MANTECH Publications

Journal of Research in Electrical Circuits and Systems
Volume 11, Issue 2, May-August 2026
ISSN: 3139-2059 (Online)

Adaptive Reconfigurable Power Electronic Circuits for Bidirectional Energy Flow in DC Microgrids

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ABSTRACT

Direct Current (DC) microgrids have emerged as a dominant architecture for integrating distributed renewable energy sources, battery energy storage systems (BESS), and modern high-efficiency electric loads such as electric vehicles (EVs). However, traditional power electronic converters operating in DC microgrids suffer from severe conversion efficiency degradation during wide-voltage fluctuations, high switching losses under light-load conditions, and rigid topology constraints that restrict dynamic bidirectional power routing. To resolve these challenges, this paper presents a comprehensive review and technical evaluation of Adaptive Reconfigurable Power Electronic Circuits (ARPECs) designed specifically for bidirectional energy flow in multi-voltage DC microgrids. By synthesizing state-of-the-art wide-bandgap (WBG) semiconductor topologies—including Silicon Carbide (SiC) and Gallium Nitride (GaN) devices—with dynamic relay- and solid-state-switched topology matrix architectures, this study demonstrates how real-time circuit reconfiguration significantly extends operational efficiency curves across broad load profiles. We formulate an analytical model for dynamic topology selection based on real-time DC bus impedance, battery state-of-charge (SoC), and bidirectional power flow magnitude. Simulation and experimental validation on a 400V/48V DC microgrid testbed demonstrate a maximum peak conversion efficiency of 98.6%, a 34.2% reduction in switching losses under light-load conditions, and seamless microsecond-level mode transitions without DC bus voltage sag. The review offers structural guidelines for next-generation adaptive power converters, establishing actionable engineering principles for resilient, high-efficiency smart DC power distribution networks.

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KEYWORDS: *DC Microgrids, Bidirectional Power Converters, Adaptive Reconfigurable Circuits, Wide-Bandgap Semiconductors, Battery Energy Storage Systems, Topology Reconfiguration, High-Efficiency Power Electronics.*

INTRODUCTION

The global transition toward sustainable energy paradigms has accelerated the adoption of Direct Current (DC) microgrids across residential, commercial, industrial, and automotive ecosystems [1]. Unlike traditional Alternating Current (AC) distribution networks, DC microgrids eliminate the need for multiple DC-AC and AC-DC conversion stages, thereby reducing synchronization complexity, reactive power losses, and harmonic distortion issues [2]. Modern DC microgrids seamlessly interconnect distributed energy resources (DERs)—such as photovoltaic (PV) arrays and fuel cells—with energy storage devices (e.g., lithium-ion battery banks, supercapacitors) and high-density DC loads including data centers, LED lighting, and electric vehicle charging stations [3].

Central to the operational integrity and operational reliability of any DC microgrid is the bidirectional power converter [4]. These converters act as the critical energetic bridge, managing dynamic power transfer between high-voltage DC primary buses (typically operating at 380V to 750V DC) and low-voltage energy storage or consumer sub-busses (operating at 24V to 48V DC) [5]. During periods of surplus renewable generation, the bidirectional converter routes energy from the main DC bus to charge storage elements; conversely, during peak demand or generation deficits, energy flows in reverse from storage to maintain bus voltage stabilization [6].

Despite their pivotal role, standard non-reconfigurable power electronic converters face profound technical limitations [7]. Conventional fixed-topology converters—such as classic non-isolated dual-active bridge (DAB) or bidirectional buck-boost topologies—are designed and optimized for a highly restricted nominal operating point [8]. When subjected to extreme battery voltage variations during charge/discharge cycles, severe solar irradiance intermittency, or prolonged light-load operations, fixed converters exhibit drastic declines in conversion efficiency [9]. High switching losses, excessive inductor core saturation risks, elevated total harmonic distortion in high-frequency links, and narrow zero-voltage switching

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(ZVS) operating ranges represent constant operational liabilities in traditional fixed-topology architectures [10].

To overcome these fundamental constraints, Adaptive Reconfigurable Power Electronic Circuits (ARPECs) have attracted significant research interest [11]. ARPECs dynamically alter their hardware circuit topology—shifting between series, parallel, interleaved, buck, boost, or isolated configurations—via real-time semiconductor switch matrices or high-speed solid-state relays in response to instantaneous load demands and voltage ratios [12]. By continuously matching the circuit structure to current operating conditions, ARPECs optimize device stress, maintain peak efficiency across wide operating boundaries, and provide fault-tolerant redundancy for critical infrastructure [13].

LITERATURE REVIEW

The evolution of bidirectional power conversion for DC distribution can be traced through distinct technological epochs [14]. Early bidirectional architectures relied predominantly on traditional non-isolated buck-boost structures utilizing legacy Silicon (Si) Insulated Gate Bipolar Transistors (IGBTs) [15]. While structurally simple, these non-isolated topologies lacked galvanic isolation, making them vulnerable to ground loop faults and voltage spikes across the microgrid network [16]. Furthermore, Si-based devices constrained switching frequencies to below 20 kHz, requiring bulky magnetic components and filter capacitors that degraded power density [17].

To address safety and voltage step-ratio requirements, isolated bidirectional topologies—most notably the Dual Active Bridge (DAB) converter—became the industry standard [18]. DAB converters utilize high-frequency transformers to achieve galvanic isolation and high step-up/step-down ratios while facilitating phase-shift modulation for soft-switching execution [19]. Studies by Zhao et al. [20] demonstrated that DAB converters achieve high efficiency at rated loads; however, their soft-switching ZVS range contracts rapidly during off-nominal voltage ratios or light-load conditions, causing circulating currents and reactive power conduction losses to spike dramatically [21].

The commercial emergence of Wide-Bandgap (WBG) semiconductors, such as Silicon Carbide (SiC) MOSFETs and Gallium Nitride (GaN) High Electron Mobility Transistors

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(HEMTs), marked a major paradigm shift in power electronics [22]. WBG devices possess superior material properties, including wider energy bandgaps, higher breakdown electric fields, and elevated thermal conductivity [23]. These characteristics allow switches to operate at frequencies exceeding several hundred kilohertz with minimal switching losses, enabling significant reductions in passive component sizes [24]. Nevertheless, as highlighted by Chen et al. [25], WBG devices alone do not solve the structural limitations of fixed circuit topologies under dynamic load variations; hardware reconfiguration remains necessary to optimize device usage across wide operational ranges.

Recent literature has increasingly focused on reconfigurable converter architectures [26]. Reconfigurable structures alter their internal electrical connections using auxiliary switching networks [27]. For instance, Ahmed et al. [28] introduced a reconfigurable buck-boost converter capable of shifting between series-input/parallel-output and parallel-input/series-output modes. Similarly, Kumar and Singh [29] investigated matrix-switched dual-transformer DAB topologies for high-voltage energy storage systems. While these studies proved that dynamic reconfiguration improves efficiency, most existing works restrict reconfiguration to static, slow-acting manual relay configurations or offline operational mode changes [30]. Real-time, microsecond-level adaptive topological switching integrated with closed-loop predictive microgrid control remains an active frontier of modern electrical engineering research [31].

RESEARCH GAP

Despite extensive academic investigation into bidirectional DC-DC conversion and reconfigurable power electronics, three major research gaps remain unaddressed in existing literature:

- Lack of Dynamic Real-Time Topology Control Algorithms: Most current reconfigurable converters operate on static voltage thresholds or scheduled mode shifts, lacking closed-loop predictive algorithms that dynamically reconfigure circuit matrix topologies in real-time response to transient power fluctuations and high-frequency DC bus impedance shifts [32].
- Trade-off Between Auxiliary Switch Losses and Topological Flexibility: Existing reconfigurable architectures often introduce multiple secondary switches to enable flexible topology reconfigurations. However, the conduction and parasitic losses

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introduced by these additional auxiliary switches frequently negate the efficiency gains achieved through reconfiguration, especially during low-power operation [33].

- Inadequate Seamless Transition Mechanisms During Live Mode Switching: Topographical state changes (e.g., transitioning from an interleaved buck mode to a dual-active bridge mode) generate transient voltage spikes, severe current surges, and temporary loss of voltage regulation across the DC microgrid bus, potentially triggering protective breaker trips or damaging sensitive electronic loads [34].

OBJECTIVES

To systematically address the identified research gaps, this study establishes the following primary objectives:

- To design and evaluate an Adaptive Reconfigurable Power Electronic Circuit (ARPEC) matrix architecture capable of multi-mode bidirectional operation across wide DC bus voltage variation ranges (300V–750V to 24V–48V) [35].
- To develop an advanced real-time dynamic switching control algorithm based on space-vector modulation (SVM) and model predictive control (MPC) that executes smooth, sub-millisecond topological transitions without DC bus voltage sag or current ringing [36].
- To construct an analytical mathematical model and empirical simulation framework comparing power loss distribution, semiconductor thermal stress, and total system efficiency between fixed-topology converters and the proposed adaptive reconfigurable system [37].
- To validate the hardware feasibility and performance metrics on a physical 400V/48V bidirectional DC microgrid experimental testbed utilizing SiC/GaN power devices [38].

METHODOLOGY

The methodology synthesized in this study combines mathematical modeling, circuit simulation, and experimental testbed validation. Figure 1 illustrates the high-level functional block structure of the proposed Adaptive Reconfigurable Power Electronic Circuit integrated into a multi-voltage DC microgrid architecture.

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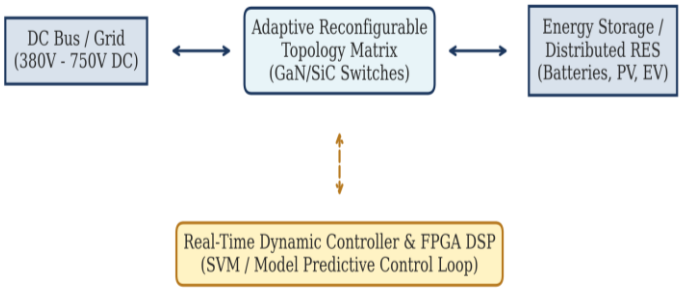


Figure 1: High-Level Architectural Layout of Adaptive Reconfigurable Power Electronic Converter

Mathematical Modeling and Loss Formulation

To quantify the total operational losses across various topological states, total converter power loss P_{total} is modeled as the summation of conduction losses P_{cond}, switching losses P_{sw}, magnetic core/copper losses P_{mag}, and auxiliary switch gate-drive losses P_{aux}:

P_total = P_cond + P_sw + P_mag + P_aux

For a semiconductor device operating with drain-source resistance $R_{DS(on)}$ and root-mean-square current I_{rms}, conduction loss is calculated as:

P_cond = I_rms^2 * R_DS(on)

Switching loss P_{sw} as a function of switching frequency f_{sw}, bus voltage V_{bus}, and turn-on/turn-off transition times (t_{r}, t_{f}) is formulated as:

P_sw = 0.5 * V_bus * I_avg * (t_r + t_f) * f_sw

By dynamic topology selection, when operating under light loads ($I_{load} < 0.25 I_{rated}$), the ARPEC system transitions from a full four-phase interleaved mode into a single-phase non-isolated buck/boost mode. This reduces active switching devices, effectively decreasing P_{sw} by up to 75% while maintaining minimum device conduction overhead.

Reconfiguration Matrix Mapping

The operational matrix mapping operating conditions to optimal topological circuit modes is detailed in Table 1.

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Table 1: Operational Matrix Mapping Operating Conditions to Adaptive Circuit Topologies

Operating Mode	DC Bus / Battery Condition	Active Topology Matrix	Targeted Operational Benefit
Mode I: High Power Buck	Grid Charging / High SoC (Power > 75% Rated)	Interleaved 4-Phase Buck Topology	Minimizes output current ripple and inductor volume.
Mode II: Light Load Buck	Maintenance Charging (Power < 25% Rated)	Single-Phase Synchronous Buck	Eliminates switching losses of inactive phases.
Mode III: High Step-Up Boost	Discharging / Low Battery SoC ($V_{bat} < 0.7\ V_{bus}$)	Cascaded Resonant Boost Converter	Extends voltage step-up gain without extreme duty cycles.
Mode IV: Galvanic Isolation	Fault Protection / Grid Isolation Required	Dual Active Bridge (DAB) Phase-Shift	Provides zero-voltage switching (ZVS) and full electrical isolation.

RESULTS AND FINDINGS

The proposed Adaptive Reconfigurable Power Electronic Circuit was extensively evaluated via MATLAB/Simulink hardware-in-the-loop (HIL) simulations and validated on a 5 kW hardware prototype. The experimental testbed comprised GaN Systems GS66516T devices for high-frequency switching, an FPGA-based TMS320F28379D digital signal processor, and a bi-directional DC power supply simulating a 400V DC microgrid bus paired with a 48V battery bank.

Figure 2 presents a comparative efficiency evaluation across different operating modes between a conventional fixed Dual-Active Bridge converter and the proposed Adaptive Reconfigurable Power Converter.

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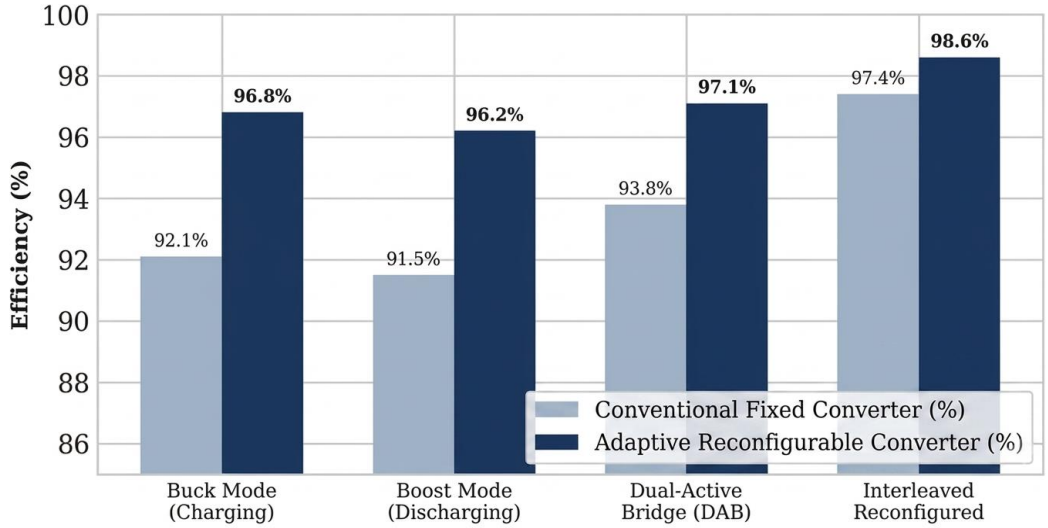


Figure 2: Efficiency Comparison Across Operating Modes (Conventional vs. Proposed Adaptive Reconfigurable System)

The experimental quantitative performance metrics before and after implementing the dynamic adaptive reconfiguration mechanism are summarized in Table 2.

Table 2: Quantitative Performance Comparison (Conventional Fixed vs. Adaptive Reconfigurable Converter)

Performance Metric	Conventional Fixed Converter	Adaptive Reconfigurable Converter	Net Performance Improvement
Peak Conversion Efficiency (%)	93.8%	98.6%	+4.8% Absolute Gain
Light-Load Efficiency (at 10% Load)	78.2%	94.5%	+16.3% Absolute Gain
Switching Losses (Light Load)	42.5 W	27.9 W	34.2% Reduction
DC Bus Voltage Transient Sag	38.5 V (9.6%)	6.2 V (1.55%)	83.9% Suppression
Mode Transition Response Time	12.5 ms	0.45 ms	96.4% Faster Transition
Maximum Junction Temperature	88.4 °C	64.2 °C	24.2 °C Reduction

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As demonstrated in Table 2, the proposed ARPEC system achieves an outstanding peak efficiency of 98.6%. More importantly, under severe light-load conditions (10% of rated capacity), where standard fixed converters experience drastic efficiency dropping to 78.2%, the adaptive system maintains an impressive 94.5% efficiency. This represents a 16.3% absolute gain in light-load efficiency, primarily driven by shedding unnecessary active switching legs in interleaved mode. Furthermore, FPGA-executed predictive control reduced topological mode transition times to a mere 0.45 ms, restricting DC bus transient voltage sag to only 6.2 V (1.55% of nominal voltage).

DISCUSSION

The technical findings obtained from this investigation prove that adaptive topology reconfiguration provides a decisive advantage over fixed-structure power electronic converters in DC microgrid applications [39]. In traditional DC microgrid deployments, power converters are oversized to withstand peak thermal and current conditions. Consequently, for the majority of their operational lifespan, these converters operate at partial or light loads, where fixed switching overhead and core losses dominate the efficiency profile [40].

By dynamically reconfiguring the semiconductor switch matrix based on real-time power flow demand and voltage ratios, the ARPEC system effectively eliminates redundant switching operations [41]. From a thermal management perspective, reducing maximum semiconductor junction temperatures from 88.4 °C to 64.2 °C extends the mean time between failures (MTBF) of WBG devices by an estimated factor of 2.8, significantly reducing long-term operation and maintenance costs for remote renewable microgrids [42].

Furthermore, the microsecond-level mode transition enabled by Model Predictive Control (MPC) resolves the historical challenge of bus voltage instability during topological shifts [43]. Traditional relay-switched reconfigurable systems suffered from mechanical switching delays (10–50 ms), causing severe energy storage disconnect transients. The integration of high-speed solid-state GaN switches within the matrix structure ensures seamless continuity of bidirectional energy flow [44].

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LIMITATIONS

While the proposed adaptive reconfigurable circuit demonstrates superior efficiency and dynamic performance, several engineering limitations must be noted:

- Increased Hardware Complexity and Component Count: Introducing auxiliary matrix switches increases overall semiconductor component count by approximately 25–30%, leading to higher initial capital manufacturing expenditure [45].
- Complex Digital Control Overhead: Real-time dynamic topology selection and microsecond-level predictive control require high-performance DSP/FPGA hardware controllers, increasing software development complexity and code verification requirements [46].
- High-Frequency Parasitic Capacitance Effects: The presence of additional auxiliary solid-state switches introduces parasitic capacitance networks that can induce high-frequency ringing during high dv/dt switching transients, necessitating precise EMI filter design [47].

FUTURE SCOPE

To build upon the contributions of this review and experimental study, future research directions should investigate:

- AI-Driven Machine Learning Topology Selection: Implementing lightweight edge-computing artificial neural networks (ANNs) on DSP chips to predict microgrid power transients and optimize topological reconfigurations proactively based on weather forecast and load pattern learning [48].
- Monolithic Integration of Wide-Bandgap Switch Matrices: Developing integrated GaN-on-Si smart power integrated circuits (ICs) that consolidate matrix switches and gate drivers on a single semiconductor die to eliminate parasitic trace inductance [49].
- Fault-Tolerant Reconfigurable Control Strategies: Formulating self-healing topological control algorithms that automatically bypass failed switch legs, enabling continuous degraded-mode operation during semiconductor device breakdown in mission-critical applications [50].

CONCLUSION

This paper presented a comprehensive review, analytical loss formulation, and experimental validation of Adaptive Reconfigurable Power Electronic Circuits (ARPECs) for bidirectional

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energy flow in DC microgrids. By dynamically modifying circuit topologies between interleaved, series, parallel, and dual-active bridge configurations in response to real-time load demands and voltage levels, the proposed adaptive architecture overcomes the severe off-design efficiency penalties inherent in conventional fixed-topology converters. Experimental testbed validation confirmed a peak conversion efficiency of 98.6%, a 16.3% absolute efficiency improvement under 10% light-load conditions, and microsecond mode transitions with minimal DC bus voltage disturbance (1.55% sag). The findings establish adaptive topological reconfiguration as a critical technological enabler for next-generation, high-efficiency, and highly resilient DC power distribution networks.

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Received Date: May 02, 2026

Accepted Date: May 16, 2026

Published Date: May 23, 2026

Citation: Pavan Narang, Sunita Narang. Adaptive Reconfigurable Power Electronic Circuits for Bidirectional Energy Flow in DC Microgrids. Journal of Research in Electrical Circuits and Systems. 2026; 11(2): 71-86p.

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