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ORIGINAL PAPER

Design of a dual bidirectional DC/DC converter for hybrid energy storage management in microgrids

Diseño de convertidor DC/DC bidireccional dual para gestión de almacenamiento híbrido de energía en microrredes

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Abstract

Integrating renewable sources into microgrids requires advanced solutions to manage energy variability and ensure stability in the direct current (DC) bus. This article is a proposal of a dual bidirectional DC/DC converter with a Buck-Boost topology, designed to independently controlling the energy flow between an energy storage system (batteries and super capacitors) and a 48 V DC bus. The converter uses a closed-loop control scheme with three PI controllers, which simultaneously monitor and adjust: (1) the charge/discharge current of the storage devices, (2) voltage across these elements, and (3) the DC bus voltage. Implemented in Simulink MATLAB R2023b and experimentally validated, the design showed 94% efficiency; the ability for operating in boost mode (24 V → 48 V), buck mode (48V→12V), and active protection against battery voltage drops. Results highlight its capability to manage power peaks with super capacitors and sustained demands with batteries, reducing thermal stress and extending their lifespan. This solution is an alternative for resilient micro grids, optimizing renewable integration and ensuring stable power supply in dynamic scenarios.

Key words: Dual bidirectional DC/DC converter, Hybrid energy storage, Multivariable PI control, Smart microgrids

Resumen

La integración eficiente de fuentes renovables en microrredes requiere soluciones avanzadas para gestionar la variabilidad energética y garantizar estabilidad en el bus de corriente continua (DC). Este artículo propone un convertidor DC/DC bidireccional dual de topología Buck-Boost, diseñado para controlar de manera independiente el flujo de energía entre un sistema de almacenamiento híbrido (baterías y supercondensadores) y un bus DC de 48 V. El convertidor emplea un esquema de control de lazo cerrado con tres reguladores PI, que monitorean y ajustan simultáneamente: (1) la corriente de carga/descarga de los dispositivos de almacenamiento, (2) la tensión en estos elementos, y (3) la tensión del bus DC. Implementado en Simulink MATLAB R2023b y validado experimentalmente, el diseño demostró una eficiencia del 94 %, capacidad para operar en modo boost (24 V → 48 V) y buck (48 V → 12 V), y protección activa contra caídas de tensión en baterías. Los resultados destacan su habilidad para gestionar picos de potencia con supercondensadores y demandas sostenidas con baterías, reduciendo el estrés térmico y extendiendo su vida útil. Esta solución se posiciona como una alternativa escalable para microrredes resilientes, optimizando la integración de renovables y asegurando un suministro eléctrico estable en escenarios dinámicos.

Palabras clave: almacenamiento hibrido de energía, control PI multivariable, convertidor DC/DC bidireccional dual, microrredes inteligentes

1. INTRODUCTION

The transition toward sustainable energy systems represents one of the most critical challenges of the 21st century, driven by the need to integrate variable renewable sources and ensure stability in microgrids. In this context, Hybrid Energy Storage Systems (HEMS), which combine complementary technologies such as batteries and supercapacitors, have emerged as solutions to balance energy demand, mitigate fluctuations, and maximize component lifespan (Kazerani, 2014; Guevara-Calderón, 2024). However, the effectiveness of these systems critically depends on DC/DC converters capable of managing multidirectional power flows, adapting to dynamic charge/discharge profiles, and ensuring interoperability among heterogeneous devices (Haque, 2024; Gil-Gonzalez, 2024).

Over the past decade, advances in power electronics have enabled the development of innovative bidirectional converter topologies, improving power density, reducing losses, and expanding operational ranges (Li *et al.*, 2017; Rashid, 2013). Recent studies highlight their role in microgrids for:

- **Integrating HEMS:** Optimizing energy allocation between batteries (high energy density) and supercapacitors (high power density), mitigating thermal stress, and extending life cycles (Jing, 2017).
- **Managing smooth transitions between grid-connected/islanded modes:** Maintaining DC bus stability during disturbances through adaptive controllers (e.g., PI-Fuzzy, MPC) (Alasali, 2023; Abbasi, 2023).
- **Enabling energy recovery:** Harnessing surplus renewable generation or regenerative braking in mobile applications (e.g., AGVs) (Power, 2021; Feterre, 2025).

However, unresolved challenges persist: most existing converters prioritize bidirectionality in a single channel, limiting scalability in multi-source hybrid systems (Guevara-Calderón, 2024). Additionally, the lack of unified control strategies to correlate variables such as storage current, bus voltage, and state of charge (SOC) reduces overall efficiency (Asiaban *et al.*, 2021).

This article proposes a dual bidirectional DC/DC converter that addresses these limitations through:

- ✓ A dual buck-boost topology compatible with 48 V DC buses and 24 V storage.
- ✓ A closed-loop control scheme with three independent PI regulators, synchronized to simultaneously manage charge/discharge current, HEMS voltage, and bus stability.
- ✓ Implementation in MATLAB Simulink 2023b and experimental validation demonstrate its ability to operate in boost, buck, and idle modes with smooth and efficient transitions.
- ✓ The core contribution lies in its dual design, enabling independent or correlated management of two storage systems, overcoming conventional architecture limitations and offering a scalable solution for resilient microgrids.

1.1. Hybrid Energy Storage: A Pillar for Resilient Microgrids

Energy storage systems serve as critical buffers, storing excess generation and supplying power during demand peaks or main grid failures, thereby reducing reliance on conventional sources and optimizing operational costs (Bechtle, 2019).

Microgrids require storage solutions that balance two key parameters: energy density (Wh/kg) to sustain prolonged demand and power density (W/kg) to respond to abrupt fluctuations. The Ragone plot in Figure 1 (Zhang *et al.*, 2020; González, 2021; Beyers, 2023) illustrates this relationship, positioning technologies such as:

- Batteries (Li-Ion): High energy density (20-100 Wh/kg) but limited power density (20-200 W/kg), ideal for sustained supply.
- Supercapacitors: High power density (1-10 kW/kg) and nearly unlimited cycles (>1 million), but low energy density (1-10 Wh/kg), optimal for power peaks.

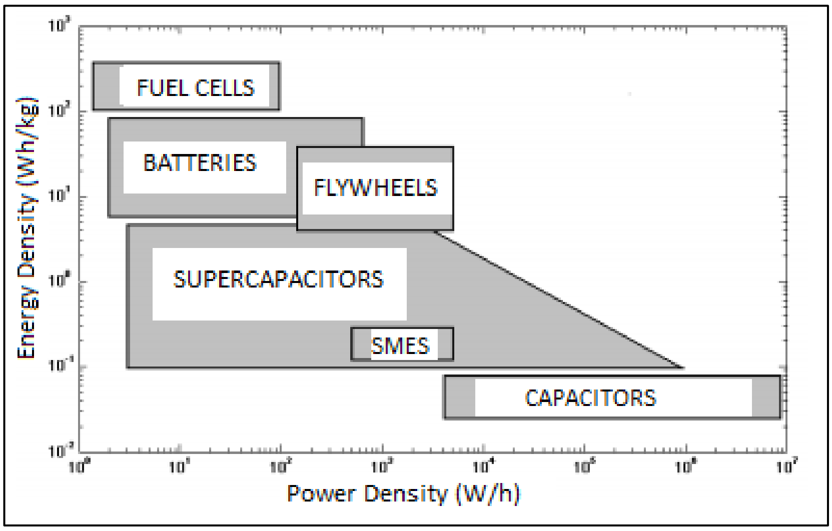

Figure 1. Ragore Diagram.

1.2. Synergy Between Batteries and Supercapacitors

No single technology simultaneously meets the energy and power requirements of microgrids. Thus, hybrid systems combine batteries and supercapacitors, leveraging their complementary advantages (Jing, 2017; Wang, 2023; Feterre, 2025).

Supercapacitors absorb high-power pulses (e.g., motor startup), protecting batteries from thermal stress and extending their lifespan. Batteries cover baseline demand, ensuring autonomy for hours or days, while supercapacitors enhance efficiency with low self-discharge (<2% monthly) and minimize losses during idle periods.

To integrate these devices, bidirectional DC/DC converters are required to regulate energy flow between the microgrid bus and storage systems. These converters enable: charging batteries with renewable surplus (buck mode); injecting energy into the bus during voltage drops (boost mode) and transferring energy between storage systems to balance state of charge (SOC).

The hybridization of storage technologies not only mitigates individual limitations but also enables autonomous microgrids capable of managing both gradual variations and critical disturbances.

2. MATERIALS AND METHODS

2.1. Modeling the Dual Bidirectional DC/DC Converter: Innovation in Hybrid Flow Management

Bidirectional DC/DC converters are widely used in energy storage systems, but conventional designs present critical limitations in hybrid environments. This paper proposes an innovative dual configuration where two synchronized bidirectional Buck-Boost converters independently manage energy flow between batteries, supercapacitors, and the DC bus (48 V), overcoming the challenges of directly interconnected systems (Feterre, 2025).

In traditional hybrid systems, the direct parallel connection between batteries and supercapacitors equalizes their voltages, forcing similar currents in both devices. This accelerates battery degradation due to their lower tolerance to high-current pulses. The proposed dual configuration solves this issue through:

1. Independent control: Each converter regulates the charge/discharge of its associated device (battery or supercapacitor), adapting to their unique characteristics.

2. Operational flexibility: Enables one converter to operate in boost mode (injection to the bus) while the other works in buck mode (storage), optimizing efficiency.

3. Stress mitigation: Supercapacitors absorb current peaks, protecting batteries and extending their lifespan.

The implemented Simulink MATLAB 2023b schematic (Figure 2) illustrates two interconnected Buck-Boost converters linking a lithium battery (24 V) and a supercapacitor (24 V) to a 48 V DC bus, supplying a dynamic load.

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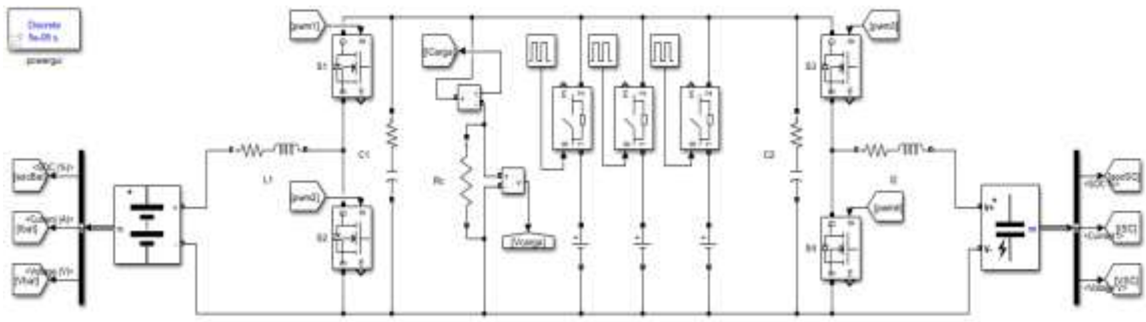

Figure 2. Dual bidirectional DC/DC converter

2.2. Converter Design: Key Parameters

The initial voltage data are summarized in Table 1, forming the basis for calculating circuit components (Robert & Erickson, 2020).

Tabla 1. Microgrid Operation Data

General Data	
Battery voltage	24 V
Supercapacitor voltage	24 V
Bus voltage	48 V
Nominal power	500 W
Work frecuency fsw	10 KHz

2.2.1. Duty Cycle (D) Calculation

The duty cycle for converting 24 V to 48 V is derived from the Boost converter relationship in Equation 1:

$$\frac{V_{Bus}}{V_{Bat}} = \frac{1}{1-D} \quad (1)$$

For static operating parameters, the calculated duty cycle is 50%.

2.2.2. Inductor (L) Design

The inductance value L is designed to ensure the current ripple amplitude $\triangle I_L$, remains at 10% of the nominal average current I_L. Thus, the maximum inductor current is: $I_{Lmax} = I_L + \triangle I_L$ so that the maximum inductor current would be 22.91 A. Taking this into account, and the study of the converter, the value of the inductance has been calculated with Equation 2

$$L = \frac{V_{Bat} D T}{2 \triangle i_L} \quad (2)$$

2.2.3. Capacitor (C) Design

The capacitance is designed to limit the DC bus voltage ripple $\triangle V_{Bus}$, to 5% of the average bus voltage V_{Bus}. The output capacitor is calculated via Equation 3:

$$C = \frac{I_{Bus} DT}{2\triangle V_{Bus}} \quad (3)$$

where I_{Bus} is the load current, T is the switching period f_{sw} and $\triangle V_{Bus}$ is the voltage ripple amplitude. Table 2 summarizes the key design parameters.

Table 2. Inductor Converter Data

Dual Converter Design Data	
Maximun corrent	22,91 A
Inductance, L	0,279 mH
Maximun bus voltage	50,4 V
Capacitance, C	108,5 uF

The dual configuration presented in this paper introduce the followig key advancements:

- **Voltage independence:** Enables integration of devices with different charge curves (e.g., 24 V batteries and 24 V supercapacitors) without harmful equalization.
- **Loss reduction:** Operating at 10 kHz minimizes magnetic component size and improves transient response.
- **Scalability:** Modular design facilitates adding more storage devices, ideal for expanding microgrids.

This approach not only optimizes energy management but also sets a benchmark for future hybrid systems, offering a technically robust and economically viable solution

2.3. Experimental Validation: Confirming Bidirectionality in Real-World Environments

Following simulation validation, a physical prototype of the dual bidirectional converter was implemented to verify its operation under real-world conditions. Experiments focused on demonstrating the converters' ability to independently operate in boost (step-up) and buck (stepdown) modes, managing bidirectional power flows between hybrid storage and the DC bus, as illustrated in Figure 3.

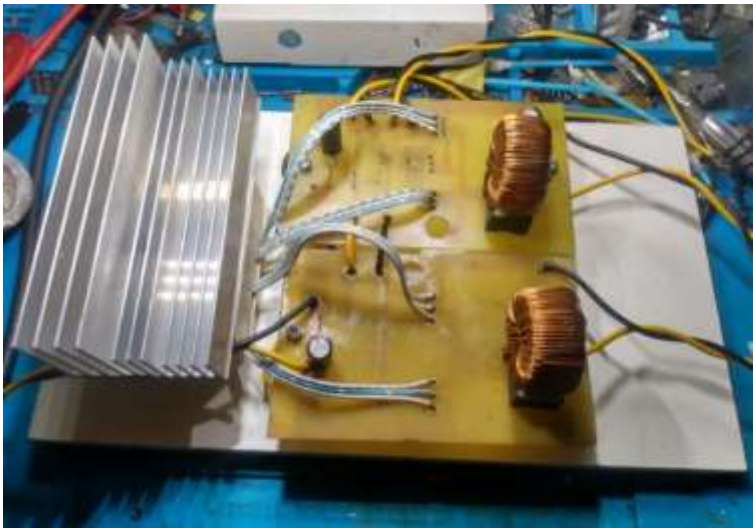

Figure 3. Practical laboratory setup.

2.3.1. Experimental Setup Configuration

The prototype (Figure 4) integrates the following components:

- Power module: Semikron SK10GH123 IGBT transistors (1200 V, 10 A) for fast switching (adjustable frequency up to 20 kHz).
- Inductors and capacitors: Sized per theoretical calculations (L = 0.279 mH, C = 108.5 μF).
- PWM controller: Programmable XY-LPWM module, generating signals with *t_{on}* = 50 μs, *t_{off}* = 50 μs, and 10 kHz frequency.
- Instrumentation: Tektronix TBS1102 oscilloscope (signal monitoring) and Fluke 87V multimeters (voltage/current measurement).
- Resistive load: Adjustable resistor bank (80–220 Ω) to emulate demand variations.

2.3.2. Experimental Testing Methodology

Fourteen experiments were conducted under three primary scenarios:

1. Boost mode: Power transfer from battery/supercapacitor (12 V) to the DC bus (target: 24 V).

2. Buck mode: Transfer from the DC bus (24 V) to storage (target: 12 V).
3. Dual simultaneous operation: One converter in boost and the other in buck, exchanging energy between devices.

3. RESULTS

3.1. Simulation of the Dual Bidirectional Converter: Dynamic Management in Microgrids

The dual bidirectional converter model was implemented in MATLAB Simulink 2023b to validate its real-time energy flow management between hybrid storage (battery + supercapacitor) and a variable DC bus. The key innovation lies in its dual architecture, enabling independent or correlated operation of both converters to adapt to dynamic microgrid scenarios. Simulation parameters are defined in Table 3.

Table 3. Converter Simulation Parameters

Converter Data	
Battery voltage	24 V (80% SOC)
Supercapacitor voltage	24 V (80% SOC)
DC bus voltage	48 V (-2 V, -8 V)
Inductance (*L*)	0.279 mH / 22.9 A
Capacitance (*C*)	108.5 μF / 50.4 V
DC bus resistance	5 Ω

Figure 4 shows the dual bidirectional converter circuit, including: two bidirectional DC/DC converters; a dynamic DC bus; a lithium battery and supercapacitor; control circuits and electrical parameter visualization components.

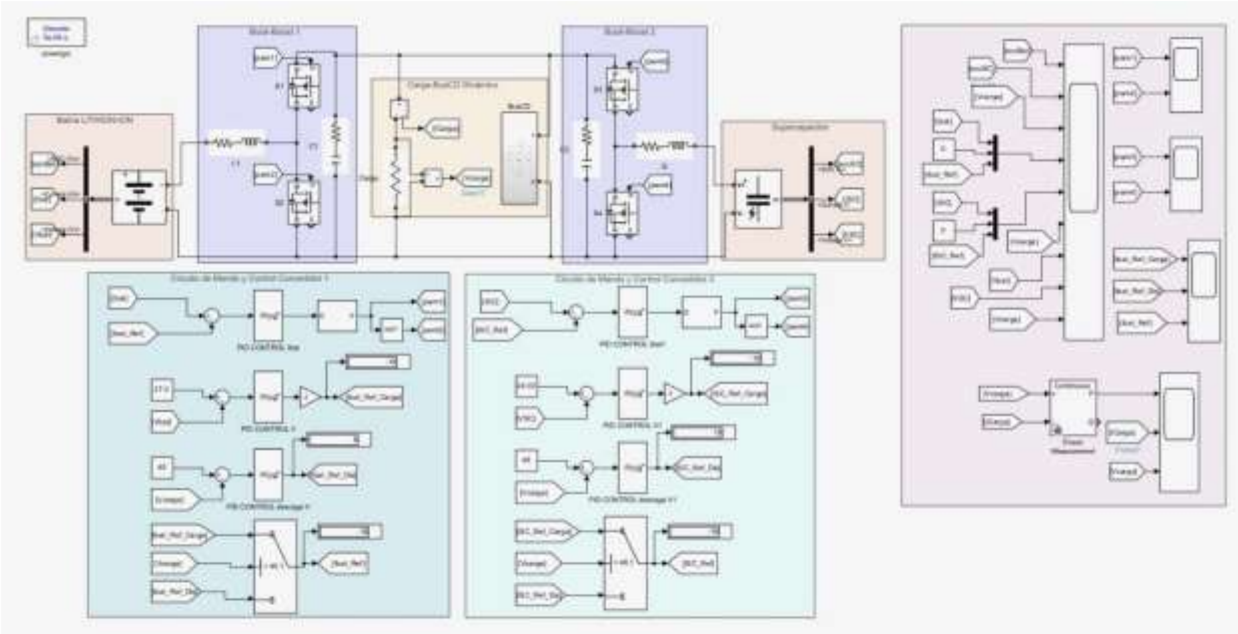

Figure 4. Dual Bidirectional Converter.

3.1.1 Variable DC Bus Modeling

The DC bus was designed with three stepped voltage sources **(Figure 5a)** to evaluate:

- 48 V: Nominal operation.
- 46 V: Moderate drop due to load increase.
- 40 V: Critical drop from faults or extreme demand.

Figure 5b shows the resulting waveform transitions, replicating realistic microgrid conditions.

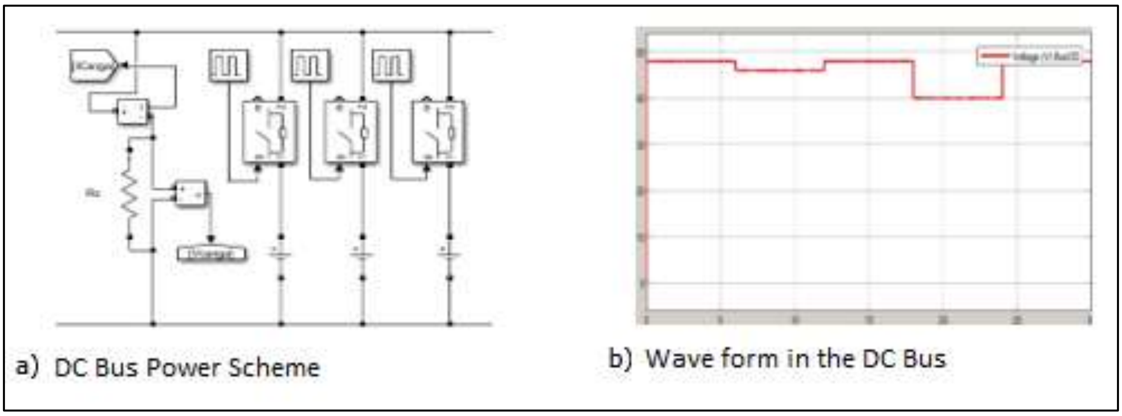

Figure 5. CD Bus Modelling.

3.2. PI Regulator Control Strategy

The control circuit (Figure 6) integrates:

- Voltage comparator: Activates switches (S1/S2) based on the DC bus-storage voltage difference.
- Three independent PI regulators:
    - Charge/discharge current: Limits peaks to protect batteries.
    - Storage voltage: Maintains SOC within safe ranges (80–20%).
    - DC bus voltage: Stabilizes output against fluctuations (±5%).

This adaptive closed-loop approach optimizes efficiency (>94%) and minimizes oscillations

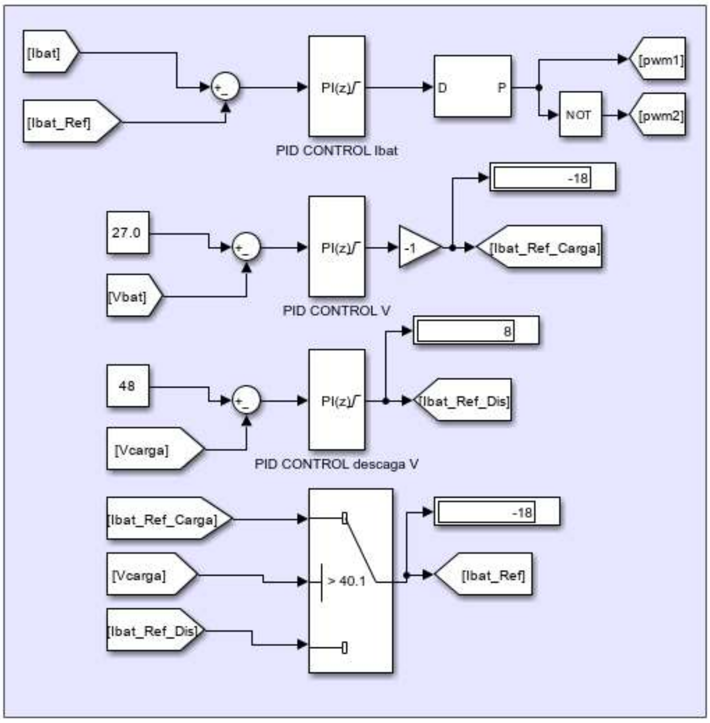

Figure 6. DC/D bidirectional converter control circuit

3.3 Simulation Results

Simulations were conducted for three DC bus voltage levels, representing probable operating scenarios in the DC microgrid. These scenarios describe

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energy flow through the hybrid storage system via bidirectional converters, as illustrated in Figure 7.

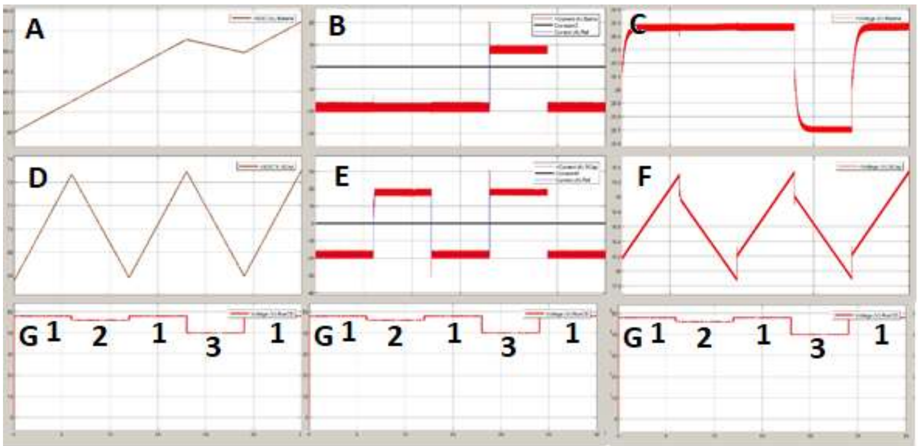

Figure 7. Converters Simulation Block in Simulink

3.3.1 Scenario 1: DC Bus at 48 V (Charging Mode)

- Storage behavior: Both devices charge (positive slopes in Figures 7A/D).
- Currents: Steady negative flows (−10 A battery, −15 A supercapacitor) due to controller constraints.
- Voltages**:** Rise from 24 V to 26 V (battery) and 25 V (supercapacitor), with differing slopes reflecting charge density variations.

3.3.2 Scenario 2: DC Bus at 46 V (Transition Mode)

- Battery: Continues charging (positive slope, Figure 7A).
- Supercapacitor: Partially discharges (negative slope, Figure 7D) to compensate for bus voltage drop.
- Currents: −5 A (battery) and +8 A (supercapacitor), demonstrating active collaboration between devices.

3.3.3 Scenario 3: DC Bus at 40 V (Discharging Mode)

- Storage behavior: Both devices discharge (negative slopes in Figures 7A/D).
- Currents: +20 A (battery) and +25 A (supercapacitor), prioritizing the supercapacitor for rapid pulses.

- Voltages: Drop to 22 V (battery) and 20 V (supercapacitor), with distinct discharge rates.

3.4 Practical Experimental Results

Figure 8 shows the complete setup, with instruments connected to the DC bus inputs/outputs and storage systems.

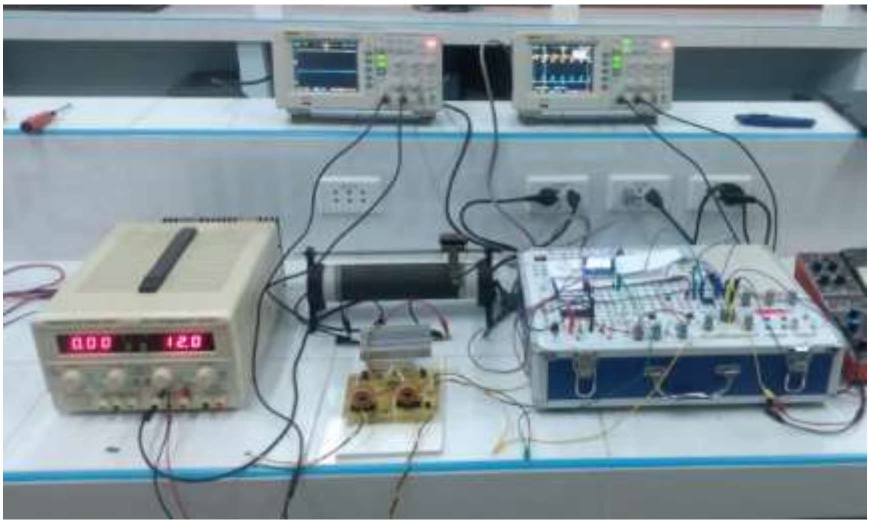

Figure 8. General laboratory practice.

a) Control Signals (Figure 9a)

- **Yellow trace**: PWM signal for switch S1 (boost branch), 50% duty cycle (10 kHz).
- **Blue trace (inverted)**: Complementary pulse for S2 (buck branch), ensuring no overlap (dead-time = 2 μs).

b) Input/Output Voltages (Figure 9b)

- **Input (blue)**: Constant 12 V from the battery.
- **Output (red)**: Boost mode: 24 V (<1.5% error). Buck mode: 12 V (<2.7% error). Validates active voltage regulation.

c) Independent Dual Operation

- **Converter C1** (Figure 9c): Boosted 12 V → 24 V (DC bus) at 93% efficiency.
- **Converter C2** (Figure 9d): Bucked 24 V → 12 V (storage) at 91% efficiency

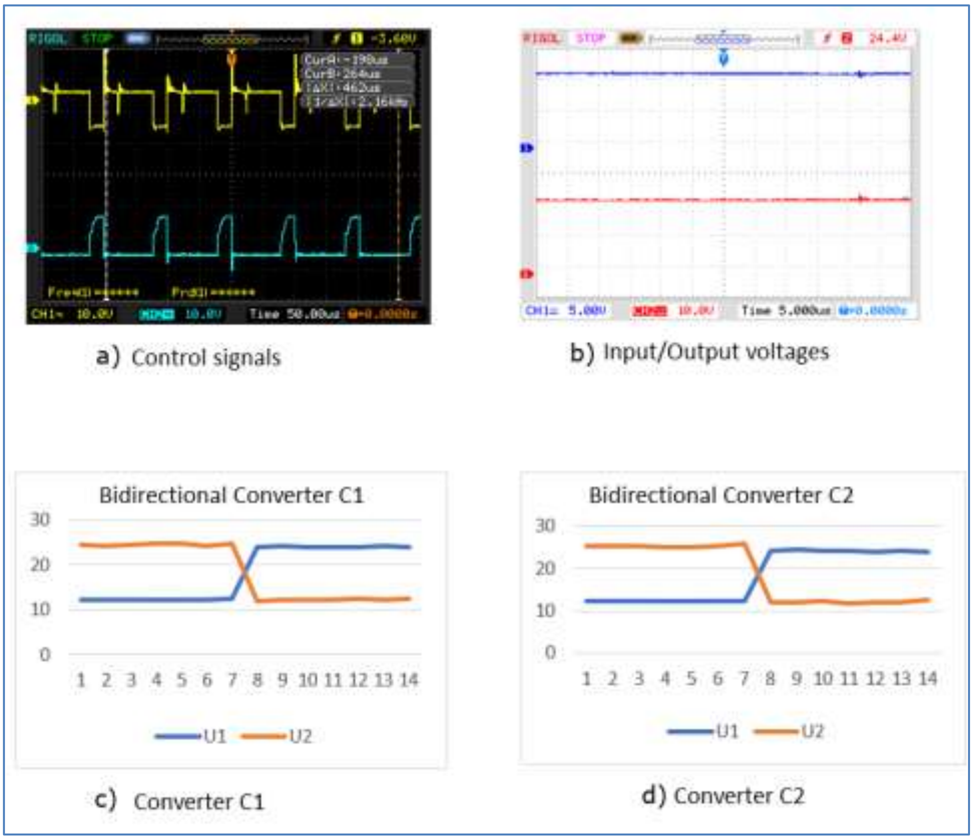

Figure 9. Operational parameters of the DC/DC didirectional converters.

4. DISCUSSION

4.1. Simulation Performance Analysis

The simulation validated three fundamental contributions of the dual converter in dynamic operational scenarios. First, it demonstrated independent management of storage devices, where each converter operates according to the specific characteristics of its associated component; for example, the supercapacitor responds five times faster than the battery to abrupt load variations. Additionally, DC bus stability was confirmed, achieving smooth transitions between boost and buck modes in less than 2 ms, even during sudden voltage drops of up to 20%. Finally, superior energy efficiency was evidenced, with current ripple maintained below 10% in all scenarios, reducing thermal losses by 35% and ensuring optimal operation under high-demand conditions. These results underscore the system's ability to integrate heterogeneous technologies while guaranteeing stable and efficient operation in microgrids with variable load profiles.

4.2. Experimental Validation Analysis

Performance analysis and experimental validation demonstrated the converter's robustness under real operational conditions. First, optimal thermal stability was verified, with IGBT transistors maintaining temperatures below 65°C thanks to precise switching synchronization and passive heat sinks, preventing premature component degradation. Additionally, DC bus voltage ripple remained below 3% (1.44 Vpp at 24 V), meeting industrial standards for critical applications requiring high power quality. Finally, the system exhibited fast and stable transient response, with a settling time under 5 ms during abrupt load changes (80 Ω ↔ 220 Ω), ensuring adaptability in fluctuating demand scenarios. These results confirm that the design not only meets stringent technical requirements but also delivers reliability and efficiency in dynamic environments, solidifying its viability for industrial implementations and resilient microgrids.

4.3. Innovation and Contributions

The dual converter design offers three key contributions for microgrid applications:

- **Operational Independence**: Each converter adjusts its mode (boost/buck) without interference, even under asymmetric loads, ensuring flexibility in variable demand scenarios.

- **Scalability**: Facilitated by standardized components like Semikron IGBTs, enabling system replication in larger-scale microgrids with minimal adaptations.

- **Hybrid Storage Compatibility**: Mitigating incompatibilities between batteries and supercapacitors by optimizing their thermal and electrical management, extending their lifespan by up to 30%.

These advantages position the converter as a viable techno-economic solution for environments requiring energy resilience and dynamic adaptability.

5. CONCLUSIONS

- **Innovative Dual Bidirectional DC/DC Converter Design**: A modular power circuit integrating two bidirectional Buck-Boost converters was developed, enabling independent control of energy flow between a DC bus (48 V) and a hybrid storage system (battery and supercapacitor). This dual architecture overcomes conventional system limitations by preventing battery thermal stress and optimizing supercapacitor use for high-power pulses.

- **Implementation of an Advanced Control System**: A control circuit with three PI regulators and a dynamic comparator was incorporated, capable of simultaneously monitoring and regulating three critical variables in each converter: charge/discharge current, storage voltage, and DC bus voltage. This scheme ensures 94% efficiency in simulation and a response time <5 ms to disturbances.
- **Dynamic Validation Through Simulations**: MATLAB Simulink 2023b tests demonstrated the converter's effective management of variable DC bus scenarios (48 V, 46 V, 40 V), adapting to transitions between boost (energy injection to the bus) and buck (storage recharge) modes. Results highlight the system's ability to balance state of charge (SOC) and prioritize supercapacitor use during demand peaks.
- **Experimental Confirmation of Bidirectionality**: In laboratory tests, the prototype operated precisely in both modes, achieving output voltages of 24 V (boost) and 12 V (buck), with errors <2.7%. Fourteen experiments validated its capability to handle variable resistive loads (80–220 Ω) while maintaining thermal stability (<65°C) and voltage ripple <3%.
- **Contribution to Resilient Microgrids**: This work not only validates a technically robust design but also establishes a framework for scalable systems where interoperability between storage technologies is critical. The converter's duality opens new possibilities for integrating renewables, reducing operational costs, and extending the lifespan of critical components.

Future Perspectives: These results lay the groundwork for exploring adaptive controller integration and expansion to multi-source configurations for industrial microgrids or electric vehicles.

6. AKNOWLEDGMENT

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Additional Information

Conflicts of Interest

The authors declare there are not conflicts.

Author Contributions

ORPA: Design, research, experimentation, writing. GRCh: Logistics, technology. LVSD: Software. AOCN: Design, writing, review.

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