, the converter raises the battery-side voltage to the DC-bus level required by the load when solar generation is insufficient or unavailable. Switch S_2 is pulse-width modulated and the S_1 device path supports energy delivery to the high-voltage side, as illustrated in Figure 4. During the energizing interval, the battery transfers energy to the inductor. During the subsequent interval, the inductor voltage adds to the battery voltage and delivers energy to the output capacitor and load.

A) Duty cycle

For boost operation, the duty cycle is expressed as in (9)

$$D = 1 - \frac{E_{\text{in}} \eta}{E_{\text{out}}}. \quad (9)$$

As in buck operation, the assumed efficiency represents a design estimate rather than an experimentally measured value is 0.55 as per (10).

$$D = 1 - \frac{24 \times 0.9}{48} = 0.55. \quad (10)$$

B) Calculation of inductor

The inductor limits the battery-side current ripple during step-up operation. The target ripple is selected as 10–20% of the input current as given in (11).

$$\Delta I_L = (0.1 \text{ to } 0.2) I_{\text{in}}. \quad (11)$$

For a rated input current of 10 A and a selected ripple factor of 10%, the inductor-current ripple is estimated as per (12).

$$\Delta I_L = 0.1 \times 10 = 1 \text{ A}. \quad (12)$$

The boost-mode inductance is estimated using the expression (13).

$$L = \frac{E_{\text{in}} D}{f_s \Delta I_L}. \quad (13)$$

Using the nominal design duty ratio, the required inductance is calculated as per (14).

$$L = \frac{24 \times 0.5}{25 \times 10^3 \times 1} = 0.48 \text{ mH}. \quad (14)$$

An appropriately selected inductor supports continuous-conduction-mode operation and limits the battery-current ripple.

C) Calculation of capacitor

The output capacitor C_{out} supplies the load during the switch-on interval and attenuates switching-induced voltage ripple. For an allowable output-voltage ripple ΔE_{out} , the minimum capacitance is estimated by expression (15).

$$C_{\text{out}} \geq \frac{I_{\text{out}} D}{f_s \Delta E_{\text{out}}}. \quad (15)$$

Substitution of the specified design values gives as per (16).

$$C_{\text{out}} \geq \frac{10 \times 0.5}{(25 \times 10^3) \times 0.48} = 416.6 \mu\text{F}. \quad (16)$$

A low-ESR capacitor with adequate voltage and ripple-current ratings is required to achieve the intended dynamic and thermal performance.

The principal converter-design and simulation parameters used for evaluating the charging and discharging operating modes are consolidated in Table 1.

4. Results and discussion

The bidirectional buck-boost converter was evaluated in MATLAB/Simulink under charging and discharging conditions. The model integrates the PV source, lithium-ion battery, power stage, PI-based control, and variable DC load. Figure 5 presents the complete simulated arrangement and its principal masked subsystems. The discussion below focuses on the direction, transient behaviour, and settling characteristics of the battery variables; no experimental efficiency or hardware-loss claim is inferred from these waveforms.

4.1. Battery charging mode

During charging, energy is transferred from the PV-fed DC bus to the battery through buck operation. The corresponding SoC and battery-current responses are presented in Figures 6 and 7, respectively.

Figure 6 shows a smooth, monotonic increase in battery SoC from its initial value of 45%. This positive slope confirms net energy accumulation during the simulated

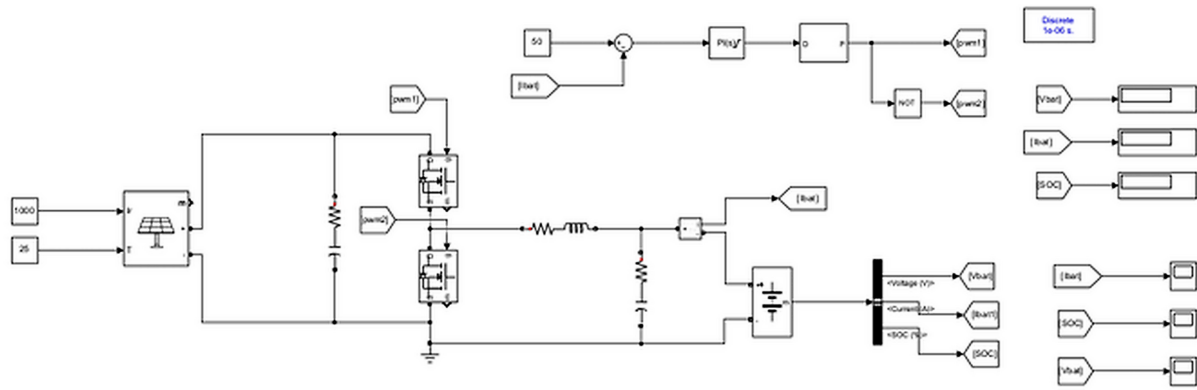


Figure 5: MATLAB/Simulink model comprising the PV source, bidirectional DC–DC converter, battery, DC load, and PI-based control.

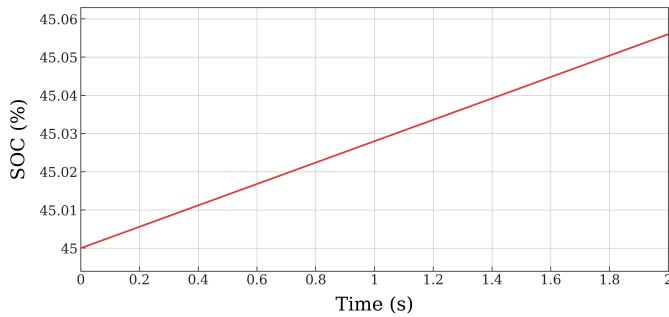


Figure 6: Battery state of charge during charging.

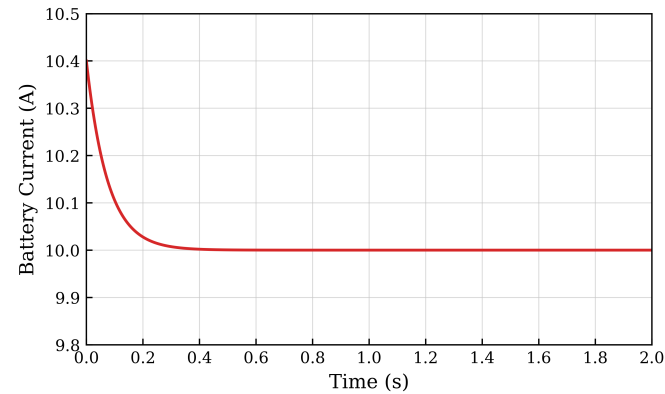


Figure 7: Battery current during charging.

charging interval. The absolute SoC change is necessarily small because the observation window is short relative to the battery’s energy capacity; the magnified axis therefore assists interpretation without implying a large change in stored energy.

The charging-current waveform in Figure 7 exhibits a short start-up transient, followed by gradual convergence towards a nearly constant value. The decay of the transient and the small subsequent variation are consistent with stable closed-loop current regulation. Considered together with the increasing SoC, the current response verifies sustained battery charging after the initial converter transition.

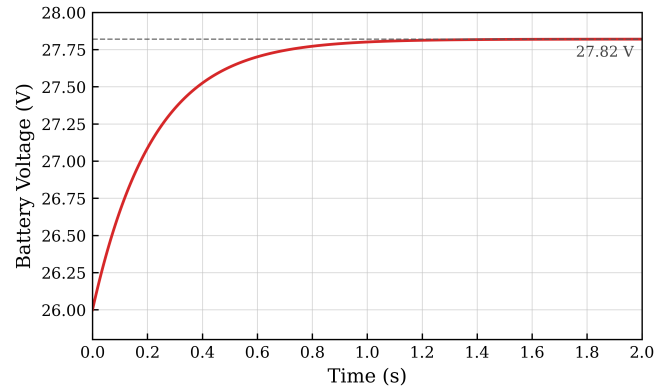


Figure 8: Battery voltage during charging.

Figure 8 presents the battery-terminal voltage during charging. Following the initial rise, the voltage converges to approximately 27.82 V and remains close to this operating level while SoC increases.

No sustained oscillation is visible after the start-up interval, indicating a well-damped simulated voltage response. Thus, the mutually consistent SoC, current, and voltage waveforms in Figures 6–8 demonstrate the intended buck-mode charging behaviour under the investigated conditions.

4.2. Battery discharging mode

When solar power is unavailable, the converter changes to boost operation and transfers energy from the battery to the DC load. Figures 9 and 10 show the SoC and battery-current responses for this condition.

The SoC in Figure 9 decreases monotonically with an approximately linear profile, confirming net energy removal from the battery. As in the charging case, the short simulation interval produces only a small absolute SoC variation. Nevertheless, its consistent negative slope distinguishes sustained discharge from an abrupt or numerically discontinuous change and provides the expected counterpart to the charging response.

Under the sign convention adopted in the model, the current waveform in Figure 10 has the polarity associated

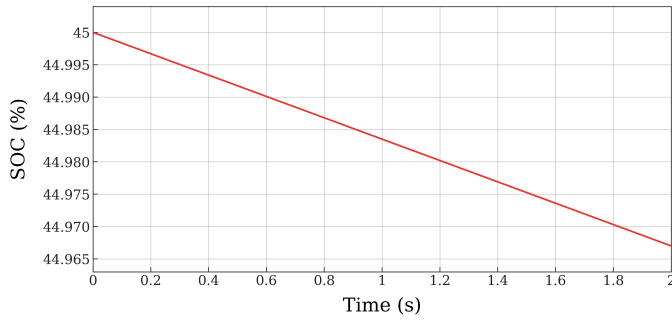


Figure 9: Battery state of charge during discharging.

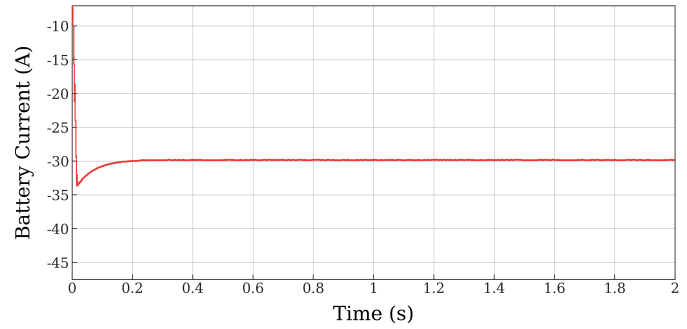


Figure 10: Battery current during discharging.

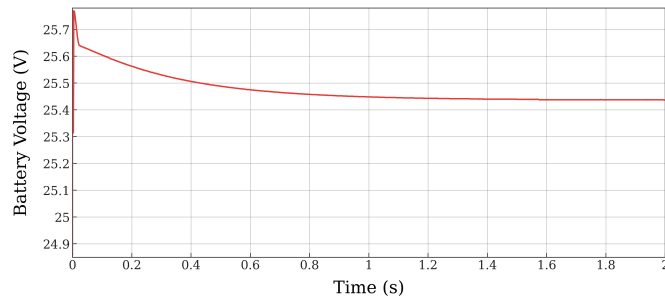


Figure 11: Battery voltage during discharging.

with battery-to-load power transfer. A pronounced but brief start-up excursion is followed by smooth convergence towards a nearly constant discharge current. The absence of repeated high-amplitude excursions after start-up indicates that the simulated current loop remains settled over the remainder of the observation interval.

The converter simultaneously raises the battery-side voltage to the DC-load level. As shown in Figure 11, the voltage undergoes a brief initial transition and then approaches a stable operating value, demonstrating satisfactory simulated boost-mode regulation.

No sustained high-amplitude oscillation is apparent after start-up. Together, the decreasing SoC, appropriately signed current, and regulated voltage provide coherent evidence that the converter reverses the direction of power flow and supports the load in boost mode. These results establish functional feasibility in simulation; however, quantitative comparison with alternative converters, efficiency mapping, robustness to parameter uncertainty, and hardware validation remain necessary before practical superiority can be claimed.

5. Conclusion

This paper presented the design and MATLAB/Simulink assessment of a non-isolated two-quadrant buck–boost converter for bidirectional energy exchange between a solar-PV-fed DC bus and battery storage. Mode-specific switching operation and preliminary passive-component design were described for PV-to-battery buck conversion and battery-to-load boost conversion.

The simulated battery variables consistently verified the intended direction of power flow. During charging, SoC increased monotonically, the battery current settled after

a short transient, and the terminal voltage converged to approximately 27.82 V. During discharging, SoC decreased steadily, the current assumed the polarity associated with battery energy delivery, and the boosted voltage stabilized after start-up. The absence of sustained oscillations in the reported responses indicates stable operation for the modelled conditions.

The conclusions are limited to functional simulation validation and do not constitute experimental confirmation of efficiency, thermal performance, device stress, or robustness. Future work should therefore develop a hardware prototype and evaluate conversion efficiency, current and voltage ripple, semiconductor losses, mode-transition dynamics, and controller performance across irradiance, load, temperature, and battery-SoC variations. Incorporating MPPT, battery-protection constraints, adaptive control, and experimentally validated energy-management logic would further support practical deployment in PV-assisted DC microgrids and charging systems.

Declarations and ethical statements

Conflict of interest: The authors declare that they have no conflicts of interest.

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Artificial Intelligence usage statement: During the preparation of this manuscript, the authors used ChatGPT solely for language refinement and grammatical correction. The authors reviewed and revised all generated content and take full responsibility for the accuracy, integrity, and originality of the final manuscript.

Availability of data and materials: The data and/or materials that support the findings of this study are available from the corresponding author upon reasonable request.

CRediT authorship contribution statement

Sudheer Peddeeti: Conceptualization, Supervision, Methodology, Writing – original draft, review & editing. Validation.
Santhosha Kumara A: Methodology & Validation.
Anni Raj Gupta: Methodology & Visualization.

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Table 1: Converter-design and simulation parameters

Parameter	Symbol	Adopted value	Description
PV irradiance	G	1000 W/m ²	Irradiance applied to the PV source during simulation.
PV-cell temperature	T	25 °C	PV operating temperature maintained during the evaluated cases.
DC-bus voltage	E_{in}	48 V	Higher-voltage terminal used as the input during buck-mode charging.
Nominal battery-side voltage	E_{out}	24 V	Lower-voltage terminal considered in the preliminary converter design.
Initial battery state of charge	SoC ₀	45%	Initial SoC used for both charging and discharging simulations.
Designed charging current	I_{chg}	10 A	Battery-current reference used during buck-mode charging.
Designed discharging current	I_{dis}	10 A	Nominal current adopted for boost-mode passive-component design.
Switching frequency	f_s	25 kHz	PWM switching frequency of the controlled semiconductor devices.
Assumed converter efficiency	η	90%	Preliminary efficiency used in the duty-ratio calculations.
Buck-mode duty ratio	D_{buck}	0.556	Calculated using $D_{buck} = E_{out}/(E_{in}\eta)$.
Boost-mode duty ratio	D_{boost}	0.55	Calculated using $D_{boost} = 1 - E_{in}\eta/E_{out}$, with the terminal definitions reversed for boost operation.
Allowable inductor-current ripple	ΔI_L	1 A	Corresponds to 10% of the nominal design current.
Selected converter inductance	L	0.48 mH	Energy-transfer inductance used in the simulated converter model.
Buck-mode voltage-ripple limit	$\Delta E_{out,b}$	0.24 V	Allowable output-voltage ripple adopted for buck-mode design.
Buck-side capacitance	$C_{out,b}$	20.83 μ F	Minimum capacitance obtained from the buck-mode design expression.
Boost-mode voltage-ripple limit	$\Delta E_{out,bo}$	0.48 V	Allowable output-voltage ripple adopted for boost-mode design.
Boost-side capacitance	$C_{out,bo}$	416.6 μ F	Minimum capacitance obtained from the boost-mode design expression.
Charging-voltage steady state	$V_{bat,ss}$	27.82 V	Settled battery-terminal voltage during the charging case.
Simulation duration	t_{sim}	2 s	Observation interval used for the reported charging and discharging results.
Controller	—	PI controller	Closed-loop controller used to regulate the converter response.