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Advancements in Multiple-Input DC–DC Converters for Hybrid Renewable Energy Systems: Topologies, Control Strategies, and Applications

Narendra Zinjad[1], Deepak Bankar[2], Digvijay Shelke[3,*]

Abstract

Multiple-input DC to DC converters (MICs) are essential components in hybrid energy systems, enabling efficient management of diverse energy inputs from renewable sources such as solar photovoltaic (PV) panels and wind turbines. These converters facilitate the seamless integration of variable power outputs, addressing the intermittent nature of renewable energy through advanced power electronics. This paper provides a comprehensive review of the topologies, control strategies, and applications of MICs within renewable energy systems, emphasizing their role in enhancing system stability and energy yield. Key converter types, including buck, boost, buck–boost, Cuk, Single-Ended Primary-Inductor Converter (SEPIC), flyback, forward, and dual active bridge (DAB), are discussed, alongside recent advancements in efficiency, power density, and sophisticated control techniques. Control methods such as Proportional-Integral-Derivative (PID), fuzzy logic, and Model Predictive Control (MPC) are highlighted for their critical roles in optimizing converter performance under dynamic operating conditions. The paper also examines MIC applications in solar–wind hybrid systems, battery management for energy storage, and electric vehicles (EVs), where they support grid independence and sustainable mobility. Future research directions emphasize improving conversion efficiency, reducing manufacturing and operational costs, and integrating intelligent control algorithms—such as artificial intelligence (AI) and machine learning (ML)—to enhance system reliability and adaptability in the face of evolving energy demands.

Keywords: Multiple-input converters, renewable energy, hybrid systems, control strategies, power electronics

INTRODUCTION

The escalating global demand for renewable energy, driven by climate change mitigation and the depletion of fossil fuels, has led to a significant shift toward sustainable energy sources. This transition has accelerated the development of hybrid energy systems that integrate multiple energy sources, such as solar PV, wind power, and sometimes biomass or hydroelectric inputs, to enhance reliability, efficiency, and performance [1].

The concept of hybrid systems dates back to the early 20th century with the advent of combined heat and power (CHP) systems, but modern iterations leverage advanced power electronics to manage diverse inputs more effectively [2]. A key enabler of this integration is the power electronic converter, a device that manages and optimizes the conversion of energy between different voltage levels and forms, thereby ensuring compatibility between renewable sources and loads or storage systems [3].

***Author for Correspondence**
Digvijay Shelke
E-mail: digshelke@gmail.com

[1]Assistant Professor, Department of Electrical Engineering, Bharati Vidyapeeth Deemed to be University, Pune, Maharashtra, India
[2]Professor, Department of Electrical Engineering, Bharati Vidyapeeth Deemed to be University, Pune, Maharashtra, India
[3]Assistant Professor, Department of Mechanical Engineering, Rajgad Dnyanpeeth's Shree Chhatrapati Shivajiraje College of Engineering (RD's SCSCOE), Dhangwadi, Pune, Maharashtra, India

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Multiple-input DC–DC converters (MICs) have emerged as a critical technological solution for efficiently handling the various energy inputs typical in hybrid systems [4, 3]. Unlike traditional single-input converters, which are limited to one energy source, MICs accommodate multiple inputs simultaneously, providing the flexibility needed for diverse applications, such as solar–wind hybrid systems, electric vehicles (EVs), smart grids, and battery management systems [5, 6]. Their ability to manage fluctuating inputs, such as variable solar irradiance and wind speed, makes them indispensable in modern energy frameworks [7]. The industry relevance of MICs is evident in their adoption by renewable energy firms and EV manufacturers, where they reduce reliance on fossil fuel-based backup systems and enhance grid stability [8, 9, 10].

This paper offers a comprehensive review of recent advancements in MICs, focusing on their topologies, control strategies, and applications within hybrid energy systems. Non-isolated and isolated converters are reviewed in detail, with technical emphasis on key topologies such as buck, boost, buck–boost, Cuk, SEPIC, flyback, forward, and dual active bridge converters [1, 11, 12]. These topologies are compared with single-input converters, which lack the multi-source integration capability of MICs, and multilevel converters, which offer higher power quality but at increased complexity and cost [13]. Additionally, the latest control strategies, including PID, fuzzy logic, and MPC, were analyzed for their effectiveness in improving the MIC performance under varying loads and environmental conditions [14, 13, 6]. Historically, control strategies have evolved from basic hysteresis control in the 1980s to today's predictive algorithms, reflecting the growing computational power available [15]. Finally, this paper discusses emerging trends and potential future directions, such as the integration of wide-bandgap semiconductors (e.g., SiC and GaN) and AI-driven control, highlighting MICs' growing importance of MICs in renewable energy integration and sustainable power systems [16, 17].

OVERVIEW OF MULTIPLE-INPUT DC TO DC CONVERTERS

Multiple-input DC to DC converters can be classified into two broad categories: non-isolated and isolated converters (Figure 1). The choice between these categories depends on the specific application requirements, including voltage levels, safety standards, and the need for galvanic isolation. Non-isolated converters are favored for their simplicity and cost-effectiveness, whereas isolated converters provide enhanced safety and are suitable for high-voltage applications [13]. This classification has evolved since the 1990s, when MICs were first proposed to address the challenges of hybrid renewable systems and continue to adapt to advancements in power electronics [18].

Non-Isolated Converters

Non-isolated converters are widely adopted owing to their simplicity, cost-effectiveness, and high efficiency, particularly in applications where galvanic isolation between the input and output is unnecessary. These converters avoid the use of transformers, thereby reducing their size and weight, which is a significant advantage in portable and distributed energy systems [18]. This section discusses the major non-isolated topologies, buck, boost, and buck–boost converters, along with Cuk and SEPIC variants, providing a technical foundation for their operation.

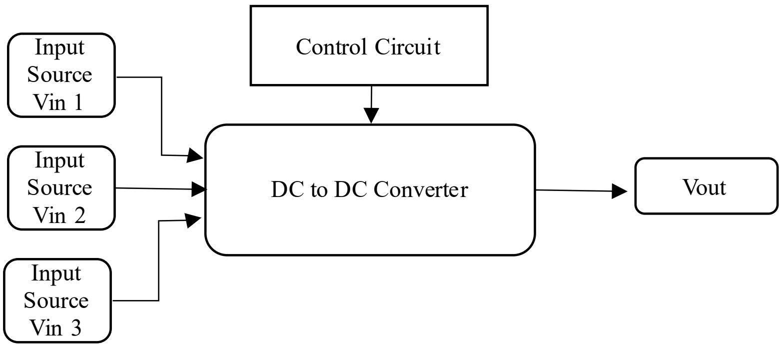

Figure 1. Conceptual diagram of a multiple-input DC to DC converter.

Buck Converters

Buck converters reduce the input voltage to a lower, more stable output voltage, making them ideal for applications such as battery-charging systems and low-voltage DC loads. Their operation relies on a switch (typically a MOSFET) and an inductor to step down the voltage through pulse-width modulation (PWM), with the duty cycle determining the output [1]. Recent advancements have focused on improving efficiency through advanced control algorithms, such as digital PID implementations [14] and component optimization, including low-resistance inductors and high-efficiency switches [4]. Industry relevance is high in renewable energy storage, where buck converters regulate charging currents to prevent overvoltage [19].

Compared to linear regulators, which dissipate excess energy as heat, buck converters offer higher efficiency (up to 95%) by switching, although they lack the step-up capability of boost converters [1]. Buck converters emerged in the 1950s with the development of solid-state switching, with significant refinements in the 1980s for power supplies [7]. Future potential includes integration with wide-bandgap devices (e.g., SiC) to further reduce switching losses and enable operation at higher frequencies, thus enhancing the power density [17].

Key insights from relevant research include: (1) studies on buck–boost converters demonstrating efficiency improvements of up to 94% for hybrid energy systems via advanced control strategies [4]; (2) achieving higher efficiency in Cuk converters by optimizing circuit design, thereby contributing to renewable energy enhancements; and (3) one study exploring SEPIC converters, focusing on design considerations and applications, offering a comparative advantage in voltage flexibility [3].

Boost Converters

Boost converters increase the input voltage, making them suitable for applications such as LED drivers, renewable energy inverters, and power supplies that require higher output voltages than the input. Their operation involves storing energy in an inductor during the switch-on phase and releasing it to the output during the off phase, achieving a voltage gain proportional to the duty cycle ($V_{out} = V_{in} / (1 - D)$) [11]. Recent research has concentrated on enhancing efficiency and reducing electromagnetic interference (EMI) through innovative circuit designs, such as interleaved topologies that distribute current and minimize ripple [20].

In the industry, boost converters are critical for solar PV systems, where they step-up low panel voltages to match inverter requirements [7]. Compared with charge pumps, which are limited to low power, boost converters handle higher power levels with better efficiency (up to 96%), although they are less compact [11]. Boost converters were refined in the 1970s for telecom power supplies, with modern versions incorporating soft-switching techniques to reduce losses [21]. The future potential lies in integration with energy harvesting systems, where adaptive control can optimize performance under variable input conditions [16].

One study explored advancements in flyback converters, emphasizing efficiency and size reduction, providing a comparative benchmark, examined forward converters for high-power applications, and focused on design enhancements. Research on dual active bridge (DAB) converters highlights their versatility, in contrast to the unidirectional nature of boost converters [11, 20, 12].

Buck–Boost Converters

Buck–boost converters offer flexibility in stepping up or down the input voltage, making them versatile for applications such as portable devices, electric vehicles, and renewable energy systems with variable inputs. Their operation uses a single inductor and switch to invert the voltage polarity, with the output voltage determined by the duty cycle ($V_{out} = -V_{in} * D / (1 - D)$) [22]. Recent efforts have aimed to enhance efficiency and reduce the size using advanced semiconductor technologies (e.g., GaN FETs) and control strategies, such as digital twin simulations for real-time optimization [14].

Industry relevance is significant in EVs, where buck–boost converters manage battery voltages across charging and discharging cycles [6]. Compared with separate buck and boost stages, integrated buck–boost designs reduce the component count and improve the transient response, although they may exhibit higher ripples than Cuk converters [23]. Buck–boost converters evolved in the 1980s for portable electronics, with modern applications expanding to renewable integration [7]. Future potential includes bidirectional designs for vehicle-to-grid (V2G) systems to enhance grid resilience [19].

An investigation explored advanced control strategies to improve system efficiency and stability [22]. An investigation of MIC integration in solar–wind systems emphasized reliability [5]. Optimized SEPIC converters offered a comparative efficiency advantage [24].

Cuk Converters

Cuk converters are valued for their ability to provide continuous input and output currents, enhance system reliability, and reduce ripple through capacitor-based energy transfer. Their operation involves a unique topology with an inductor-capacitor-inductor (L-C-L) network, enabling non-inverted output voltage control and proposed efficiency improvements, focusing on reducing switching losses, which is critical for hybrid energy systems [23].

In the industry, Cuk converters are used in solar PV applications, where low ripple is essential for inverter compatibility [4]. Compared to buck–boost converters, they offer better current continuity but at the cost of an increased component count [23]. Cuk converters were introduced in the 1970s with recent advancements in high-frequency operation [18]. Future potential includes integration with energy storage to smooth renewable output [17].

SEPIC Converters

SEPIC converters are ideal for applications that require both step-up and step-down voltage control and galvanic isolation. They are commonly used in battery-charging systems and renewable energy applications. Optimization of design parameters is crucial for improving efficiency and reliability under varying environmental conditions [22, 5, 24]. Extensively reviewed the advancements in non-isolated converters, highlighting their importance in modern electronics and renewable energy systems [18].

Isolated Converters

Isolated converters offer electrical separation between the input and output, providing enhanced safety and supporting higher-voltage applications. This section covers three primary isolated converter topologies: flyback, forward, and dual active bridge converters.

Flyback Converters

Flyback converters are suitable for low-power applications requiring galvanic isolation. Recent research has focused on improving efficiency, reducing size, and increasing reliability [21]. These developments make flyback converters well-suited for renewable energy applications, such as LED lighting systems, where performance improvements in power regulation are critical. Another study also highlighted the advancements in materials and designs that make flyback converters more compact and efficient for low-to-medium power systems [21].

Forward Converters

Forward converters are preferred in medium-to high-power applications because of their higher efficiency compared with flyback converters. Recent studies have aimed to increase power density and reduce EMI using advanced materials and design techniques [13, 23, 18].

A study compared the performance of isolated and non-isolated MICs, emphasizing the importance of selecting the right converter type for renewable energy systems, and achieved efficiencies of up to 92% in forward converters by optimizing core materials and control strategies [13].

Dual Active Bridge Converters

Dual active bridge converters provide bidirectional power flow and high efficiency, making them suitable for applications such as electric vehicle chargers and grid-tied inverters. Recent studies have concentrated on improving control strategies and reducing switching losses to enhance system efficiency [6, 25, 26].

A study of the role of MICs in electric vehicles demonstrated how MICs can optimize power flow and improve energy efficiency [6]. A study examined the use of MICs in battery management systems, highlighting improvements in the system lifespan and performance [25]. Focused on advanced control techniques for DAB converters to improve operational stability and efficiency [26].

CONTROL STRATEGIES

Advancements in MIC control strategies have significantly enhanced the system performance, reduced the size, and improved efficiency. An investigated adaptive control technique that dynamically adjusts to varying input and load conditions improves the power management in complex energy systems [16] (Table 1).

Popular control strategies include:

- *PID control:* Simple and robust recent developments have focused on enhancing adaptability across various operating conditions [14, 27, 28].
- *Fuzzy logic control:* Ideal for handling nonlinearities in hybrid energy systems, improving stability and performance [13, 23, 18].
- *Model predictive control (MPC):* This provides advanced control by predicting system behavior and optimizing actions in real time, enhancing efficiency [6, 25, 26].

One study compared various control strategies, highlighting their impact on MIC performance [29, 30]. A study demonstrated how fuzzy logic control improves the performance of renewable energy systems by adapting them to environmental changes [31]. A study explored MPC in high-frequency MICs, showing its ability to optimize switching actions in real time [15].

APPLICATIONS IN HYBRID ENERGY SYSTEMS

MICs play a vital role in energy systems by managing power from multiple renewable energy sources, thereby improving the overall system reliability and efficiency.

Solar–wind hybrid systems: MICs enhance the system's reliability by efficiently managing the variable outputs of renewable sources [31, 7, 32].

Battery management systems: MICs optimize charging cycles, prolong system lifespan, and improve energy integration [19, 33, 15].

Electric vehicles: MICs improve energy management in electric vehicle powertrains and promote more sustainable transportation solutions [34, 35, 36].

Table 1. Control strategies.

Control strategy	Complexity	Robustness	Adaptability	Reference
PID Control	Low	High	Medium	[14, 27, 28]
Fuzzy Logic Control	Medium	Medium	High	[13, 23, 18]
Model Predictive Control	High	High	High	[6, 25, 26]
PID Control	Low	High	Medium	[14, 27, 28]

FUTURE TRENDS AND RESEARCH DIRECTIONS

Future research on MICs should focus on enhancing efficiency, reducing costs, and integrating intelligent control algorithms. Promising areas include the development of advanced materials, smart grid integration, and the application of machine-learning-based control strategies.

CONCLUSION

Multiple-input DC–DC converters are essential for the integration of renewable energy sources into hybrid energy systems. Recent advances in converter topologies, control strategies, and applications have significantly improved their efficiency, reliability, and versatility. As renewable energy systems continue to evolve, MICs will play an increasingly important role in managing diverse energy inputs, enhancing system stability, and promoting widespread adoption of clean energy technologies. By synthesizing the latest research on MICs, this review highlights their critical role in future sustainable energy solutions, paving the way for more robust and efficient energy systems.

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