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State-of-the-Art DC-DC Converters for Electric Mobility and Renewable Integration: Trends, Challenges, and Future Directions

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Abstract: As electric vehicles and renewable energy systems become more widespread, there is an increasing need for DC-DC converters that can provide higher voltage gain, better efficiency, and improved reliability. This paper presents a comprehensive review of the latest advancements in enhanced gain DC-DC converter technologies. It covers a range of topologies including interleaved, coupled-inductor, switched-capacitor, multiport, and resonant converters, each suited for different application requirements. The review also explores the role of emerging semiconductor materials such as silicon carbide (SiC) and gallium nitride (GaN), as well as the integration of modern control strategies like model predictive control (MPC), fuzzy logic, and sliding mode control. Artificial intelligence (AI) and digital twin technologies are also discussed as tools for improving real-time performance and predictive maintenance. Through comparative studies and application-specific recommendations, this paper identifies key research gaps and future directions that could enhance scalability, cost-effectiveness, and thermal performance in power conversion systems for EVs and renewable energy.

Key words: DC-DC Converters, Electric Vehicles (EVs), Renewable Energy Systems, High-Gain Converters, Wide-Bandgap Semiconductors

1. Introduction:

The global trend toward sustainable energy solutions has placed significant efficiency demands on power electronics, particularly in electric vehicles (EVs) and renewable energy systems, which are subjected to dynamic load variations and demand high efficiency. In the midst of this revolution stands the DC-DC converter—a central enabler technology for power flow management and voltage levels across a host of applications [1]. DC-DC converters have a twofold role in EVs: they connect high-voltage battery systems and low-voltage auxiliary electronics and also facilitate efficient energy transfer during regenerative braking [2]. Similarly, in renewable energy systems such as solar photovoltaic (PV) arrays and wind turbines, these converters transform oscillating voltages to meet grid or storage demands with maximum energy use while losses are minimized [3].

Over the past five years, research on high-gain DC-DC converter technologies have grown rapidly, driven by the dual demands of efficiency and cost-effectiveness [4]. While traditional boost converters are efficient, they are prone to inefficiency at high voltage ratios, and as such, researchers have been searching for alternative topologies such as interleaved boost, coupled inductor, and multilevel converters [5]. These technologies have been shown to provide enhanced performance in terms of gain enhancement, component reduction, and thermal management. For instance, coupled-inductor-based converters have been shown to achieve greater voltage gains with the smallest magnetic component sizes, making them an option for space-restricted applications like EVs [6]. Similarly, multilevel converters have drawn attention for their potential to lower voltage stress on semiconductor devices, thereby improving overall system reliability [7]. The use of advanced semiconductor materials has further hastened advancements in DC-DC converter technologies. Silicon carbide (SiC) and gallium nitride (GaN) semiconductors, due to their improved switching speeds and thermal management capabilities, have enabled the design of converters that can operate at higher efficiencies and frequencies compared to traditional silicon-based converters [8]. Recent studies have identified the potential of GaN transistors to reduce switching losses by up to 50% in certain applications, significantly enhancing the efficiency of renewable energy systems [9]. Similarly, SiC-based converters exhibit exemplary performance in high-temperature environments, rendering them suitable for rigorous applications such as EV motor controllers and solar inverters [10].

In parallel, control methodologies have undergone significant development, with model predictive control (MPC) and adaptive algorithms being notable facilitators of enhanced converter performance [11]. Such novel control approaches allow converters to adapt dynamically to varying load conditions and input voltages and offer optimal efficiency across a wide range of operating conditions [12]. For example, MPC-based systems have been shown to improve transient response times in EV charging plans, reducing energy loss in high-rate load transients [13]. Further, digital control systems are rapidly gaining prominence due to their flexibility and precision, offering software-upgradeable implementations that can be tailored to the evolving needs of technology [14]. AI-based optimization is transforming DC-DC converter design, enabling real-time performance tuning and predictive maintenance. Recent developments demonstrate the potential of artificial intelligence (AI) to enhance real-time performance, predict future failures, improve reliability, and reduce maintenance costs [15]. Similarly, digital twin technology has also been employed in simulating virtual representations of physical systems so they can be real-time monitored and optimized according to real operating conditions [16]. These technologies are particularly beneficial in off-grid solar applications where system reliability is of prime concern [17].

Thermal management remains a significant challenge for high-power DC-DC converter applications. Novel cooling techniques have been investigated, such as bio-inspired heat dissipation systems and phase-change materials, to address heat dissipation challenges [18]. These innovations not only improve the efficiency of converters but also their operational lifespan, making them more suitable for demanding applications such as EVs and renewable energy systems [19]. Low-cost integration techniques for power electronics based on wide-bandgap semiconductors have also been the focus of recent work [20]. Aiming to make new converter technologies affordable without compromising performance, these techniques will enable more affordable, leading-edge converter technologies, particularly in emerging economies [21]. Similarly, scalable multilevel converter topologies have been proposed to cater to the demands of high-scale renewable energy systems with seamless integration into the grid [22].

Interleaved boost converters are now a promising contender for high-efficiency energy harvesting in renewable energy systems [23]. Their ability to provide enhanced efficiency and lower component stress has been demonstrated by recent studies to render them highly appropriate for use in applications such as solar PV systems and wind turbines [24]. Coupled inductor-based converters have, nonetheless, been engineered to offer greater efficiency in EV applications, eliminating problems with dynamic load conditions and thermal management [16]. These converters are essential for balancing energy supply and demand under dynamic environmental conditions [13]. New materials such as gallium oxide (Ga_2O_3) and diamond semiconductor-based materials are also emerging to further enhance converter performance with record-breaking breakdown voltages and switching speeds [14].

As the world advances toward a sustainable energy future, sophisticated gain DC-DC converters are a key facilitator of innovation, efficiency, and resilience [17]. Emerging trends suggest that converters will become increasingly critical to grid integration, energy storage, and electric transport, driving the transition to cleaner and sustainable energy systems [23].

This paper offers a comprehensive taxonomy of DC-DC converters based on their topology, isolation characteristic, switching mechanism, and fields of application. It presents a close examination of high-gain converter configurations like interleaved, coupled-inductor, switched-capacitor, and hybrid converters and their efficacy in electric vehicles and renewable energy systems. The study examines the role of wide-bandgap semiconductors such as GaN, SiC, Ga_2O_3, and diamond in making systems more efficient, switching faster, and remaining reliable under conditions of heat. Various sophisticated control techniques such as MPC, FLC, SMC, and AI-based technologies are compared on the basis of robustness, complexity, and self-learning capability. The paper points out the dominant research areas in cost, scalability, EMI suppression, and long-term reliability. It also recommends a converter-controller choice matrix with specific application so as to ease practice implementation. It presents a performance heatmap in the paper so that efficiency, components used, complexity, and costs are easily visualized in a trade-off context. Finally, the paper describes future developments incorporating AI, digital twin technology, and formulation of sustainable, next-generation designs of converters.

The rest of this manuscript is organized as follows. Section 2 presents the limitations of current DC–DC converters and the gap in research in the existing literature. Section 3 provides an elaborate classification of the DC–DC converters in both isolated and non-isolated types. Section 4 describes control strategies used in DC–DC converters, with a focus on their advantages, limitations, and suitability for applications. Section 5 summarizes better converter topologies with higher gain and efficiency for the integration of electric vehicles and renewable energy. Section 6 offers a comparative analysis of the above-discussed converters in aspects of performance and design characteristics. Section 7 presents possible future advancements and new research directions. Section 8 concludes the paper with major findings and observations.

2. Drawbacks and Research Gaps

Power electronics for renewable energy and electric vehicles [1] provides basic information but lacks detailed analysis of AI integration, IoT, and emerging materials such as gallium oxide (Ga_2O_3). Bridging these knowledge gaps with AI-based control and material advancements can improve converter performance. Likewise, research on power electronic converters' reliability

[2] identifies failure modes but lacks practical solutions, calling for predictive maintenance and fault-tolerant designs. There is limited literature on the subject, including the Power Electronics Handbook [3], that provides general coverage but no case studies and wide-bandgap semiconductor discussions. GaN, SiC, and AI-based control methods should be included in future work. Interleaved boost converters [4] enhance efficiency at the expense of complexity and cost, demanding research into scalable and simplified designs. Recent results show a 35–40% reduction in current ripple, and 8–12% lesser switching losses, but these benefits increases controller complexity. Model Predictive Control (MPC) [5], [11] is computationally intensive, requiring algorithmic simplifications for real-time implementation. Control strategies for EVs must also be optimized to balance performance and computational efficiency. Coupled inductor-based converters [6], [24] incur losses and electromagnetic interference (EMI), highlighting the importance of improved thermal management and EMI mitigation techniques. Stability methods in DC microgrids [7] are not scalable, and real-world verifications are required. GaN-based converters [8], [9] incur high costs and thermal issues, and cost-effective production and enhanced thermal techniques are needed. SiC-based converters [10] are costly, and cost reductions and scalability enhancements are needed for ultra-high-voltage applications.

Digital control methods [12] need expert skills, and integration with AI is required for widespread use. Transient response optimization [13] is not in dynamic load conditions, necessitating adaptive algorithms. AI-based optimization [14] needs vast amounts of data and computational power, necessitating simplification for real-time use. Digital twin technology [15] is expensive, requiring feasibility studies and cost-effective solutions for applications of small scale.

Thermal management [16] is hampered by phase-change material degradation, demanding long-term testability and novel cooling methods. Gain converters with higher gain [17] are not scalable for use in large off-grid systems, demanding modularity and affordability in design. Wide-bandgap material fabrication [18] is still in its infancy, demanding standardization and cost-reduction methods. Economical wide bandgap materials [20] also demand scalable manufacturing methods to increase commercial attractiveness. Multilevel converters [19] bring in complexity and cost issues, leading to investigation of reduced complexity and modular configurations. Hybrid renewable energy systems [21] have to contend with random inputs, and there is a need for adaptive real-time energy balancing algorithms. High-end materials [22] like Ga_2O_3 and diamond are not commercially viable yet and need investigation of scalability and durability. Speculative directions in DC-DC converters [23] need to be experimentally confirmed by pilot projects. Closing these gaps—like making AI algorithms easier to simplify, material costs more affordable, and thermal management better is what will promote the use of power electronics in electric vehicles and renewable energy. Table 1 provides a brief discussion of different articles on DC-DC converters, highlighting their focus and key implementations.

Table 1: Summary of Enhanced-Gain DC–DC Converters and Their Contributions

Paper	Main Focus	Key Attention	Implementations	Applications
[1]	Power electronics in renewable	Detailed review on power converters for renewable & EV applications	Provides the initial insights on the role of power electronics in	EVs, renewable energy systems

	energy and EVs		sustainable energy solutions	
[2]	Reliability of power converters	Industry-focused reliability analysis of power converters	Classifies typical DC-DC converter failure modes and reliability challenges.	Industrial, EVs and renewable energy systems
[3]	Power electronics handbook	Overview of devices, circuits, and applications in power electronics	Comprehensive resource for understanding power electronics fundamentals	Broad applications, including EVs and renewables
[4]	High-efficiency interleaved boost converters	Interleaved boost converter topology with enhanced gain	Demonstrates high efficiency and reduced component stress in solar PV systems	Renewable energy systems
[5]	Control strategies for EVs	Advanced control strategies (MPC) for DC-DC converters	Proposes dynamic load management techniques to improve efficiency in EV charging systems	Electric vehicles
[6]	Coupled inductor-based converters	Coupled inductor design for high-gain DC-DC converters	Achieves higher voltage gains with reduced magnetic component sizes	Electric vehicles
[7]	Stability in DC microgrids	Dynamic behavior analysis and stabilization techniques for DC microgrids	Enhances stability in systems with fluctuating loads	Microgrids with constant-power loads
[8]	GaN-based converters	Gallium nitride (GaN) transistors for high-frequency operation	Reduces switching losses by up to 50%, improving efficiency	Renewable energy systems
[9]	Efficiency analysis of GaN converters	Efficiency modeling of GaN-based DC-DC converters	Demonstrates superior performance of GaN transistors	Renewable energy systems
[10]	SiC-based converters	Silicon carbide semiconductors for high-temperature operation	Proves exceptional thermal performance and reliability in demanding environments	Electric vehicles, solar inverters

[11]	Model predictive control (MPC)	MPC for dynamic load management in EV charging systems	Improves transient response and reduces energy losses during rapid load changes	Electric vehicle charging
[12]	Digital control techniques	Digital control methods for enhanced gain DC-DC converters	Offers software-upgradable solutions for improved precision and adaptability	General applications
[13]	Transient response optimization	MPC-based optimization for transient response	Enhances dynamic performance and reduces energy losses in EV applications	EV charging systems
[14]	AI-based optimization	AI for real-time optimization of DC-DC converters	Enables predictive maintenance and real-time performance optimization	General applications
[15]	Digital twin technology	Virtual replicas for real-time monitoring	Facilitates real-time optimization and fault prediction	Off-grid solar systems
[16]	Thermal management	Advanced cooling techniques for high-power converters	Introduces bio-inspired heat dissipation systems to address thermal issues	High-power applications
[17]	Off-grid solar applications	Enhanced gain DC-DC converters for off-grid solar systems	Improves system reliability and energy utilization in remote locations	Off-grid solar energy
[18]	Cost-effective wide-bandgap materials	Cost reduction strategies for SiC and GaN semiconductors	Makes advanced materials more accessible for widespread adoption	EVs, renewable energy systems
[19]	Scalability of multilevel converters	Multilevel converter designs for large-scale systems	Ensures seamless integration with the grid while maintaining efficiency	Grid-tied renewable energy systems
[20]	Interleaved boost converters	High-efficiency energy harvesting using interleaved boost topology	Achieves higher efficiency and lower component stress	Solar PV systems, wind turbines
[21]	Hybrid renewable energy systems	Enhanced gain converters for balancing energy supply and demand	Ensures stable and reliable energy flow under fluctuating environmental conditions	Hybrid solar-wind systems

[22]	Advanced materials	Impact of advanced materials on converter performance	Presents next-generation materials for unparalleled breakdown voltages and switching speeds	EVs, renewable energy systems
[23]	Future trends in DC-DC converters	Emerging trends in DC-DC converter technologies	Identifies future directions for grid integration and electrified transportation	Renewable energy integration
[24]	Coupled inductor-converters	Coupled inductor design for FCEVs	Optimizes efficiency and addresses thermal management issues	Electric vehicles

This Table provides a thorough summary of state-of-the-art work in enhanced gain DC-DC converters, for the purpose of finding trends, gaps, and areas for further research. There are multiple references highlighting new converter topologies such as coupled inductors [6], interleaved boost converters [4], and multilevel converters [19]. These topologies maximize voltage gain while reducing component size and stress. Wide-bandgap semiconductors like SiC [10] and GaN [8] are known for their high switching speeds and thermal efficiency. New materials like Ga_2O_3 and diamond are under consideration for future use [22]. Sophisticated control methods, including model predictive control (MPC) [11] and artificial intelligence-based optimization [14], are increasingly being adopted to improve efficiency and responsiveness. From the literature organized in Table 1, the following research gaps are identified:

Limited use of new materials: Whereas extensive bandgap devices like SiC and GaN have shown excellent switching performance and efficiency ([8], [9], [10], [18]), the cost-effectiveness, thermal stability, and long-term reliability in high-power EV and renewable systems are not fully addressed.

Control strategy integration: Research on emerging control methods like MPC and AI-based control ([5], [11], [13], [14]) presents encouraging outcomes. Regrettably, insufficient comparative studies exist across control schemes (VMC, CMC, FLC, SMC, MPC, AI) for various converter topologies and application areas.

Thermal management issues: Although efficiency gains are reported, few studies properly discuss heat dissipation solutions. Adaptive and bio-inspired cooling designs for high-power, compact converters are less than fully researched ([16]).

Application-specific optimization: Interleaved boost and coupled-inductor topologies ([4], [6], [17], [20], [24]) provide greater gain. Converter designs optimized for EV charging, regenerative braking, and renewable–grid hybrid applications are limited.

Gaps in scalability and modularity: Multiport and multilevel converters ([19], [22], [23]) show promise for large-scale applications in renewables and microgrids. Nevertheless, modularity, fault tolerance, and cost-effective deployment remain practical concerns.

Smart and digital solutions: New methods like digital control, digital twin concepts, and AI-optimization ([12], [14], [15]) hold the promise of flexibility and predictive maintenance. Their real-time application and harmonious integration with hardware-based converter platforms need further examination.

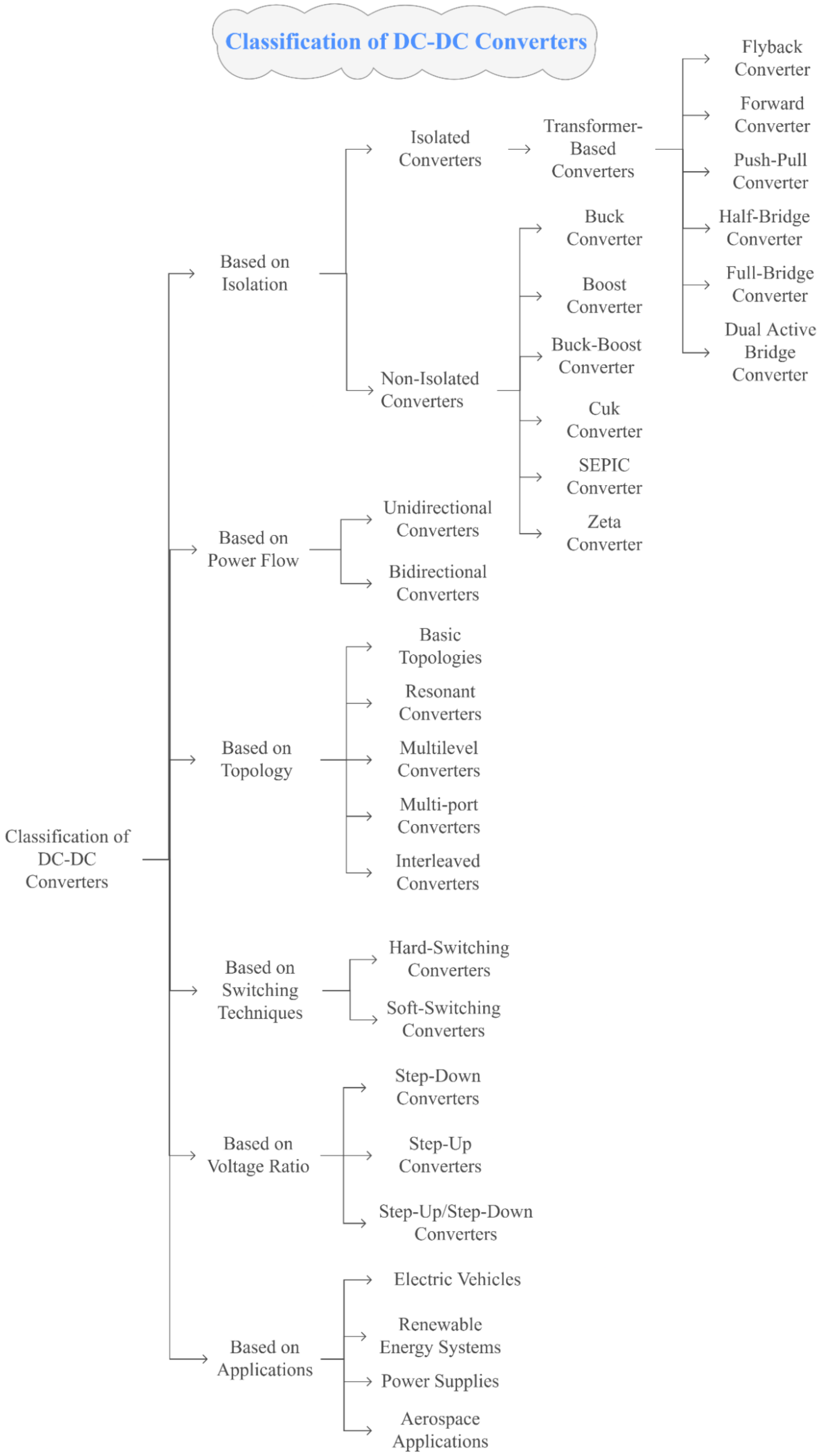


Fig. 1. DC-DC converter classifications: isolation, topology, switching technique

Overall, the trade-offs across topologies (gain vs efficiency, switching frequency vs EMI, control complexity vs dynamic response) are quantifiable limits that persist despite recent innovations. While we have seen a typical limit of 90–92% for high-gain converters, a 35–40% reduction in ripple in interleaved structures, and a charge loss of 8–12% in switched-capacitor converters, these values demonstrate the challenges that the next generation of DC–DC converters will encounter.

3. Classifications of DC-DC Converters

DC-DC converters are critical elements in most applications, such as renewable energy systems, electric vehicles, and power supplies. They convert a DC voltage level to another, meeting the load's exact requirements. The classifications described in this section show different functional perspectives on DC-DC converters. Some converters show up with a multiple perspective (e.g., boost, flyback, resonant, interleaved) because they belong to more than one classification simultaneously. To prevent redundancy, later descriptive sections will focus on performance, application-oriented characteristics, and, in Section 3, only present the structural classification, as shown in Fig. 1.

3. 1. Classification based on Isolation

DC-DC converters can be broadly categorized into two categories based on whether or not they offer galvanic isolation between input and output:

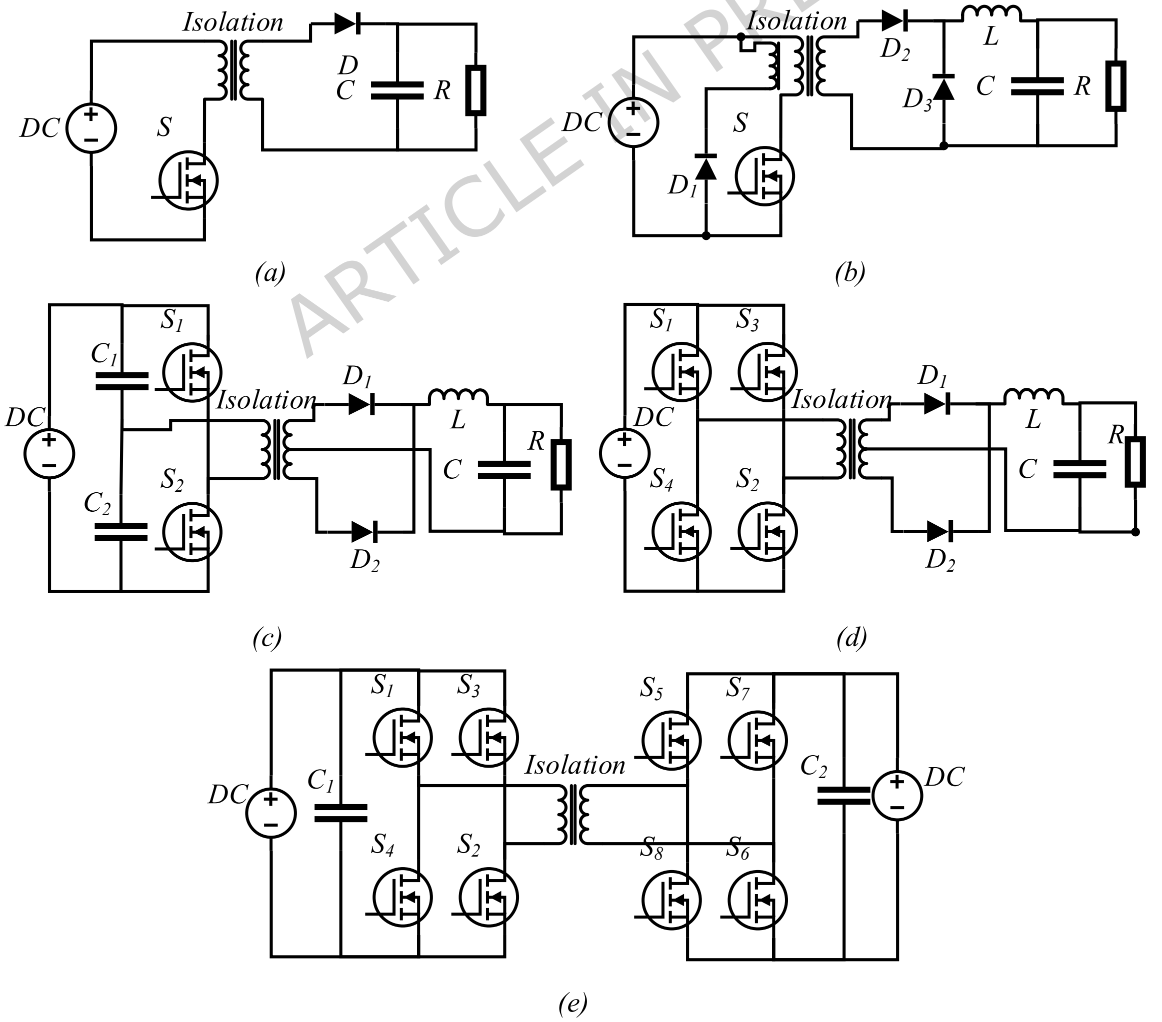


Fig. 2. Isolated DC – DC converters, (a) flyback, (b) forward, (c) Half-Bridge, (d) Full-Bridge, and (e) Dual Active Bridge (DAB).

i) Isolated DC-DC Converters: These DC-DC converters include a transformer to offer electrical isolation between the output load and the input source. This isolation provides a number of benefits such as safety, noise reduction, and the capacity to deal with various ground potentials. Fig. 2 shows a few traditional isolated DC–DC converters.

Transformer-Based Converters: Galvanically isolated and transfer energy from input to output using a transformer [25]. Topologies are:

a) Flyback Converter: A basic and common isolated converter, best suited for low-power applications. It works by storing energy in the transformer during the switch-on time and delivering it to the output during the switch-off time.

b) Forward Converter: Slightly different from the flyback converter but with higher efficiency and power handling. Conveys energy to the output at switch-on time via the primary and secondary windings of the transformer.

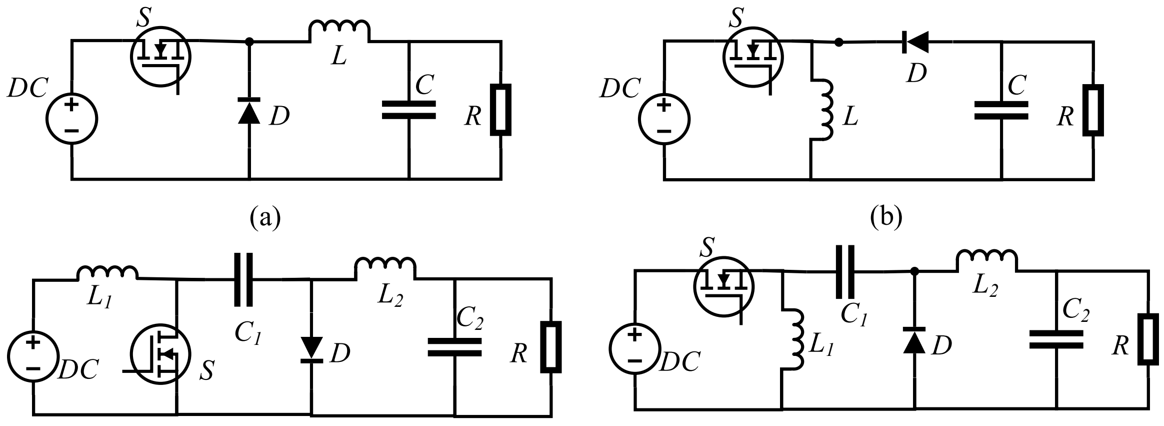
c) Push-Pull Converter: Utilizes two switches and a center-tapped transformer to deliver increased power output and efficiency in contrast to flyback and forward converters.

d) Half-Bridge Converter: Utilizes two switches and a capacitor divider to produce a balanced voltage across the primary winding of the transformer. It is applied in medium-power applications.

e) Full-Bridge Converter: Utilizes four switches to form a full-bridge arrangement on the transformer primary side with high power delivery and efficiency.

f) Dual Active Bridge (DAB) Converter: A two-way isolated converter with two active bridges that are coupled using a transformer. It has soft-switching ability, high efficiency, and bidirectional power flow control [26]. They are employed in the systems such as energy storage, electric vehicle on-board chargers and solid-state transformers [26]. While Dual Active Bridge (DAB) converters offer soft-switching and bidirectional operation, they require precise phase-shift control and may lose Zero Voltage Switching (ZVS) under light loads, increasing switching losses [26].

g) Impedance-Source Converters: These converters solve the drawbacks of traditional solutions with the help of particular impedance-source networks [25]. They are suitable for renewable energy source distributed generation systems [25].



(a) (b)

(c) (d)

Fig. 3. Non-Isolated DC – DC converters, (a) buck, (b) buck-boost, (c) Cuk, and (d) ZETA.

ii) Non-Isolated DC-DC Converters: These converters lack a transformer and offer a direct electrical link between the input and output can be seen in Fig. 3. Non-isolated converters are typically smaller, lighter, and more efficient than isolated converters and are thus appropriate for applications where isolation is not a major requirement.

a) Buck Converter: Step-down converter decreasing the input voltage to a low output voltage. It is frequently used in systems where voltage is needed to be regulated.

b) Boost Converter: Step-up converter raising the input voltage to a higher output voltage. It is generally found in power factor correction (PFC) and renewable energy devices [27].

c) Buck-Boost Converter: Either steps up or steps down the input voltage based on the duty cycle. The output voltage is generally inverted relative to the input voltage.

d) Cuk Converter: Like the buck-boost converter but with less switching noise and ripple because it has an inductor at the input and output.

e) SEPIC (Single-Ended Primary Inductor Converter): A non-inverting buck-boost converter that gives a positive output voltage from a positive input voltage.

f) Zeta Converter: Similar to the SEPIC converter but has different characteristics and uses.

These isolated topologies are also shown in the topology-based classification (Section 3.3) because isolation and topology represent different aspects of classification.

3. 2. Classification Based on Direction of Power Flow

DC-DC converters may also be divided according to how they can control the direction of power flow:

i) Unidirectional DC-DC Converters: These converters permit power flow in one direction, from the input source to the output load. They are appropriate for use in applications where power transfer in one direction is needed, like in power supplies and battery chargers.

ii) Bidirectional DC-DC Converters: Bidirectional DC-DC converters have the ability to control power flow in both directions, enabling energy transfer between two DC sources or buses. They are crucial in applications like energy storage systems, electric vehicles, and uninterruptible power supplies (UPS) [28]. Bidirectional DC-DC converters serve as key devices for interfacing storage systems between source and load in renewable energy systems [29]. They control power direction between two sources with certain switching schemes [29]. A basic non-isolated unidirectional boost and bidirectional boost converters are illustrated in the Fig. 4 (a) & (b) respectively.

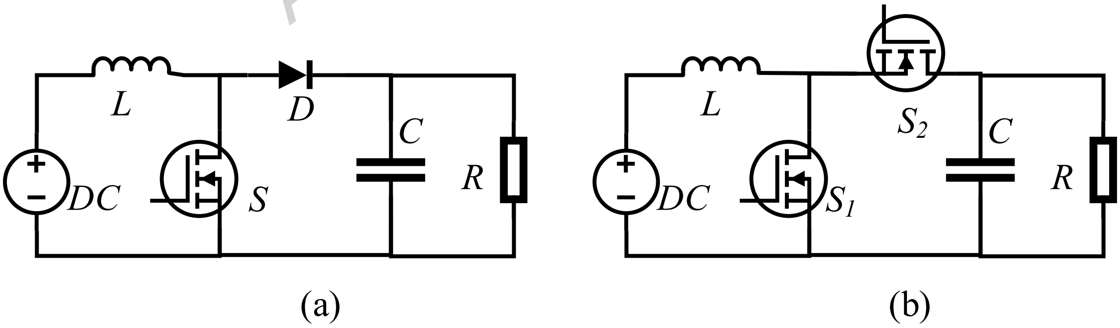


Fig. 4. An example of Non-Isolated DC–DC converters (a) unidirectional boost, and (b) bidirectional boost.

3. 3. Classification Based on Topology

Topology of a DC-DC converter means the organization of its parts, such as switches, inductors, capacitors, and transformers. Different topologies exhibit varying performance levels in efficiency, voltage gain, and component stress.

i) Simple Converter Topologies: As noted above, the buck, boost, buck-boost, Cuk, SEPIC, and Zeta converters are the basic building blocks for most DC-DC converter configurations.

ii) Resonant Converters: These converters use resonant circuits to provide soft-switching, which minimizes switching losses and enhances efficiency. They are ideal for high-frequency applications and provide low electromagnetic interference (EMI). DC-DC resonant converters have attracted a lot of research attention due to improvements in their applications [30]. These converters improve soft-switching, smooth waveforms, high-power density, and high efficiency [30]. The basic Half-bridge resonant DC – DC converter is given in Fig. 5.

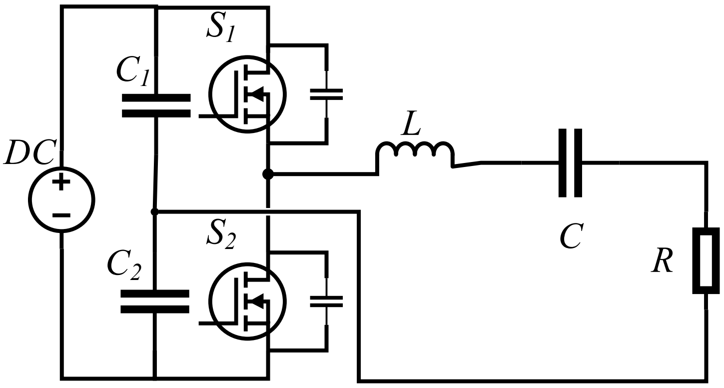


Fig. 5. A simple Half-bridge resonant DC – DC converter.

iii) Multilevel Converters: Multiple voltage levels are employed in multilevel converters to synthesize the output voltage (as shown in Fig. 6), minimizing the voltage stress across the switches and enhancing efficiency. They are employed in high-voltage applications. Multilevel converters are discussed in this paper with regard to their topologies, classifications, merits, demerits, combined topologies, applications and challenges [31]. Bidirectional integrated multilevel inverters will be in huge demand in the near future [31].

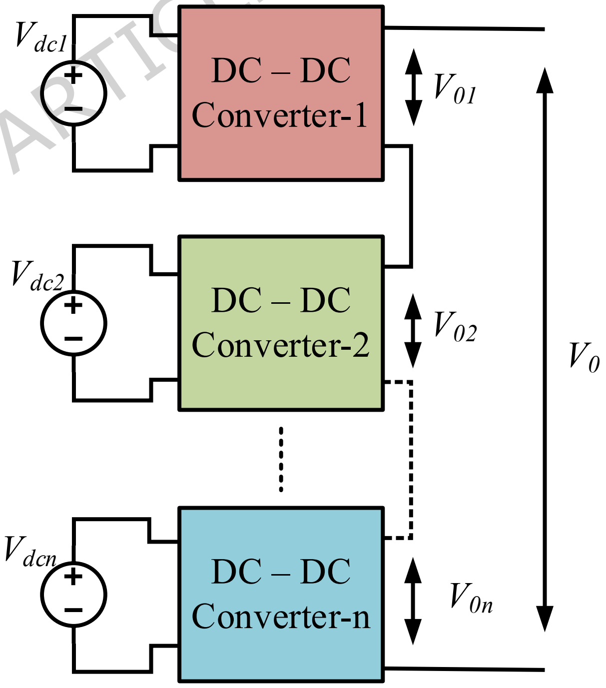


Fig. 6. Traditional multilevel DC – DC converter structure.

iv) Multiport Converters: They combine several input sources and/or output loads into one converter, minimizing the size and cost of the overall system. They find applications in hybrid electric vehicles and microgrids. There are several types of multiple-port DC-DC converters and a great many circuit topologies [32]. In Fig. 7 a dual input single output SEPIC DC – DC converter topology is given.

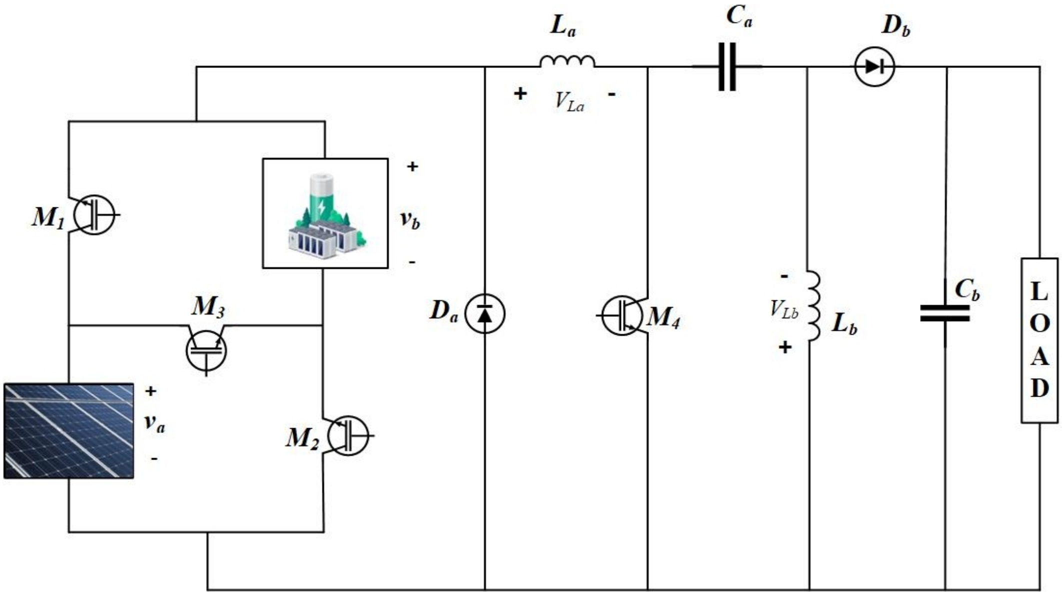


Fig. 7. Multi-Input SEPIC DC-DC converter topology

v) Interleaved Converters: These converters link many converter modules in parallel, which assists in minimizing input current ripple and output voltage ripple, as well as enhancing efficiency. They are employed in high power applications [33]. Fig. 8 shows an interleaved DC-DC converter based on basic boost topology.

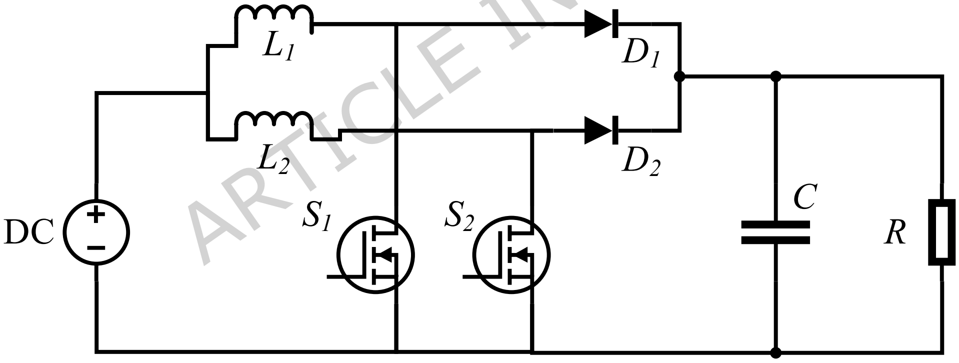


Fig. 8. Interleaved DC-DC converter based on basic boost topology

Some of the converters here also appeared in the other classification (isolation, switching technique), showing that these converters provide multi-functionality and are not simply repeated discussion.

3. 4. Classification Based on Switching Techniques

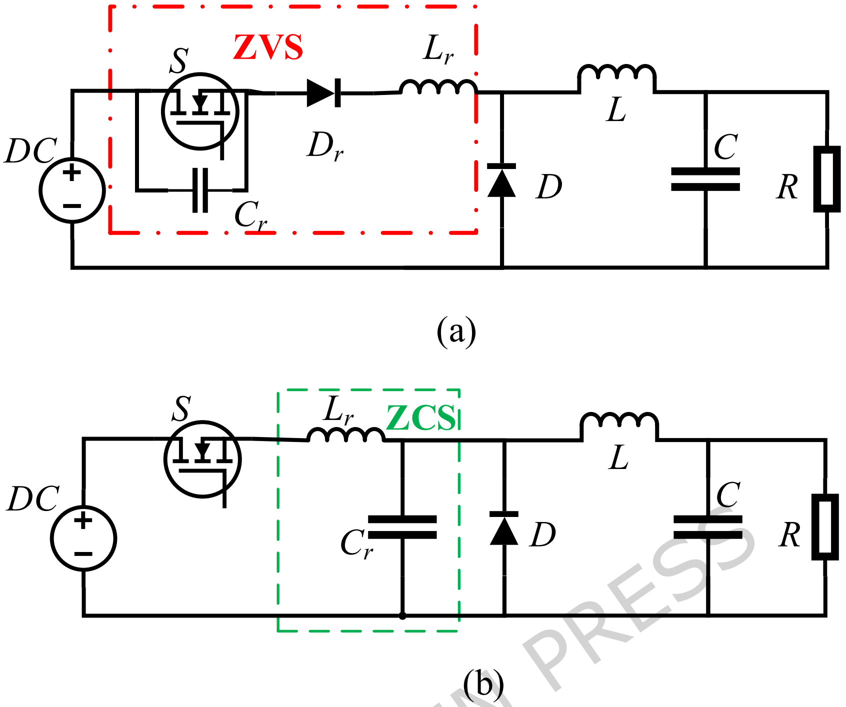
Switching techniques are essential in the operation of DC-DC converters, especially with regard to efficiency and EMI.

i) Hard-Switching Converters: They switch with hard transition, and this results in EMI and switching losses. The switches switch on and off at high voltage and current conditions, causing power to be dissipated.

ii) Soft-Switching Converters: They use resonant circuits or other methods to accomplish zero-voltage switching (ZVS) or zero-current switching (ZCS), decreasing the switching losses and EMI. Soft-switching techniques are applied extensively in DC-DC converters to enhance efficiency [34]. There will be a family of soft – switching converters, however here just a basic buck topology based ZVS & ZCS configurations are given in Fig. 9.

a) Zero-Voltage Switching (ZVS): The switch is switched on or off whenever the voltage across it is zero, reducing switching losses.

b) Zero-Current Switching (ZCS): The switch switches on or off when the current through it is zero, minimizing switching losses.



(a)

(b)

Fig. 9. Soft – switching DC-DC converters based on basic buck topology (a) ZVS buck (b) ZCS buck

3. 5. Classification Based on Step-Up/Step-Down Ratio

DC-DC converters are also categorized by the voltage conversion ratio:

i) Step-Down (Buck) Converters: They decrease the input voltage to a lower output voltage.

ii) Step-Up (Boost) Converters: They raise the input voltage to a greater output voltage [35]. High step-up DC-DC converters serve as an interface to utilize renewable energy systems [36].

iii) Step-Up/Step-Down Converters: These converters are capable of increasing or reducing the input voltage, based on the control scheme.

3. 6. Applications based classification

DC-DC converters have a multitude of applications and thus can be sorted according to those applications:

i) Electric Vehicles (EVs): DC-DC converters are employed for charging batteries, motor control, and auxiliary power supplies in EVs [37], [38]. They play a constructive function in EV applications, both charging and vehicle-to-grid (V2G) [37].

ii) Renewable Energy Systems: DC-DC converters are utilized to interface energy storage systems, solar panels, and wind turbines with the grid or load [39].

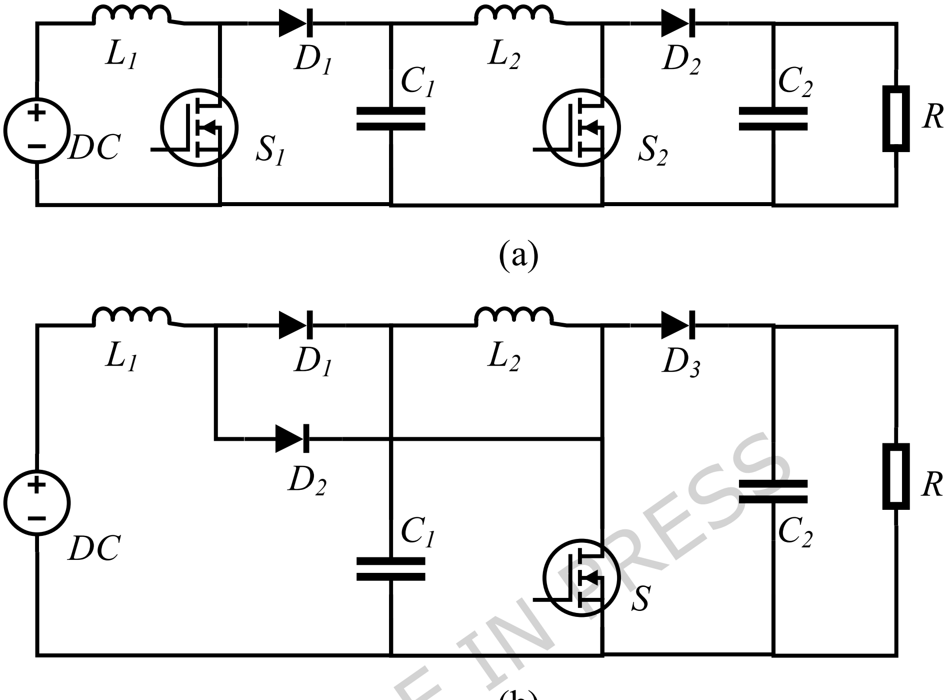
iii) Power Supplies: DC-DC converters are employed in some power supplies for electronic equipment, computers, and telecommunication devices.

iv) Aerospace Applications: High-power conversion equipment is attracting attention for its use in aircraft applications [40]. Bidirectional DC-DC converters isolated are usually put forward for contemporary aircraft distribution systems [40].

3. 7. Advanced High Step-Up DC-DC Converters

Non-isolated high step-up DC-DC converters are more and more utilized in high voltage gain applications without galvanic isolation [27], [36]. They play a crucial role in renewable energy systems and electric vehicles.

i) Derived Topologies: Many derived topologies from the boost converter have been presented to eliminate its drawbacks and enhance the voltage gain [27]. The cascading derived boost converter and single-switch quadratic boost converters are given in Fig. 10 respectively.



(a)

(b)

Fig. 10. Derived DC-DC converters based on boost topology (a) cascaded boost (b) single-switch quadratic boost

ii) Switched-Capacitor-Based Converters: Such converters employ capacitors as the energy transfer elements to provide high voltage gain. Fig. 11 shows a switched capacitor integrated DC – DC converter.

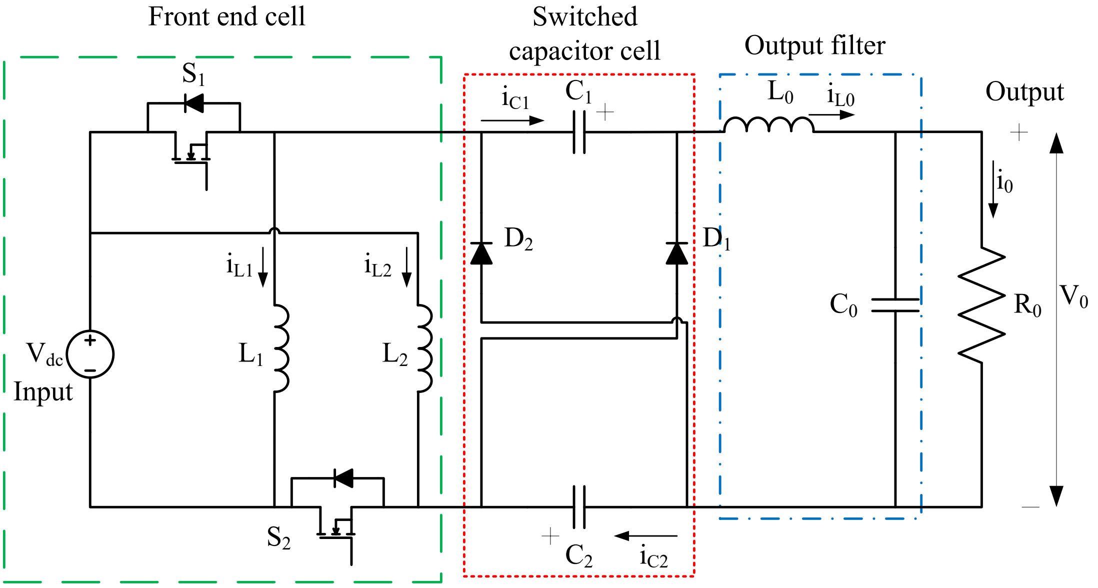


Fig. 11. Switched capacitor integrated DC – DC converter

iii) Coupled-Inductor-Based Converters: Coupled inductors are utilized in the converters to increase the voltage gain and minimize component stress. The conventional ZETA topology based coupled inductor DC – DC converter is shown in Fig. 12.

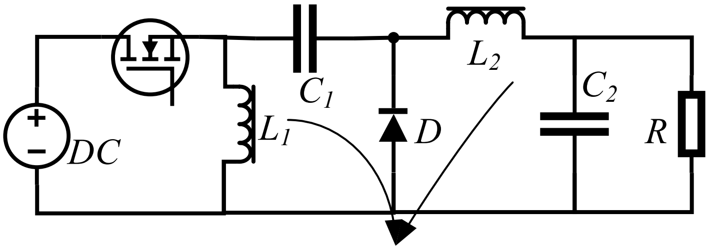


Fig. 12. Classical ZETA topology based coupled inductor DC – DC converter

4. Control Schemes for DC-DC Converters:

DC-DC converters are essential building blocks in contemporary power electronic systems, facilitating efficient energy conversion and voltage regulation in a broad spectrum of applications, ranging from renewable energy systems to electric vehicles. In order to ensure reliable operation, accurate output regulation, and fault tolerance under diverse conditions, several control strategies are utilized. These control strategies control the switching activities of the converter through feedback signals by modifying parameters such as duty cycle or switching frequency. This review discusses several control techniques, including Voltage Mode Control (VMC), Current Mode Control (CMC), Hysteresis Control, Fuzzy Logic Control (FLC), Model Predictive Control (MPC), and Sliding Mode Control (SMC), and presents their basic concepts, merits, demerits, and recent developments.

4.1 Voltage Mode Control (VMC)

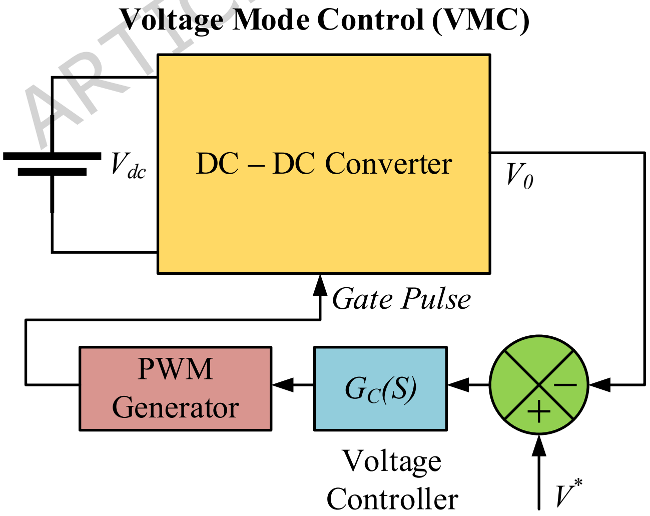


Fig. 13. Basic block diagram of VMC technique for DC – DC converter

Voltage Mode Control (VMC) is one of the most widespread control methods for DC-DC converters, due to its operational and implementation simplicity. In this mode, the output voltage is used as the principal mechanism of feedback as given in Fig. 13, with an immediate impact on the duty cycle of the power switch. The controller operates by comparing the output voltage with a known reference level, generating an error signal fed into a compensator, usually a proportional-integral (PI) controller, for the purpose of maximizing the regulation of the converter. Although VMC has simple structure and offers good steady-state voltage regulation, it suffers from serious disadvantages. It is particularly notable for its sensitivity to load change and input voltage ripple, with the result of a bad transient response and risk of instability.

Additionally, its control loop dynamics are intrinsically coupled with the output filter behavior, thus requiring high-bandwidth performance without compromising stability to be difficult. In response to these constraints, recent studies have focused on the improvement of VMC using the incorporation of advanced compensation strategies and hybrid control methods [41], [42], [43]. These improvements, such as the use of methods such as fuzzy logic and predictive control, aim to enhance the dynamic performance and robustness of VMC for faster response and improved disturbance handling.

4.2 Current Mode Control (CMC)

Current Mode Control (CMC) addresses some of the shortcomings of Voltage Mode Control by using the inductor current as the feedback signal (see Fig. 14). This method changes the control loop dynamics, leading to a better transient response and improved current limiting capability. CMC is especially useful in applications involving a quick response to high-speed load transients since it measures the inductor current directly and adjusts the duty cycle accordingly.

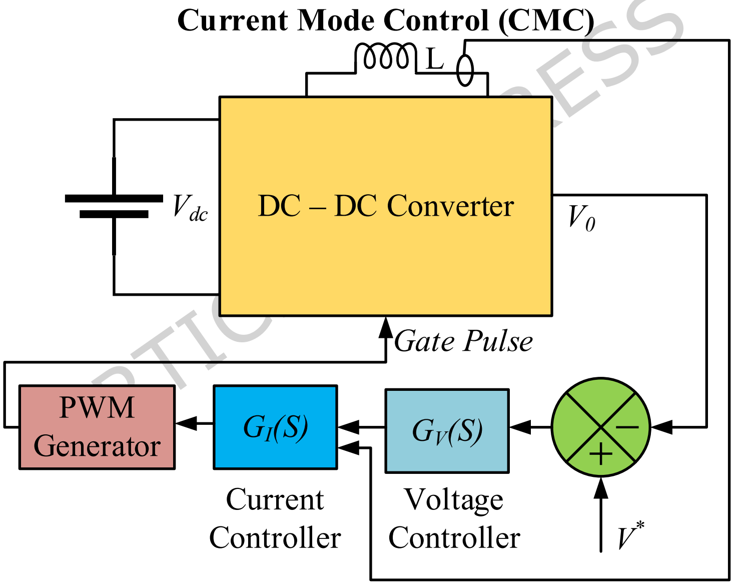


Fig. 14. Basic block diagram of CMC technique for DC – DC converter

But CMC is more difficult to implement than VMC, requiring extra circuitry for sensing and processing the inductor current. Subharmonic oscillations can also be present at duty cycles greater than 50%, and slope compensation techniques must be used to guarantee system stability. Hybrid implementations have been investigated in recent research, where CMC is combined with other control techniques to provide additional performance enhancements. As another widely used control method, CMC controls the output of the converter through the use of the inductor current as the feedback. The technique has a number of advantages over VMC, such as a better transient response and built-in overcurrent protection. CMC can be applied either using peak current mode or average current mode, both with their strengths and weaknesses. One of the main disadvantages of CMC is that it is prone to subharmonic oscillations, which can be avoided by introducing a compensating ramp into the current signal.

Recent developments in CMC have been directed towards improving its stability and performance using digital control methods and adaptive algorithms [44], [45], [46].

4.3 Hysteresis Control

Hysteresis control is a simple yet efficient technique for controlling DC-DC converters using a hysteresis band around the target output voltage to control the switching action. As seen in Fig. 15 the output voltage goes outside this specified band, the controller switches on the switch operation to bring the voltage back to the normal range. This technique is able to provide extremely high transient performance, and hence it is especially suitable for applications involving fast-changing conditions, like motor drives and battery charging. Though it has advantages, hysteresis control is prone to variation in switching frequency, which is difficult to design and filter for EMI.

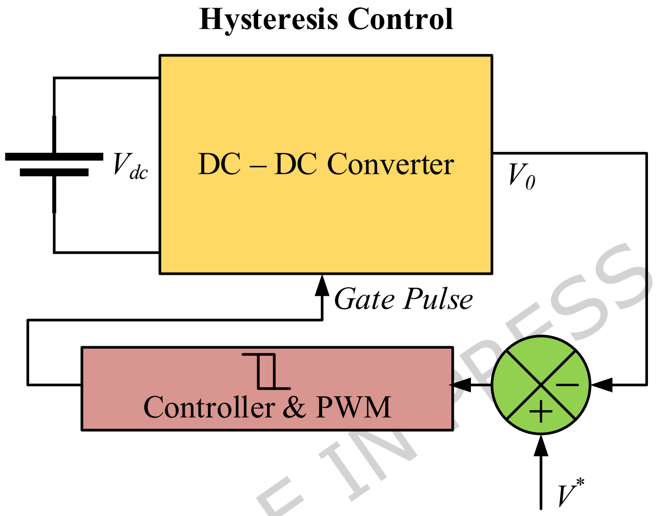


Fig. 15. Basic block diagram of hysteresis control technique for DC – DC converter

Efforts have been made to overcome this limitation by the use of fixed-frequency operation or by hybridizing hysteresis control with other control methods. Hysteresis Control, in fact, is a straightforward but effective method of controlling power converters, particularly in applications requiring a rapid dynamic response. The basic principle is to keep the output voltage or current within a specified hysteresis band, which naturally results in a variable switching frequency. Although this method provides superior transient performance, the variable frequency operation can cause higher electromagnetic interference (EMI). Recent developments in hysteresis control have been directed towards alleviating these problems by incorporating methods such as sliding mode control and fuzzy logic to stabilize the switching frequency and minimize EMI [41], [43], [47].

4.4 Fuzzy Logic Control (FLC)

Fuzzy Logic Control (FLC) is a powerful replacement for conventional linear controllers, particularly for systems involving imprecision and nonlinearity. FLCs utilize linguistic rules to map input variables, e.g., the error and the rate of change of error, to suitable control actions with the potential to provide greater robustness and flexibility. Research has shown that FLCs used in DC-DC converters have the capability to outperform traditional PID controllers in overshoot, ripple, and settling time, especially during dynamic operating modes (see Table 2).

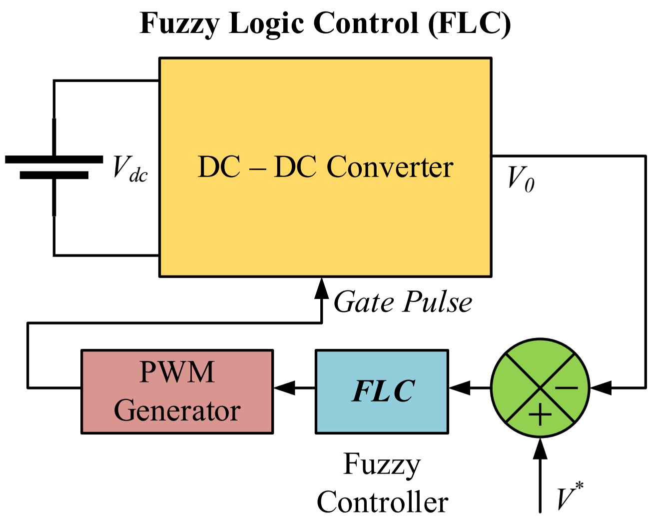


Fig. 16. Basic block diagram of Fuzzy control technique for DC – DC converter

The basic schematic diagram with FLC as a controller is shown in Fig. 16. Latest studies have also confirmed the effectiveness of FLCs in efficiently coping with parameter changes and external disturbances. These studies highlight the ability of FLCs in meeting the challenges due to inherent nonlinearities and uncertainties in power electronic systems. Being an intelligent control method, Fuzzy Logic Control emulates human-like reasoning in coping with uncertainties and nonlinearities in control systems. FLC is especially useful in situations where it is difficult to create accurate mathematical models. It uses a collection of linguistic rules to decide on control actions, thus giving it robustness against parameter changes and external disturbances. Recent developments in FLC have been towards its combination with other control methods, such as sliding mode control and model predictive control, to improve its performance and flexibility in complicated systems [42], [45], [46].

4.5 Model Predictive Control (MPC)

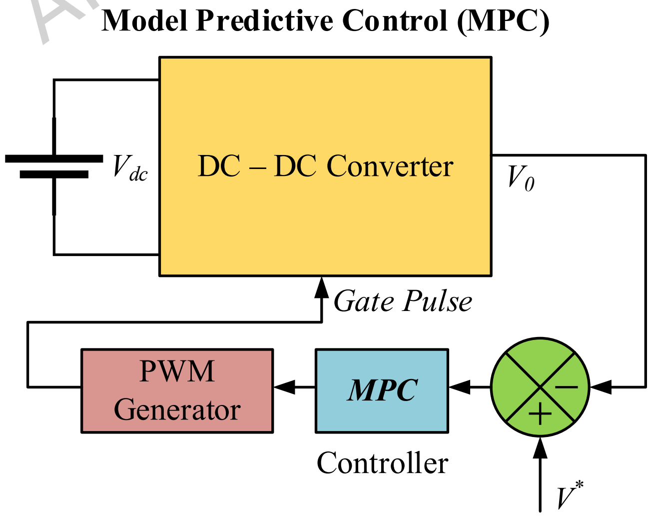


Fig. 17. Basic block diagram of MPC technique for DC – DC converter

Model Predictive Control (MPC) given in Fig. 17, is a leading model in control theory, whereby future system performance is forecast by using a model of the system and the control policy is then adjusted according to this prediction. The method gives gains in dynamic performance, robustness, and flexibility and thus finds particular relevance for advanced power electronic systems. By solving an optimization problem at every sampling moment, MPC determines the optimal pattern of switching events to accomplish particular goals, such as minimizing output voltage ripple or improving efficiency. The main drawback of Model Predictive Control is its high computational requirement, which may limit its application in resource-limited real-time systems. To overcome this disadvantage, researchers have investigated the implementation of reduced-order models together with hardware acceleration approaches to make MPC more practical.

Model Predictive Control has been identified as a sophisticated control strategy that uses a system model to forecast future behavior and to optimize control moves. MPC is especially known to be effective in managing multivariable systems and constraints. It provides outstanding performance in setpoint tracking and disturbance rejection. Yet, MPC is computationally intensive, which may restrict its usage in systems with rapid dynamics. The latest developments in MPC have been oriented towards easing its computational load using methods like event-triggered control and distributed algorithms, hence expanding its possibility for real-time use [42], [48], [49].

4.6 Sliding Mode Control (SMC)

Sliding Mode Control (SMC) is a widely known nonlinear control method renowned for its insensitivity to system parameter variations and external disturbances. SMC achieves robustness by defining a sliding surface in the state space of the system, toward which the trajectories of the system are forced in order to meet the desired performance features. By continuous tuning of the control inputs to force the system to stay on this sliding surface, SMC bestows stability and robustness against uncertainties. The greatest disadvantage of SMC is the phenomenon of chattering, which occurs as a result of the inherent discontinuity of the control law. Recent developments integrate SMC with innovative methodologies, like artificial intelligence and adaptive control techniques, aimed at reducing chattering while maximizing overall efficiency of the control system simultaneously.

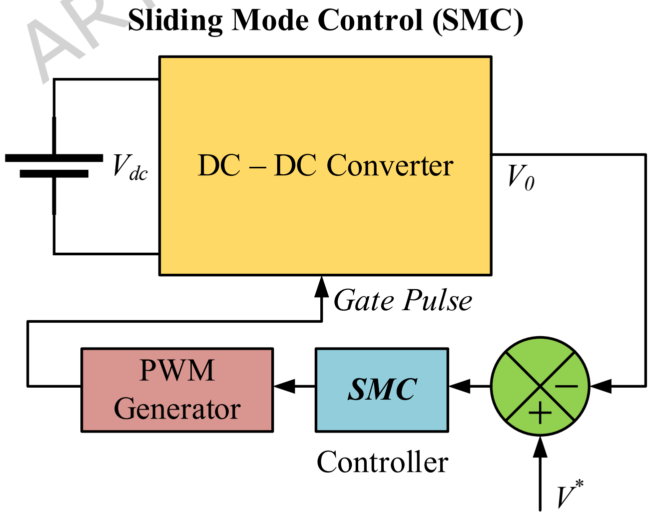


Fig. 18. Basic block diagram of SMC technique for DC – DC converter

Sliding Mode Control is a powerful control method that works through forcing the state of the system to approach and then stay on a pre-specified sliding surface, thus guaranteeing the desired dynamic performance. The block diagram of a SMC fed to DC – DC converter is shown in Fig. 18. SMC is especially famous for its robustness against parameter changes and disturbances. However, it can be plagued by chattering, an unwanted high-frequency vibration near the sliding surface, which can prove troublesome in most applications. Recent developments in SMC have focused on reducing chattering by different approaches, such as the incorporation of fuzzy logic and the use of adaptive control techniques. These developments are intended to improve the performance and extend the range of SMC applications to various fields, such as power electronics and robotics [41], [44], [45], [50].

4.7 AI and Digital Twin Integration:

Artificial intelligence (AI) and digital twin technologies are emerging as powerful tools for enhancing DC-DC converter performance. AI algorithms, such as neural networks and reinforcement learning, can optimize control parameters in real time, improving efficiency under variable loads. Digital twins enable virtual replication of physical systems, allowing real-time monitoring, fault prediction, and adaptive control. In off-grid solar systems, digital twins have demonstrated a 25% reduction in downtime through early failure detection [15]. Future integration with edge computing can enable low-latency AI deployment on embedded platforms.

Table 2: Comparative analysis of various control techniques with respect to applications

Control Method	**Complexity**	**Transient Response**	**Settling Time**	**% Overshoot**	**Robustness**	**Computational Requirements**	**Main Applications**
VMC	Low	Poor	Slow	High	Low	Low	General purpose
CMC	Medium	Good	Medium	Medium	Medium	Medium	High-speed loads
Hysteresis	Low	Excellent	Very Fast	Medium	Medium	Low	Motor drives, battery charging
FLC	Medium	Good	Fast	Low	High	Medium	Nonlinear systems
MPC	High	Excellent	Very Fast	Very Low	High	High	Advanced power electronics
SMC	Medium	Excellent	Fast	Low	High	Medium	Uncertain systems

As can be seen from Table 2, the selection of control strategy plays an important role in determining dynamic performance characteristics like settling time and percentage overshoot. Traditional techniques such as VMC have slow settling time and large overshoot because they rely on error-amplifier dynamics and don't provide direct current regulation [12], [34]. CIMC offers less improvement compared to CMC because it indirectly regulates the inductor current, leading to smaller settling time and overshoot than VMC [12], [35]. High-performance techniques like FLC and SMC provide further reduction in overshoot as well as better settling time through nonlinear decision-making and robust control laws, which are most effective under parameter fluctuations and load disturbances [41], [44], [46]. Among them, MPC provides the quickest settling and minimum overshoot since it anticipates future system conditions and uses optimal control actions in real-time, thus providing better transient performance [11], [13], [42]. The above results show that advanced control methods are more appropriate for applications with high stability and fast transient response, like EV charging, integration of renewable sources, and microgrids.

Besides transient response, computational requirement and robustness are essential issues of converter control in renewable energy and EV systems. Conventional methods like VMC and CMC entail relatively low-to-medium computational burdens but limited robustness under parameter uncertainties and external disturbances [12], [34], [35]. Hysteresis control has satisfactory robustness with low computation cost, and it is effective in battery charging systems and motor drives, albeit at the cost of variable frequency of switching [43], [47]. FLC and SMC are more robust as they take care of nonlinearities and uncertainties with modest computation cost, and thus are suited for renewable energy input-fluctuating systems [41], [44], [46], [50]. MPC, though the most accurate and robust, is with high computational demand, which might restrict its usage in budget-constrained or resource-restricted embedded systems [11], [13], [42]. Thus, the selection of control method is a compromise between robustness and computationally efficiency, which has a significant impact on its viability for real-world use.

Various converters utilize certain control approaches based on their dynamic needs, stability requirements, and computational constraints:

- Boost and Interleaved Boost Converters: Often resort to CMC or VMC for current shaping and voltage control because they are simple and efficient in medium-speed operations [4], [33], [35]. For renewable energy systems that demand high efficiency across various solar/wind inputs, FLC and SMC are used for most instances because of their robustness toward parameter changes [41], [46].
- Bidirectional Converters (e.g., in EV regenerative braking): Typically utilize SMC or MPC, since they require good transient response speed and stability in broad bidirectional power flow conditions [28], [29], [38].
- Hysteresis Control: Frequently utilized in battery charger converters and motor drives, where a very rapid transient response is necessary, although the variable switching frequency can result in EMI issues [43], [47].
- Grid-Connected PV and Microgrid Converters: Gradually adopt MPC and AI-based hybrid controllers, as they provide ultra-fast settling time and low overshoot, essential for power quality and grid compatibility [11], [13], [42].
- Resonant or High-Gain Converters: Favor advanced controls such as SMC or digital twin-based control to deal with non-minimum phase dynamics and provide stable operation under high step-up conditions [15], [53].

Classical methods like Voltage Mode Control and Current Mode Control are still in common use because of their simplicity and reliability; however, newer techniques like Fuzzy Logic Control, Model Predictive Control, and Sliding Mode Control offer improved performance in adverse conditions. Recent advances have centered on hybrid techniques and computational techniques that attempt to overcome the limitations of single techniques. With these developments, engineers can now design DC-DC converters to satisfy the high demands of sophisticated power electronic systems.

5. Improved DC-DC Converter Topologies

Power electronics has developed advanced DC-DC converter topologies for electric vehicles (EVs) and renewable energy systems in recent times. These converters are important to enhance efficiency, raise power density, and provide stable voltage regulation under different load conditions [51]. Advanced converter types discussed here are included in the structural classification chapter in Section 3, but a more extensive discussion of their operational principles, efficiency trends, and application suitability are extended here.

5.1 High-Gain Multiport Converters

Multiport DC-DC converters provide simultaneous power delivery from multiple energy sources, like solar panels and batteries, to the load. These topologies improve power handling capacity and minimize energy losses and hence are very well suited for hybrid renewable energy systems [52]. They frequently include coupled inductors and transformer-based implementations in order to achieve maximum power transfer and efficiency.

5.2 Ultra-Step-Up Converters

Ultra-step-up converters provide high voltage gain with reduced voltage stress on switching elements. With coupled inductors and switched capacitors, the converters improve efficiency significantly, especially for photovoltaic (PV)-fed systems [53]. They allow voltage levels appropriate for integration into the grid without bulky and costly transformers.

5.3 Switched Capacitor Converters

Switched-capacitor (SC) converters achieve voltage conversion by alternately charging and discharging capacitors through semiconductor switches. Switched-capacitor converters eliminate magnetic components, enabling compact designs. However, they suffer from charge redistribution losses and limited scalability at high power levels, restricting efficiency at gains above 4× [54]. They work on charge transfer mechanisms between capacitors, allowing both step-down and step-up voltage conversion. This makes SC converters highly attractive for applications requiring compact design, high power density, and integration in on-chip power management circuits.

5.4 Modular and Interleaved Converters

Modular and interleaved converter structures enhance power distribution and scalability. These topologies achieve minimum current ripple, improved efficiency, and fault tolerance, and thus are suitable for high-power applications [55]. Interleaved operation decreases inductor current stress and improves transient response, resulting in improved performance for challenging environments.

5.5 High-Efficiency Bidirectional Converters

Bidirectional DC-DC converters allow energy exchange in both directions and are thus a requirement for EV battery storage systems and smart grids. These converters maximize energy management in the charging and discharging processes [56]. One of the major applications is regenerative braking in EVs, where redundant kinetic energy is recovered back into electrical energy and stored.

5.6 Soft-Switching Converters

Soft-switching methods, including zero-voltage switching (ZVS) and zero-current switching (ZCS), are extensively used to minimize switching losses and enhance thermal performance. These converters increase efficiency in EV powertrains and grid-connected renewable energy applications by avoiding switching stress on semiconductor devices [57].

5.7 Resonant Converters

Resonant converters utilize soft-switching methods to minimize switching losses and maximize efficiency. High-frequency operation of these converters facilitates compact designs, and they find applications in wireless EV charging and photovoltaic inverters [57]. The converters provide seamless transitions between switching states, thus minimizing electromagnetic interference (EMI).

5.8 Hybrid and Cascaded Converters

Hybrid and cascaded structures combine various topologies, for example, buck-boost and SEPIC, to attain maximal efficiency and voltage amplification. These converters are particularly useful for integration of renewable energy and EVs power management systems [56]. With flexibility, tailored voltage regulation can be achieved while increasing power conversion.

5.9 Isolated DC-DC Converters

Isolated DC-DC converters, such as forward and flyback topologies, enable galvanic isolation, thus improving system safety and reliability. Isolated converters are essential for high-voltage step-down/step-up in grid and EV systems [53]. Isolation avoids ground loop problems and maintains electrical separation between input and output stages.

All these topologies of advanced DC-DC converters have their own strengths based on the application. High-gain multiport and ultra-step-up converters are best suited for renewable energy systems, while modular, interleaved, and bidirectional converters are best for EV drives. Soft-switching and resonant converters are best suited for high-frequency applications, while hybrid and isolated converters are best in terms of flexibility and safety. The topology selection is based on efficiency, voltage gain, power density, and system reliability.

It's important to acknowledge that a number of the converter families considered in this section draw on traditional foundation design principles while offering small improvements in gain, efficiency, or component use. In contrast, new concepts (for example, AI-assisted converter control, multiport hybrid structures, and ultra-wide-bandgap semiconductor integration) are disruptive concepts that go beyond simple refinements. Noting the different levels of maturity allows for a more critical analysis of their readiness for real-world application. Having reviewed advanced converter topologies and their operational characteristics, Section 6 provides a comparative analysis of these designs in terms of efficiency, voltage gain, component stress, and suitability for EV and renewable applications.

6. Comparison study

The comparison Tables 3 and 4 brings out the most important features as elaborated below, of various DC-DC converter topologies applied in electric vehicles (EVs) and renewable energy systems.

Table 3: A comparative study for the converter section

Converter	M	%η	T	WS	SL	CG	C	CD	P	Applications
High-Gain Multiport	H	M-H	H	LA	M	N	H	H	H	Hybrid energy systems, Microgrids
Ultra-Step-Up	VH	H	M	M	L	Y	M	M	M	PV-fed systems, High-voltage applications
Switched Capacitor	M-H	H	L	CO	L	N	L	L	L	Low-power DC applications, Portable electronics
Modular & interleaved	H	VH	H	LA	L	Y	H	H	H	High-power EVs, DC microgrids
Bidirectional	M	H	M	M	M	Y	M	H	M	EV battery systems, Energy storage
Soft-Switching	M	VH	M	M	VL	N	H	H	H	EV Powertrains, Smart grids
Resonant	M	H	M-H	CO	VL	N	H	H	H	Wireless charging, High-frequency applications
Hybrid & Cascaded	VH	H	H	LA	L	N	VH	VH	VH	Renewable integration, EV powertrains
Isolated	M-H	H	H	LA	M	N	H	H	H	High-voltage step-up/down, Safety-critical applications

*M=Voltage Gain, T= Component Count, WS= Weight & Size, SL=Switching Losses, CG=Common Ground, C= Complexity, CD=Control Difficulty, P=Price, CO=Compact, LA=Large, L=Low, M=Moderate, H=High, VH=Very High, VL= Very Low, Y=Yes, N=NO,

Table 4 illustrates the voltage gain as a function of duty cycle of different topologies of the converter. This correlation is very important since it defines how effectively a converter can step up or step down the input voltage to supply the needs of EVs and renewable energy systems:

For EVs: Battery packs tend to run at reduced voltages (e.g., 48 V, 72 V, or 120 V), whereas traction inverters and motors draw higher voltages (200–400 V). A converter having a greater gain at medium duty cycles is desirable since it minimizes switch stress, enhances efficiency, and enables improved thermal management. Converters based on high duty cycles for high-gain can be prone to high conduction losses and low reliability.

For Renewable Energy Systems: Fuel cells and PV modules also have low voltages (per module 18–40 V). This voltage needs to be boosted efficiently in order to input into the DC link of an inverter or into the grid. A topology with moderate duty cycle operation and linear gain properties guarantees stable maximum power point tracking (MPPT), prevents high current ripples, and reduces switching stress.

Table 4: Voltage Gain vs. Duty Cycle

Converter Type	Max Gain (V_{out}/V_{in})	Duty Cycle (D)	Efficiency (η)	Major Concerns
Conventional Boost	4 times	0.75–0.85	85–90%	Efficiency drops at high D
Interleaved Boost	5–6 times	0.75	94–96%	Lower ripple, higher power density
Coupled Inductor	8–10 times	0.6–0.8	92–95%	Magnetic component size optimized
Quadratic Boost	9 times	0.6–0.7	90–93%	Single-switch, higher gain
Cascaded Boost	12 times	0.6–0.7	88–91%	Two-stage, bulky but effective
Switched Capacitor	6 times	0.6–0.8	87–92%	No magnetics, limited scalability

Converters that achieve required voltage gain at moderate duty cycles (0.4–0.6) are typically more efficient and thermally stable for EV traction and PV-fed systems. Operating a converter at duty cycles near 1 decreases efficiency, raises switch/diode stress, and makes control more difficult. Hence, the comparative analysis of gain versus duty cycle aids in finding converters that supply high voltage gain at realizable duty cycles (0.3–0.6), thus being more applicable to EVs and renewable systems. Therefore, Table 4 acts as a design reference by correlating the basic gain–duty cycle relationship with actual-world performance demands in sustainable energy applications.

6. 1. Voltage Gain

Voltage gain is the capability of a converter to step up or step down the voltage level effectively. Ultra-step-up converters and hybrid/cascaded converters have the highest voltage gain, and they are best for use in applications requiring high voltage boosting, like PV-fed high-voltage DC systems. Switched capacitor and bidirectional converters have moderate voltage gain since they are mainly used for energy transfer instead of extreme voltage change. Isolated converters have high voltage gain but need magnetic isolation, which makes them heavier.

6. 2. Efficiency

Efficiency is important in power electronic circuits to reduce energy losses. Soft-switching and modular/interleaved converters are most efficient since they cut down switching losses using zero-voltage switching (ZVS) or zero-current switching (ZCS) methods. Ultra-step-up and switched capacitor converters retain high efficiency but are subject to design parameters like inductor winding ratio or capacitor charge balancing. Hybrid and cascaded converters can experience moderate losses due to added components and complicated power transfer mechanism.

6. 3. Component Count

Component count influences cost, reliability, and circuit complexity. Switched capacitor converters use the fewest components, as they make extensive use of capacitors and switches over inductors. Multiport, modular, and hybrid/cascaded converters use a large number of components because there are multiple power paths, which makes them scalable for energy systems but results in larger size and cost. Soft-switching and resonant converters use extra circuitry, e.g., resonant tanks or auxiliary switches, which elevates component count.

6. 4. Size & Weight

This is a vital parameter in space-limited applications like EV powertrains and portable renewable energy systems. Switched capacitor and resonant converters are the most compact, as they dispense with large inductors or utilize high-frequency operation to minimize component sizes. Modular and isolated converters are bulky and heavy because they contain multiple inductors, transformers, and heat dissipation systems. Ultra-step-up converters find a compromise, employing coupled inductors or switched capacitors to be of reasonable size without being too heavy.

6. 5. Switching Losses

Switching losses impact efficiency and heat dissipation directly. Soft-switching and resonant converters have extremely low switching losses since they utilize techniques like ZVS, ZCS, and resonant frequency operation. Interleaved and bidirectional converters also minimize losses by applying phase-shift techniques, but the losses are a function of duty cycle and frequency. High-gain multiport and hybrid converters experience moderate switching losses, particularly under dynamic loads.

6. 6. Common Ground

A common ground's existence decides if the input and output circuits have a shared reference voltage. Ultra-step-up, modular, bidirectional, and interleaved converters have a common ground, making control and system integration easier. Isolated, resonant, and hybrid converters do not have a common ground because of galvanic isolation, enhancing safety but increasing design complexity.

6. 7. Complexity

Circuit complexity impacts design, implementation, and reliability. Switched capacitor converters are simplest because they work based on principles of charge transfer with little control needed. Hybrid, multiport, and interleaved converters are very complex in that they need more than one stage of switching, sophisticated control algorithms, and synchronization methods. Soft-switching and resonant converters add complexity with extra passive elements and precise frequency tuning.

6. 8. Control Difficulty

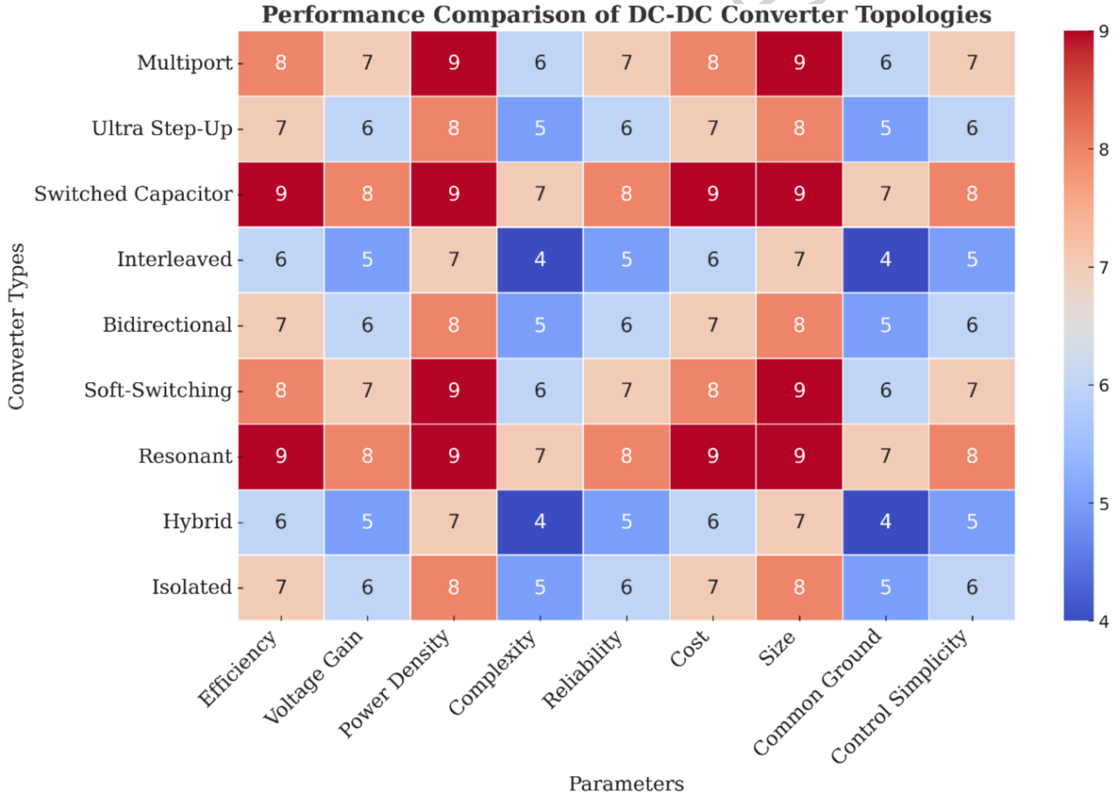
Control difficulty determines ease of voltage, current, and power flow regulation. Switched capacitor converters are the least complex to control since they use constant duty cycles. Bidirectional and interleaved converters need moderate control complexity since they utilize several operation modes. Soft-switching, resonant, and hybrid converters need maximum control difficulty as they need real-time feedback, phase-shift modulation, and frequency tuning.

6. 9. Cost

The cost incorporates component costs, production, and complexity of operation. Basic boost and switched capacitor converters are inexpensive due to fewer components and straightforward control methods. Soft-switching, resonant, and hybrid converters are high cost, as they include advanced materials, extra components, and specialized control hardware. Multiport converters and interleaved are medium to high-priced based on the power path number and scalability.

6.10. Observations from the heat-map:

The heatmap in Fig. 19, graphically displays the performance comparison of different DC-DC converter topologies on multiple parameters such as efficiency, voltage gain, power density, complexity, reliability, cost, size, common ground, and control simplicity. The values in the heatmap (4 to 9) represent relative performance, with higher values indicating improved performance in that particular parameter. Collectively, these comparative assessments highlight the maturity of traditional topologies while recognizing, in tandem, that some of the more interesting trends are still in the research context and require further experimentation before being accepted into widespread application. This differentiation highlights which topologies are ready for deployment and which require further laboratory or field validation, especially for high-power EV and renewable environments.



	Efficiency	Voltage Gain	Power Density	Complexity	Reliability	Cost	Size	Common Ground	Control Simplicity
Multiport	8	7	9	6	7	8	9	6	7
Ultra Step-Up	7	6	8	5	6	7	8	5	6
Switched Capacitor	9	8	9	7	8	9	9	7	8
Interleaved	6	5	7	4	5	6	7	4	5
Bidirectional	7	6	8	5	6	7	8	5	6
Soft-Switching	8	7	9	6	7	8	9	6	7
Resonant	9	8	9	7	8	9	9	7	8
Hybrid	6	5	7	4	5	6	7	4	5
Isolated	7	6	8	5	6	7	8	5	6

Fig. 19. Heat-map comparison of different topologies

Efficiency: Resonant, Soft-Switching, and Ultra Step-Up Converters receive the highest score (9), which reflects highest efficiency. Interleaved and Hybrid Converters receive lower scores, as their added complexity in design adds more losses.

Voltage Gain: Ultra step-up and hybrid converters offer the highest voltage gain, making them ideal for high-voltage applications such as renewable energy systems integration. Switched

Capacitor and Interleaved Converters have moderate voltage gain, which restricts them from being applied to high-voltage systems.

Power Density: Resonant and Soft-Switching Converters exhibit high power density, taking advantage of high-frequency operation and minimized losses. Multiport and Bidirectional Converters score moderately due to increased energy management complexity.

Complexity: Multiport and Hybrid Converters are lower-scoring (more complex), needing multiple control loops and complex designs. Switched Capacitor and Soft-Switching Converters are comparatively less complex, with fewer components and easy control.

Reliability: Soft-Switching and Isolated Converters rank better as they reduce stress on the switching devices, which makes them more durable. Hybrid and Multiport Converters rank worse as they have higher numbers of components and complex designs.

Cost: Switched Capacitor and Interleaved Converters are economical because of their simple structure. Multiport and Hybrid Converters are more costly because of the need for extra circuitry and sophisticated control algorithms.

Size: Switched Capacitor Converters are compact as they do not need magnetic components. Ultra Step-Up and Multiport Converters necessitate larger inductors and transformers, so they have larger size scores.

Common Ground: Certain topologies, including Bidirectional and Interleaved Converters, have a common ground, making it easier to integrate. Isolated Converters are lower scored because of the fundamental galvanic isolation necessity.

Control Simplicity: Switched Capacitor and Soft-Switching Converters provide less complicated control mechanisms. Multiport and Hybrid Converters need sophisticated control strategies, resulting in a lower score.

The quantitative limits illustrated in Section 2 (e.g., 10–20% increase in EMI for coupled-inductor converters, 8–12% converter switching loss in high-gain structures, and 35–40% ripple reductions limits in interleaved converters) inform the future research directions discussed in Section 7.

7. Future Improvements:

7. 1. Established vs. Emerging Trends in DC–DC Converters

Even though the area of DC–DC conversion has evolved greatly, all technologies currently being considered in research are likely to be classified as either traditional approaches or new, emerging next-generation approaches. For example, traditional converter configurations, including interleaved boost configurations, resonant/soft-switching converters, coupled-inductor converter configurations, and wide-bandgap materials such as SiC and GaN, have all undergone ample experimental study and are in common use due to their predictable performance and established reliability.

In contrast, several recent developments represent truly new trends that are beyond the evolution of existing technologies. These include the utilization of ultra-wide-bandgap materials such as Ga_2O_3 and diamond; hybrid multiport converter architectures; AI-assisted control and prediction algorithms; digital-twin-assisted monitoring; and EMI suppression using metamaterials. While these emerging technologies have indications of promise from laboratory studies, their deployment is limited by factors such as high materials and fabrication costs, computation cost, thermal stability, and weak long-term data from the field. This distinction serves to demonstrate the technology readiness levels for the approaches, and it can focus the research agenda on next steps that are likely to have the greatest impact.

A detailed review of the available literature on enhanced gain DC-DC converters presents diverse research shortcomings and limitations. Addressing these deficiencies presents significant opportunities for future innovations. Improving cost-effectiveness, scalability, thermal regulation, computational intensity, and general improvement in overall performance to ensure greater efficiency and dependability in EVs and solar systems of renewable energy poses opportunities for potential enhancements. The remainder of the section discusses opportunities for future enhancement through improved areas according to main emphasis areas. Based on the application requirements, the preferred converter with the suitable control method is suggested in the Table 5.

7. 2. Cost Effectiveness and Scalability

Challenges: Expensive prices of superior materials such as gallium nitride (GaN) and silicon carbide (SiC). Advanced, multilevel, and interleaved converter configurations which reduce scalability and accessibility. Gallium oxide (Ga_2O_3) and diamond semiconductors offer ultra-high breakdown voltages (>8 kV) but exhibit poor thermal conductivity and are not yet commercially viable for mainstream power converters.

Improvements: Scientific work on cutting-edge materials including gallium oxide (Ga_2O_3) and diamond semiconductors will reduce manufacturing expense and make products more commercially acceptable. Consolidating manufacturing procedures in the wide-bandgap materials market will aid in achieving economies of scale. Developing modular and scalable architectures will enable seamless integration into various applications, from off-grid solar systems to large-scale renewable energy installations, facilitating upgrades and reducing lifecycle costs. Advances in additive manufacturing and nanotechnology can help reduce the cost of key components such as magnetic elements, heat sinks, and semiconductors, making enhanced converters more affordable.

Table 5: Application-oriented converter and controller recommendation matrix

Application Type	Required Gain	Isolation	Preferred Converter	Suitable Control Strategy	Supporting Literature
EV Battery Charging	Medium	No	Interleaved Boost	MPC / CMC	[4], [33], [55]
EV Regenerative Braking	Medium	Yes	Bidirectional Isolated Boost	SMC / MPC	[28], [29], [38]
Off-grid Solar	High	No	Coupled-Inductor or Quadratic	FLC / SMC	[6], [20], [21], [36]
Grid-Tied PV Inverter	High	Yes	Ultra-Step-Up	FLC / VMC	[19], [23], [53], [54]
Microgrid Energy Transfer	Variable	Yes	Multiport Modular	AI-enhanced MPC	[5], [17], [32], [52]

7. 3. Thermal Management

Challenges: Excessive generation of heat in high-power applications, especially in EVs and CSP systems. Poor scalability and longevity of current cooling methods, like phase-change materials

Improvements: Bio-inspired cooling, liquid cooling, and hybrid thermal management systems can improve heat dissipation. Development of phase-change materials with better thermal stability is also required. Incorporating thermal management in the early design stage assures component placement and airflow optimization, minimizing the risk of overheating and increasing component life. Artificial intelligence-based monitoring systems can adaptively modify cooling strategies according to real-time temperature fluctuations, enhancing operating efficiency.

7. 4. Advanced Control Strategies

Challenges: Computational complexity of sophisticated control methods like model predictive control (MPC) and artificial intelligence (AI). Advanced hardware needs constraining adoption in low-cost applications

Improvements: Developing lightweight MPC and AI algorithms for cost-effective embedded devices will make accessibility better. Approaches such as edge computing and federated learning can minimize the computational load with the ability to adapt. Algorithmic capabilities that can handle random inputs, for example, uncertain solar irradiance or varying electric vehicle loads, will enhance reliability and robustness. Integrating conventional techniques (e.g., PID) with AI-based optimization balances simplicity and performance in a wide range of applications.

7. 5. Integration of AI

Challenges: High cost and complexity of implementation and limited experimental verification in hardware systems.

Improvements: AI-based maintenance systems can forecast failures prior to their occurrence, minimizing downtime and operational expenses. Combining AI and digital twin technology with material science and thermal management innovations can deliver solutions to several challenges as a whole.

7. 6. Topology Innovations

Challenges: Traditional boost converters face efficiency limits at high duty cycles. Advanced designs like interleaved converters and coupled inductor designs incur extra costs and design complexity

Improvements: Investigations of new designs like quasi-Z-source and multiport converters can avoid the efficiency and scalability issues associated with traditional topologies. Interleaved and coupled inductor designs blended together can boost performance while reducing issues like electromagnetic interference (EMI) and thermal losses. Upcoming designs must accommodate EVs' quick load changes and renewable energy systems' variable inputs for stable performance.

7. 7. EMI Mitigation

Challenges: High-frequency GaN-based converters' switching elevates EMI, compromising system reliability.

Improvements: Integrated into converter designs, compact, efficient filters will keep interference to a minimum without a large cost or weight increase. New shielding materials and metamaterials have the potential to absorb EMI without degrading efficiency. Studies on soft-switching and zero-voltage/zero-current switching methods can minimize noise and improve overall system performance.

7. 8. Scalability for Large-Scale Applications

Challenges: Most converter designs are inappropriate for large-scale applications such as grid-connected renewable systems or fleets of EVs.

Improvements: High-gain DC-DC converters must cater to bidirectional power flow and dynamic load balancing to ensure stability in high renewable energy penetration situations. Compatibility with a wide range of energy storage technologies, such as lithium-ion and solid-state batteries, will allow for compatibility with hybrid energy systems. Universal standards will promote interoperability and scalability between varied industries.

7. 9. Long-Term Reliability and Durability

Challenges: Lack of confidence in long-term reliability of advanced materials and cooling technologies under harsh conditions

Improvements: Extensive real-world testing under different conditions, including high temperatures and mechanical stress, will ensure durability. Applying redundancy and fault-tolerant mechanisms will increase reliability, especially in mission-critical applications such as EVs and microgrids. Predictive models to evaluate component degradation over a period of time will allow proactive maintenance and replacement strategies.

7. 10. Environmental Consideration and Sustainability

Challenges: Environmental concerns regarding high-tech material production and disposal of electronics.

Improvements: Investigating recyclable, sustainable, or biodegradable materials helps in reducing environmental loads from converters. Techniques of manufacturing like precision by laser cutting or additive processes reduce the consumption of resources. Creating recycling strategies for DC-DC converters will make the recovery and reuse of precious materials such as GaN, SiC, and copper easier.

Conclusion

DC-DC converters play an essential role in facilitating efficient power management in electric vehicles and renewable energy systems. This review has provided an extensive classification of high-gain topologies interleaved, coupled-inductor, multiport, and resonant converters and compared their performance in voltage gain, efficiency, size, and control complexity. The application of wide-bandgap semiconductors (SiC, GaN) has improved switching performance and thermal robustness considerably, while sophisticated control approaches such as MPC, FLC, and SMC provide better dynamic response and robustness. Even with advancements, there are issues to be resolved in terms of cost, scalability, EMI, and long-term reliability. Next-generation DC-DC converters will have to address modular designs, AI-based predictive maintenance, and eco-friendly materials in order to enable the global energy transformation towards clean energy. Filling these gaps, next-gen DC-DC converters will be the key to delivering high-efficiency, reliable, and scalable power systems for sustainable mobility and energy. By clearly distinguishing between established technologies and emerging research trends, this review provides a balanced perspective that can help researchers, designers, and practitioners identify both immediately deployable solutions and areas where further investigation is essential. This review not only synthesizes existing converter technologies but also provides a structured framework that links topological improvements, control strategies, and emerging materials to specific application needs in EVs and renewable systems.

Nomenclature & Acronyms

Symbol / Term	Description
V_{in}	Input voltage to the converter
V_{out}	Output voltage from the converter
I_{in}	Input current
I_{out}	Output current
D	Duty cycle
fs	Switching frequency
L	Inductance
C	Capacitance
R	Load resistance
η	Efficiency
G_V	Voltage gain
T_S	Switching period ($Ts = 1/f_S$)
ΔV	Voltage ripple
ΔI	Current ripple
Vref	Reference voltage
FLC	Fuzzy Logic Controller
SMC	Sliding Mode Controller
MPC	Model Predictive Controller
AI	Artificial Intelligence
WBG	Wide-Bandgap (semiconductors like SiC, GaN)
SiC	Silicon Carbide
GaN	Gallium Nitride
Ga_2O_3	Gallium Oxide
EV	Electric Vehicle
PV	Photovoltaic
VMC	Voltage Mode Control
CMC	Current Mode Control
ZVS	Zero Voltage Switching
ZCS	Zero Current Switching
BLDC	Brushless DC Motor
DSP	Digital Signal Processor
SOC	State of Charge
BMS	Battery Management System
IoT	Internet of Things
EMI	Electromagnetic Interference
MTBF	Mean Time Between Failures

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