

A Survey on High-Efficiency DC-DC Converters: Architectures, Performance Enhancements, and Applications in Renewable Energy and EVs

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ABSTRACT

The demand for very effective power conversion solutions has increased due to the growing emphasis on electric transportation and sustainable energy systems worldwide. In electric vehicles and renewable energy systems, DC-DC converters are a vital component between power interfaces, storage components, and loads. A thorough analysis of current developments in high-efficiency DC-DC converter technologies is provided in this study, with a focus on their use in wind, solar photovoltaics, and electric transportation platforms. In addition to discussing performance-enhancing measures including soft-switching, wide bandgap semiconductors gallium nitride and silicon carbide, digital control approaches, and thermal optimization tactics, the paper categorizes converter topologies. Efficiency standards and trends in technology adoption are highlighted through a summary of comparative findings from current research. The study also highlights prospective research avenues to tackle problems including power density, bidirectionality, and integration with smart systems, as well as design obstacles. For academics, engineers, and system integrators working on the development and deployment of next-generation power electronics, this review is intended to be a useful resource.

Keywords: DC-DC converters, high efficiency, electric vehicles, renewable energy, power electronics, converter topologies, digital control.

1. INTRODUCTION

An important change in energy use and power infrastructure is the global trend toward renewable energy (RE) and electric vehicles (EVs). Power electronic systems, which enable energy collecting, conversion, and distribution in an efficient and sustainable manner, are at the center of this evolution due to worries about climate change and the constraints of fossil fuels. A thorough analysis of the many facts of integrating RE for climate resilience is provided in [1], with an emphasis on the main obstacles, solutions, and prospects. This study provides insights into many ways of integrating RE and its implications for improving climate resilience at local, regional, and global scales using the most recent research findings and case studies. In order to illustrate the function of PE, a research presented in [2] examines wind energy and photovoltaics (PVs), which are the most popular RE sources. First, the needs of PE and the advancement of RE sources are examined. Secondly, grid codes for wind and PVs are then covered, along with power conversion and control technologies. The purpose of the study described in [3] is to talk about how RE integration fits within sustainable development. It offers a current analysis of the most recent worldwide trend of different RE integrations within the power industry. There is a thorough discussion of the nega-

tive impacts of each RE source as well as the function and environmental impact of this high integration level. In order to solve the issues with energy grid management and its integration with RE systems, the block-chain concept is introduced in a research published in [4]. To ensure that energy grid management systems are sustainable, first a novel block-chain integration process with RE systems was created from the standpoint of the circular economy. This is followed by talks about the benefits of the suggested integration procedure for energy policymakers. Second, the difficulties that block-chain has encountered while integrating with a circular economy are discussed. A new BAC-SDS consensus designed especially for energy transferring from vehicle to vehicle block-chain was described in a research in [5], allowing resilient systems to maximize the usage of RE. To improve the scalability of the system, proposed research used the sharing approach and suggests a cryptography-based EV leader election. Additionally, this method guarantees the safe transfer of energy values, provided that all EVs behave sensibly and maintain their existing proofs. Decomposition of a whole ensemble empirical mode and fuzzy logic control energy management strategy is proposed in a study presented in [6]. The aim of this study is to lessen the lithium-ion batteries aging brought on by high-frequency power demand and enhance the effectiveness of EVs energy storage systems.

The DC-DC converter, a vital part and in charge of managing power flow and regulating voltage in a variety of applications, is at the heart of contemporary energy conversion systems. Because these converters connect storage components, load demands, and RE sources, their effectiveness is crucial to system-level performance. In a study published in [7], a novel transformer less high-gain DC-DC converter with a single switch for RE systems is suggested. By increasing The PV panel's voltage and supplying a constant input current, respectively, the suggested converter addresses two primary issues: the low voltage that PV solar

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panels produce and the intermittent input current brought on by the switching power supplies. A voltage multiplier stage and a switched capacitor/inductor cell are added to the conventional boost converter to create the suggested converter. A new zero-voltage soft-switching high gain DC-DC converter is introduced in [8] to increase the efficiency of high gain DC-DC converters that use MOSFETs as switching devices. The output diode in a conventional boost converter is replaced with a main switch tube, and an auxiliary network is added to enable true zero voltage switching (ZVS) soft turn-on for both switches and true zero current switching (ZCS) soft turn-off for all diodes. This boosts effectiveness and successfully mitigates the drawbacks of diode reverse recovery. A bidirectional four-port DC-DC converter is suggested in a work, which is published in [9], for the integration of a DC micro grid with a hybrid RE system. When compared to the current bidirectional multiport converters, the suggested converter requires the fewest devices. A novel nonisolated soft-switching coupled-inductor (CI) step-up DC-DC converter is introduced in this work in [10]. The suggested architecture raises the ratio of voltage conversion without requiring a high duty cycle by using a voltage multiplier circuit in conjunction with a three-winding CI. An effective DC-DC converter for use in RE applications is suggested in a study published in [11]. The voltage multiplier cell and switching inductor cell are used in the design of the suggested high-gain converter. Switched inductor cells provide the constant source current in the suggested converter, while voltage multiplier cells provide the high voltage gain. An innovative high-step-up converter for use in RE like fuel cell and solar power systems is presented in a work published in [12]. Its foundation is an inductor that is coupled to a voltage multiplier cell. This converter uses a linked inductor and voltage multiplier cell to produce a high voltage conversion ratio. A research presented in [13] proposes a novel multi-port DC-DC power converter to address the delayed response and intermittent nature of RE applications. The suggested circuit incorporates many RE sources besides the energy storage devices, and the suggested converter combines a DC-DC converter and a DC-AC inverter.

Early converter designs provided rudimentary functionality, but in recent years, high-efficiency systems that attempt to reduce size, energy loss, and thermal stress have become more prevalent. However, switching losses, electromagnetic interference (EMI), and inadequate thermal control make it difficult to achieve high efficiency. Design concerns and performance evaluation of converter approaches based on switching loss and ripple characteristics is presented in [14] which introduces a novel idea of converter techniques, because these technique is mainly used in industries. This work also focuses on the design and simulation of converters using PSIM software. Three distinct topologies for DC-DC converters are suggested in this study: Zeta, Single-Ended Primary Inductor Converter (SEPIC), and Luo. These topologies are designed and theoretically derived. A novel method for measuring LLC rectifiers and other isolated converters switching losses is put forward in this study presented in [15]. Additionally, two novel circuits that may be used with both semiconductor devices with high and low voltages are shown for isolation and quantifying of the output capacitance hysteresis loss. In a research published in [16], the conventional equivalent circuit of a step-up DC-DC converter was altered to account for the impacts of both conduction and switching losses. A more accurate average model is made possible by the resulting formulation, which is applicable to all DC-DC converters and is especially well-suited for the analysis of multi-converter systems and the most current uses of RE sources. A unique idea for switch-mode DC-DC boost converters with lower switching losses

is put forth in a work, which was published in [17]. To accomplish ZVS when a transistor is turned off, the converters make use of an auxiliary switching cell. The new idea makes it easier to raise an IGBT-based boost converter's efficiency or switching frequency. For an n-port multiactive bridge (MAB) DC-DC converter made up of n active full bridges and a multiwinding transformer, an article presented in [18] provides unified and generalized modeling, circuit analysis, and power flow optimization approaches. The paper suggests an ideal phase-duty control variable-based modulation technique with the goal of increasing the MAB converter's efficiency throughout a broad load and port voltage gain range. An investigation on the design of transformer thermal management for dual active bridge power converters is detailed in [19]. The temperature control of the winding components and the magnetic core is given special attention. Reducing the core volume to less than 80 cm³, increasing power efficiency to over 99%, and integrating the serial inductance of 8.7 μ H as the transformer's leakage inductance are the goals for a 7 kW dual active bridge DC-DC converter. Since high temperatures can impair the performance of PE components, a study, which was given in [20], reviews thermal management solutions for important PE components in EVs as well as their failure scenarios. This study also examines cooling trends for the upcoming generation of PEs as well as cooling designs now used in EVs. A study, which is presented in [21], recommends a finite control set model prognostic mechanism to enable electro-thermal control on semiconductor devices by selecting the best switching states for real-time thermal management while reducing power quality concerns. Study, which is given in [22], suggests a unique thermal management technique for improving the constancy of IGBT heat stress in a converter in order to solve the issue of heat stress in converters. The IGBT junction temperature is monitored at the converter level using a technique constructed on bus voltage ringing. In order to improve the harmonic sideband extension capability of periodic pulse-width modulation (PWM) and to address the accretion of low-frequency harmonic components produced by chaotic PWM, a research presented in [23] uses discrete chaotic sequences to restrain the varying frequency of the periodic function a second time. Research which is presented in [24], uses various snubber circuits in a three-level T-type isolated bidirectional DC-DC converter to lessen EMI, which is the primary issue that occurs in high switching power converters like DC-DC converters. To determine how well the snubber circuits reduce noise, the converter is simulated in PSIM. The design and implementation of a 15 W continuous conduction boost converter with a 25 kHz switching frequency is demonstrated in a study described in [25]. It makes use of an inductor-capacitor-inductor, pi, an inductor capacitor (LC) with damping, and LC EMI filters. Additionally, this study presents the modeling and analysis of the boost converter in terms of tiny signal and state space.

Researchers have resorted to cutting-edge technologies like digital control, soft-switching methods, WBG semiconductors i.e. GaN and SiC, and modular topologies in order to get control on the switching losses, EMI and inadequate thermal control in order to improve the efficiency. These innovations promise improved performance metrics including power density, fast response, and energy efficiency. According to a research published in [26], it is showcased that GaN and SiC are the most promising semiconductor materials being explored for the next generation of power devices. In order to achieve small power converters, this proposed study also looks at the usage of modern power semiconductor devices, high electron mobility transistors, which minimize switching losses and enable high switching frequencies from kHz to MHz. Results of the performance and effectiveness of a DC-DC

resonant converter with a switched capacitor topology, outfitted with GaN transistors and SiC diodes, are shown in the work published in [27]. This study also looked at issues pertaining to the DC-DC converter’s optimization for high efficiency, reduced size, and a simpler design. Evaluating the effectiveness of SiC and GaN in electric car chargers was the study’s main goal, as stated in [28]. With the overall objective of increasing efficiency and attaining higher performance for electric cars, this study comprised a comparative review of their basic performance criteria and application costs. For 800V EV on-board charging, a 6.6kW 500kHz bidirectional isolated DC-DC converter based on GaN and SiC wide band gap semiconductor devices is created. This method is more straightforward and dependable than the multilevel architecture approach for 800V output, as demonstrated in [29]. With the use of LTSPICE modeling software, the performance comparison of Si, SiC, and GaN based power MOSFETs is demonstrated in the article published in [30] with regard to a DC-DC Boost converter. It is evident that using GaN and SiC switches for switching mostly boosts the converter’s efficiency. The technology underlying rotor design that minimizes the strengths and weaknesses associated with key performance parameters like energy conversion efficiency, switching frequency, thermal resistance, EMI, cost, and system reliability is evaluated in a comparative analysis of SiC and GaN-based power converters in RE systems presented in [31]. According to a study published in [32], the use of devices with a WBG, specifically SiC and GaN, will determine future trends, benefits, and drawbacks in the creation and use of multi output DC-DC converters. Founded on their primary topologies and formations, uses, results, and tendencies, this research also provides an overview of the most significant subjects pertaining to multiple-output DC-DC converters. Over thirty distinct configurations and topologies of multiple-output DC-DC converters are displayed, including single and multiple switches, isolated and non-isolated, and based on soft and hard switching techniques. These configurations and topologies are utilized in a wide range of applications and solutions. Soft-switching methods and WBG-based switches are compared in this work, which was published in [33], for a PV energy application in DC-DC boost converters. Using theoretical analysis, modeling, and experimental data, the performance of four prototypes including soft-switched and hard-switched DC-DC converters with both cutting-edge Si and GaN switches is assessed in terms of cost, power density, efficiency, and reliability.

A systematic overview is necessary to comprehend the current state and potential future directions in high-efficiency DC-DC converters, given the speed at which technology is developing and the wide range of available solutions. Consolidating recent developments, categorizing novel topologies, and highlighting important design trends for EV and renewable applications are the aims of this analysis.

The core objectives of this proposed survey are listed below:

- To categorize and evaluate contemporary DC-DC converter topologies utilized in EV and RE systems, emphasizing their applicability and working principles.
- To look at ways to increase efficiency, such as digital control schemes, soft-switching techniques, and new semiconductor technologies (GaN, SiC) that allow for better power conversion performance.
- To recognize new developments in technology and design, such as modular converter topologies, AI-driven control optimization, and bidirectional power flow capabilities.
- In order to satisfy the needs of next-generation clean energy and transportation applications, future research should concentrate

on integration, thermal management, standardization, and cost reduction.

Section 2 outlines the classification of DC-DC converters, forming the foundation for the research survey. Section 3 discusses efficiency enhancement techniques, incorporating graphical representations of key survey findings. Section 4 examines applications in RE and EV systems. Section 5 provides a comparative analysis of recent literature, while Section 6 presents the study’s conclusions. Finally, Section 7 addresses the challenges and outlines potential directions for future research.

The graphical abstract, which visually summarizes the study’s key steps, is presented in Figure 1.

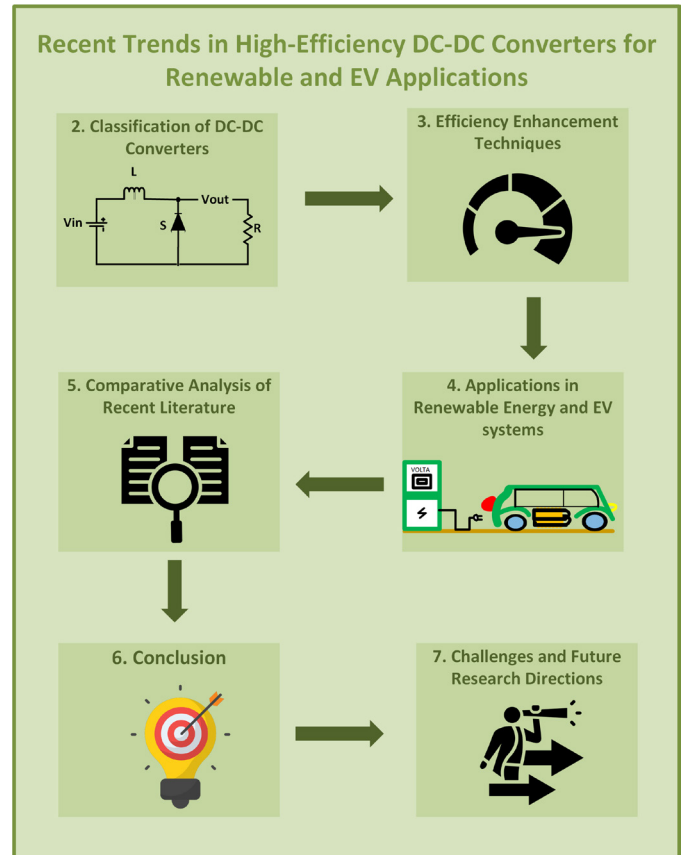


Fig. 1 Graphical abstract of the proposed study

2. CLASSIFICATION OF DC-DC CONVERTERS

DC-DC converters are essential components of PE systems that are utilized in EV and RE applications for energy flow regulation, impedance matching, and voltage level transformation [34-35]. These converters can be categorized according to the voltage conversion ratio, power flow direction, and isolation. Non-isolated and isolated converters are the two main types, and each has several topological variations.

2.1 Non Isolated Converters

Galvanic isolation between the input and output is not a feature of non-isolated converters. Because of their excellent efficiency and small size, they are frequently utilized in low-to-medium power applications.

2.1.1 Buck Converter

A buck converter, often called a step-down converter, lowers an input voltage to a reduced output voltage. It is frequently utilized in battery charging circuits, point-of-load (POL) regulation, and EV onboard electronics. Efficiency often exceeds 90% due to its simple switching mechanism.

The buck converter, specifically, achieves this step-down function using a semiconductor switch (S), a capacitor (C), an inductor (L), and a diode (D). In this analysis, V_{in} denotes input voltage and R is the load resistance [36]. Assume an ideal switch and neglect non-linearities and noise caused by stray inductors and parasitic capacitors, as their effects are minimal during switching. The specific design details of the buck converter is presented in Figure 2.

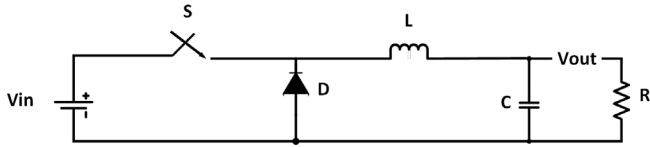


Fig. 2 Schematic illustration of a buck converter

Since for buck converter voltage output is always lesser than the input voltage and is given by equation 1;

$$V_{out} = dV_{in}, \tag{1}$$

Where duty ration is denoted by d and is defined as $d = \frac{t_{on}}{T}$. t_{on} is the switch ‘S’ ON time while switching time period is ‘T’. The inductance L has a crucial value, L_c , that acts as the dividing line for a buck converter’s continuous and discontinuous current modes and it must be larger than the chosen inductance value in order to guarantee the conduction mode of continuous current.

Equation 2 provides the inductance’s critical value;

$$L_c = (1-d) \frac{R}{2f}, \tag{2}$$

Where the switching frequency is denoted by f .

When selecting the inductor value, it is important to keep in mind that the right inductor value determines both the load current and the ripple current magnitude in the output capacitor. Therefore, for the design to produce satisfactory results, a ripple current of 10% to 20% of the average output current is often assumed. The following formula presented in equation 3 determines the inductor’s value;

$$\Delta I_L = \frac{V_{in} T_p d(1-d)}{L}, \tag{3}$$

Where time period is denoted by T_p .

Assuming that the output voltage ripple is between 1% and 2% of the output voltage, the value of the capacitor is calculated. The value of the capacitor is established by equation 4;

$$\Delta V = \Delta I_L \times \frac{1}{8fC}. \tag{4}$$

2.1.2 Boost Converter

The input voltage is raised to a higher output level using a boost converter, also known as a step-up converter. This architecture is widely used in fuel cell interfaces, solar PV systems, and EV drivetrain DC-link stabilization. The layout and construction of a functional model for a 5-12V DC-DC boost converter utilizing a MOSFET, resistor, capacitor, inductor, and diode is shown presented in [37]. The basic idea behind how the converter works is that an inductor resists fluctuations in current. A ferrite pot core with windings is used in the custom-designed inductor. The technology of switched-mode power supplies for the movement of energy from the input to the output is briefly reviewed in the study. MATLAB simulations and real-world hardware results are used to validate the suggested design. Figure 3 shows the design circuit of a boost converter.

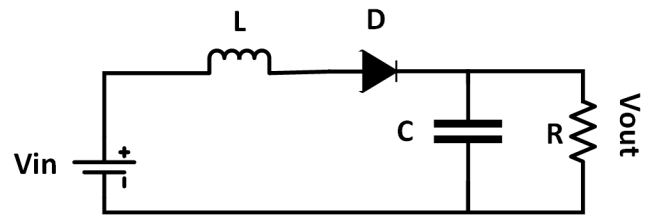


Fig. 3 Design circuit of a boost converter

2.1.3 Buck-Boost Converter

Applications with changing input voltages, like battery-powered systems where voltage varies with state-of-charge, can benefit from this topology’s step-up and step-down capabilities. Conventional implementations flip the polarity of its output. A step down/step up buck boost converter’s primary use is in regulated DC supplies, where it may be necessary to have a negative polarity output with regard to the input voltage’s common terminal. The output can be either lower or higher than the input voltage depending on necessity [38]. The two fundamental converters i.e. the step up converter (boost) and the step down converter (buck) can be connected in a cascade to create the buck-boost converter. The output to input voltage conversion ratio in steady state is calculated by multiplying the conversion ratios of the two cascaded converters. The output and input voltage ratio is calculated by equation 5;

$$\frac{V_{out}}{V_{in}} = \frac{-d}{1-d}. \tag{5}$$

Therefore, whether the converter functions as a boost or buck converter in the output mode will depend on how the duty ratio changes. Figure 4 displays the buck boost converter’s schematic diagram.

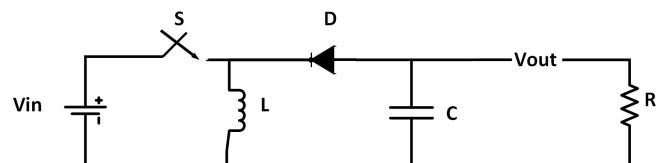


Fig. 4 Schematic diagram of a buck boost converter

2.1.4 Cuk Converter

One kind of DC-DC converter that transfers energy from the source to the load both during the ON and OFF phases is the Cuk converter. Like a buck-boost converter, a Cuk converter generates an output voltage that is inverted and either higher or lower than the input voltage. The Cuk converter provides low ripple characteristics and continuous current at both the input and output sides. Its energy transmission is accomplished by a capacitor, which improves EMI performance and is appropriate for applications that demand high stability and low noise.

Figure 5 depicts the circuit architecture of a Cuk converter.

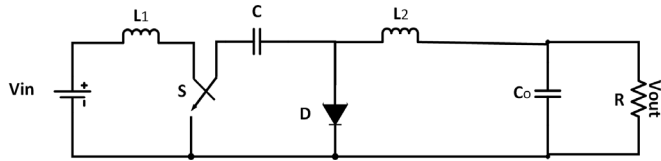


Fig. 5 Topology of a Cuk converter circuit

When turning ON the switch (S), capacitor (C) gives the diode’s anode a negative polarity this causing it to become reverse-biased and cease conduction. Energy is stored by the inductor L1 from the source. Energy is transferred from it to the load, inductor, L2, capacitor, and Co. Capacitors discharge and inductors store energy concurrently during the ON phase. Throughout this period, the inductor current rises from its lowest to its highest value. The diode becomes forward-biased and starts conduction when the switch is turned off. Capacitor C receives the energy stored in inductor L1, and capacitor Co receives the energy stored in inductor L2 and its source. Inductor currents decrease from their highest to lowest values throughout this time frame. Like the buck-boost converter, the Cuk converter’s ratios of voltage and resistance conversion are the result of the buck and boost converters respective voltage conversion ratios and resistance conversion ratios [39].

2.1.5 Single-Ended Primary Inductor Converter (SEPIC)

Regardless of the polarity of the input, the SEPIC topology permits positive output voltage. It is frequently used in systems, such as automobile start-stop systems, where the input voltage fluctuates both above and below the output voltage.

A SEPIC converter’s primary benefit over buck-boost and Cuk converters is that it produces an output voltage that is not reversed. Schematic of a SEPIC converter is displayed in Figure 6.

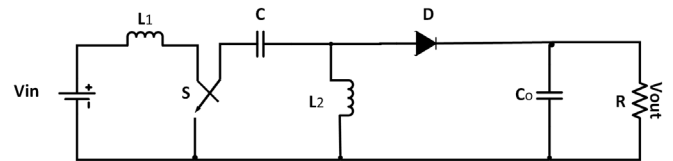


Fig. 6 Schematic of a SEPIC converter

While turning ON the switch (S), capacitor (C) gives the anode of the diode negative polarity, causing it to become reverse-biased and cease conduction. L1 Inductor stores energy from the source, while the inductor L2 receives the energy from the capacitor C. The output capacitor Co ensures that the load current is constant. During this time, inductor currents increase from their lowest to their highest value. Diode gets forward-biased and starts conduction when the switch (S) is turned OFF. Capacitor C receives energy stored in the inductor L1, while capacitor Co and the load receive energy stored in the inductor L2 and its source. During this time, inductor currents decrease from their maximum to their lowest value. Compared to a Cuk converter, a SEPIC converter uses capacitors and inductors to transmit energy, and switching stress is far lower. The SEPIC converter’s voltage conversion ratio and resistance conversion ratio are identical to those of the Cuk and buck-boost converters [39].

2.2 Bidirectional Converters

Reversible power flow is made possible by bidirectional DC-DC converters, which is crucial for energy storage systems (ESS), EV regenerative braking, and vehicle-to-grid (V2G) applications. These converters have the ability to function in both boost and buck modes, and for stable operation in both directions, their control technique frequently consists of dual-loop or current-mode control.

These converters are generally classified based on isolation, topology, and control approach. Table 1 summarizes the main types of bidirectional converters along with their characteristics and applications [40-41].

Table 1 Types of Bidirectional DC-DC Converters

Type	Isolation	Main Topology	Typical Application	Advantages	Limitations
Non-Isolated Buck-Boost	No	Synchronous Buck-Boost, Cuk, SEPIC	Battery charging/discharging, DC microgrids	Simple design, high efficiency	Limited voltage conversion range
Isolated Full-Bridge	Yes	Dual Active Bridge (DAB), Full-Bridge LLC	EV charging stations, renewable integration	High power capability, galvanic isolation	Higher cost, more complex control
Isolated Half-Bridge	Yes	Half-Bridge Bidirectional	Low-to-medium power applications	Fewer switches than full-bridge, isolation	Limited voltage range
Multiphase Non-Isolated	No	Interleaved Buck-Boost	High-current EV auxiliary systems	Reduced ripple, higher efficiency	More components, control complexity
Resonant Bidirectional Converter	Yes/No	LLC Resonant, Series Resonant	Wireless charging, high-frequency applications	Soft-switching, high efficiency	Narrow load range, control challenges
Switched-Capacitor Bidirectional	No	Series/Parallel Capacitor Networks	Portable electronics, low-power energy storage	Lightweight, compact	Limited power capability

2.3 Isolated Converters

When galvanic isolation is necessary for safety, noise immunity, or ground loop elimination, isolated converters are employed. These are frequently found in communication interfaces and high-voltage systems [42-43].

2.3.1 Flyback Converter

The flyback converter, which is widely used in low-power applications, stores energy in a transformer during the ON phase and moves it to the output during the OFF phase. Although it is less effective for high-power designs, its simplicity makes it affordable.

2.3.2 Forward Converter

In comparison to the flyback topology, the forward converter offers continuous energy transfer through the transformer, resulting in increased efficiency and less voltage stress. It is employed in isolated, medium-power applications.

2.3.3 Full-Bridge and Half-Bridge Converters

These topologies are suited for high power applications like DC fast chargers for EVs and utility-scale renewable systems. They offer high efficiency and excellent voltage regulation. Their control often involves phase-shift modulation and zero ZVS to minimize switching losses. Table 2 provides a detailed overview of the DC-DC converter topologies commonly used in RE and EV applications.

Table 2 Classification and schematic overview of common DC-DC converter topologies used in RE and EV systems.

Topology	Isolation	Directionality	Voltage Conversion	Common Applications
Buck	No	Unidirectional	Step-down	Battery chargers, POL regulators
Boost	No	Unidirectional	Step-up	PV systems, fuel cells
Buck-Boost	No	Unidirectional	Step-up/Step-down	LED drivers, UPS
Cuk	No	Unidirectional	Inverting	EMI sensitive equipment
SEPIC	No	Unidirectional	Step-up/Step-down	Automotive electronics
Bidirectional	No/Yes	Bidirectional	Step-up/Step-down	ESS, Regenerative braking
Flyback	Yes	Unidirectional	Step-up/Step-down	Offline chargers, Auxiliary supplies
Forward	Yes	Unidirectional	Step-down	Medium power isolated converters
Full-Bridge	Yes	Unidirectional	Step-up/Step-down	EV fast chargers, Grid interfaces

Recent developments also include hybrid isolated architectures such as active-clamp resonant and dual-mode LLC PWM converters that blend resonant and hard switched features to extend efficiency and power density. These have been included to ensure completeness of classification.

3. EFFICIENCY ENHANCEMENT TECHNIQUES

In high-power industrial applications, EVs, and RE systems, DC-DC converter efficiency is a crucial performance indicator. Operating costs, thermal performance, and system dependability are all immediately impacted by any conversion loss. Therefore, a variety of efficiency-focused strategies that target switching losses, conduction losses, thermal dissipation, and control optimization are included into modern converter designs at both the circuit and system levels. The main methods and their underlying ideas are presented in this section.

3.1 Soft Switching Techniques

Because of the simultaneous overlap of voltage and current during MOSFET/IGBT transitions, conventional hard-switching results in considerable switching losses. Soft-switching reduces dynamic power dissipation by altering the switching moment so that either the voltage or the current is close to zero.

3.1.1 Zero Voltage Switching

To reduce capacitive turn-on losses, the gadget activates

when the voltage across it is zero. This method is frequently used in resonant and quasi-resonant converters to accomplish gentle transitions by using parasitic capacitances. ZVS greatly lowers EMI and switching loss, although it often necessitates more circuit components or larger circulating currents.

3.1.2 Zero Current Switching

In order to minimize turn-off losses and decrease current spikes, the device shuts off when the current is zero. ZCS, which is frequently achieved by resonant tank circuits, is very efficient in converters managing inductive loads. ZCS may result in larger conduction losses because of the increased RMS current, even if it increases efficiency and device dependability.

3.1.3 Advantages

- Higher switching frequency is made possible by lower switching loss.
- Decreased EMI and device dv/dt stress.
- Enhanced thermal efficiency.

These techniques are widely implemented in LLC, series and parallel resonant converters and phase-shift full-bridge converters with ZVS capability.

3.2 Synchronous Rectification

The forward voltage loss associated with conventional diode-based rectification is usually between 0.5 and 1 V for Schottky diodes. This drop causes a significant amount of conduction loss in low-voltage, high-current applications. Actively regulated MOS-

FETs, which have a significantly lower on-resistance than diodes, are used in synchronous rectification (RDS(on)).

3.2.1 Advantages

- Up to 80% less conduction loss in low-voltage converters.
- Increased overall effectiveness, particularly while carrying a large load.
- Digital control compatibility for optimal timing.

This method is widely applicable in DC-DC converters for CPUs, GPUs, EV auxiliary systems and telecom power supplies.

Table 3 Comparison of Diode vs. Synchronous Rectification

Parameter	Schottky Diode	MOSFET (Synchronous)
Forward Voltage Drop	0.4–0.7 V	$\sim I \times RDS_{(ON)}$
Conduction Loss	High	Low
Gate Drive Required	No	Yes
Efficiency Gain	-	3–6% (typical)

3.3 Digital Control

Although they don't have adaptive capabilities, traditional analog controllers operate steadily. Communication with other system controllers, adaptive compensation, and real-time parameter adjustment are made possible by digital control, which is achieved using MCUs or DSPs.

3.3.1 Advantages

- Adaptive dead-time management for maximum effectiveness.
- Operating in several modes (e.g., burst mode under light load).
- Enhanced fault management and protection.
- Wireless monitoring integration (IoT-enabled power systems).

This digital control strategy is implemented in TI TMS320 series MCUs in EV converters and microchip dsPIC series in solar maximum power point tracking (MPPT) converters.

A DC-DC converter's digital control loop design exemplifies the contemporary method of controlling power conversion through the use of fast digital signal processing. This setup converts the analog feedback signal into a digital format by sensing the converter's output voltage and feeding it into an analog-to-digital converter. A digital controller, which is frequently built on a microcontroller, DSP, or FPGA, processes this data and runs control algorithms such as adaptive control, model predictive control, and PID. After determining the required duty cycle modifications, the controller generates a digital control word that may either be directly driven by the PWM generator or transformed into an analog PWM signal via a digital-to-analog converter.

Precise control, programmability, fault detection, and dynamic performance improvement are made possible by this closed-loop design. Advanced features including multi-loop regulation, real-time monitoring, adaptive parameter tuning, and interface with supervisory systems are made possible by digital control as opposed to analog control. Because performance and dependability are crucial in RE and EV applications, it has consequently become a crucial component of high-efficiency DC-DC converters.

3.4 Wide Bandgap Devices (GaN, SiC)

Devices made of GaN and SiC have greater material qualities than traditional silicon, including higher breakdown voltage, increased electron mobility, and improved thermal conductivity.

3.4.1 Advantages

Greater switching frequencies (for GaN, up to several MHz). Lower switching and conduction losses.

Smaller passive parts as a result of operating at a higher frequency.

Increased resistance to junction temperature (SiC devices up to 200–250 °C).

Table 4 Comparison of WBG and Silicon Devices

Property	Silicon MOSFET	GaN HEMT	SiC MOS-FET
Bandgap (eV)	1.1	3.4	3.3
Breakdown Field (MV/cm)	0.3	3.3	3.0
Electron Mobility (cm ² /Vs)	~1500	2000	900
Max Junction Temp (°C)	150	200	250
Typical Switching Freq.	<500 kHz	>1 MHz	~500 kHz

3.5 Thermal Management

Heat is produced by residual losses even with efficiency-boosting methods, and this heat needs to be released to keep junction temperatures safe and avoid thermal runaway.

3.5.1 Techniques

- Heatsinks, PCB thermal vias, and heat spreaders are examples of passive cooling.
- Liquid cooling loops and forced-air blowers are examples of active cooling.
- To lower thermal resistance, use thermal interface materials (TIMs).

3.5.2 Strategies for Optimization

- Arranging components to reduce thermal hotspots.
- PCB has many layers and copper planes specifically designed to disperse heat.
- Thermal sensor integration for active control.

Although GaN and SiC devices offer remarkable improvements in switching speed, thermal endurance, and efficiency, their adoption in mass-market EV applications must consider the trade-off between cost and performance. Recent analyses indicate that wide-bandgap devices may increase device-level cost by approximately 30–50% compared with silicon counterparts; however, this is offset by system-level benefits such as 2–4% higher conversion efficiency, smaller magnetic and passive components, and simplified cooling systems. An analysis is presented in [44] quantifies the performance gains, cost, and reliability of SiC MOSFETs over Si IGBTs for electrified vehicle motor drives through drive-cycle simulation. These factors collectively yield a net system cost reduction of up to 10–15% when evaluated over the full production scale. [45] reviews the use of SiC and GaN semiconductors to achieve superior efficiency, power density, and reliability in power converters for applications like EVs and renewable energy, including an experimental comparison against Silicon-based con-

verters. Furthermore, advances in large-wafer GaN-on-Si fabrication and mature SiC supply chains are progressively narrowing the cost gap, making WBG-based powertrains increasingly viable for next-generation high-efficiency EV platforms.

4. APPLICATIONS IN RENEWABLE ENERGY AND ELECTRIC VEHICLE SYSTEMS

DC-DC converters are essential to the shift to electric mobility and RE. Subsystems for EVs, energy storage, and RE sources can all be seamlessly integrated thanks to their effective voltage regulation, stepping up, and stepping down capabilities. The primary application domains EV powertrains and RE systems are examined in this part, with an emphasis on converter topologies, operating specifications, and system-level integration tactics.

4.1 Renewable Energy Systems

Due to changing climatic circumstances, RE sources like wind turbines and PV panels naturally have variable voltage and power characteristics. In order to provide optimal power extraction and stability, DC-DC converters serve as the essential interface between the source and downstream systems (storage batteries, inverters, or loads).

4.1.1 Solar Photovoltaic Systems

Boost converters are frequently used in PV systems to raise the panel output voltage to levels that correspond to the inverter or storage voltage. To optimize energy harvesting under varying temperature and irradiance circumstances, these converters are frequently combined with MPPT algorithms, such as Perturb and Observe (P&O), Incremental Conductance, or sophisticated neural-network-based MPPT. SEPIC are also appropriate for partial shading situations because of their adaptability in managing input voltages above or below the output.

In modern DC-DC converter design for renewable and EV applications, several technical factors play a decisive role in ensuring performance and reliability. High efficiency under low irradiance conditions is typically achieved through soft-switching techniques, which minimize switching losses and thermal stress on components. Control precision is another critical aspect, where digital controllers enable adaptive MPPT algorithms to dynamically adjust to fluctuating environmental and load conditions. Additionally, compliance with EMI standards becomes essential as high-frequency switching can generate significant noise, thus necessitating the integration of EMI filters to meet grid interconnection requirements and ensure safe operation.

4.1.2 Wind Energy Systems

By electrically disconnecting the turbine generator from the load or grid, isolated forward converters

and cuk converters offer galvanic isolation, which guarantees safety in small to medium wind energy systems. When combined with super capacitors or battery banks, intermediate DC-DC stages provide power smoothing, which is frequently necessary in wind systems to offset gust-induced variations.

Bidirectional operation is a key requirement in hybrid RE systems, particularly for applications such as peak shaving, where excess energy can be stored and later discharged to stabilize demand. Another critical consideration is wide input voltage handling, as sources like wind turbines experience significant variations in output with changing wind speeds, requiring converters to maintain stable performance across a broad operating range. Furthermore, compliance with isolation and safety standards, such as IEC 62109 for power conversion equipment in RE systems, is essential to ensure user safety, reliability, and adherence to international regulatory frameworks.

4.2 Electric Vehicle Systems

DC-DC converters are crucial to the propulsion and auxiliary operations of EVs. To increase driving range and adhere to temperature limitations, these converters must fulfill strict size, weight, and efficiency standards.

4.2.1 On-Board Chargers (OBC's)

To enable charging (G2V) and discharging (V2G) processes, OBCs use bidirectional DC-DC converters. To reduce switching losses at high power levels, these bidirectional systems frequently use zero-voltage switching (ZVS) or zero-current switching (ZCS).

4.2.2 Low-Voltage Power Distribution

A variety of auxiliary systems included in EVs, including as lighting, infotainment, HVAC, and sensors, need 12V or 48V rails. Buck converters ensure a steady supply under a range of load scenarios by stepping down the high-voltage traction battery output to these lower values.

4.2.3 Battery Management Systems (BMS)

Buck-boost converters are used by BMS modules to offer segregated charging/discharging routes in modular battery packs and to control cell voltage during balancing operations.

High efficiency across the entire load range is a fundamental requirement for modern converters, as maintaining partial-load efficiency is especially critical during idle or low-power operation. Equally important is robust thermal management, particularly in high-power EV converters, where liquid-cooled housings are often employed to dissipate heat effectively and ensure long-term reliability. Additionally, electromagnetic compatibility (EMC) compliance is mandatory, requiring advanced EMI shielding and high-quality filtering to meet stringent automotive standards and prevent interference with other onboard systems.

Table 5 DC-DC Converter Roles in Renewable and EV Applications

Application Domain	Converter Type	Function
Solar PV Systems	Boost, SEPIC	MPPT implementation and voltage regulation
Wind Energy	Isolated Forward, Cuk	Galvanic isolation and power smoothing

EV Powertrains	Buck, Bidirectional	Voltage control for motors and regenerative braking
Battery Charging	Bidirectional, ZVS Boost	Fast, efficient charging/discharging
Low-Voltage EV Loads	Buck	Step-down from traction battery to auxiliary systems
Hybrid Renewable-Storage Systems	Bidirectional Buck-Boost	Energy flow management between storage and source

5. COMPARATIVE ANALYSIS OF RECENT LITERATURE

Recent studies conducted between 2020 and 2025 show a significant trend toward high-efficiency DC-DC converter designs that incorporate WBG semiconductors like SiC and GaN, as well as sophisticated control algorithms, thermal management techniques, and magnetic material optimization. This section synthesizes data from previous papers to present a comparative overview of important converter topologies, device technologies, performance measures, and application scenarios.

According to the comparative analysis, the achievable efficiency, power density, and reliability are determined by the combination of topology selection, switching device type, and control approach. For instance, resonant converters like LLC are favored in EV chargers because they can achieve ZVS at high frequencies,

thereby lowering switching losses, while interleaved architectures have gained popularity in high-power PV systems because of their intrinsic current-sharing capability and ripple minimization.

A key component of these advancements are WBG devices. GaN devices can operate at multi-megahertz frequencies with little loss because of their exceptionally low gate charge and strong electron mobility. Conversely, SiC devices perform exceptionally well in high-voltage, high-temperature settings, including utility-scale wind and solar energy systems. As costs come down, WBG devices are gradually replacing traditional silicon devices, which are still competitive in applications requiring moderate performance or those that are cost-sensitive.

Representative high-efficiency designs from current research are compiled in Table 2, which emphasizes the interaction of topology, semiconductor selection, and intended use.

Table 6 Summary of Recent High-Efficiency Converter Designs

Topology	Device Type	Efficiency (%)	Application	Key Feature
Interleaved Boost	SiC	97.2	Solar PV	Digital MPPT control
Bidirectional Buck-Boost	GaN	96.5	EV Charging	High-frequency operation
SEPIC	Si	94.8	Wind Turbine	Ripple reduction design
Full-Bridge LLC	GaN	98.1	On-board charger	ZVS and compact design

6. CONCLUSION

Recent developments in high-efficiency DC-DC converters for EV and RE systems have been thoroughly reviewed in this article. The study highlights the revolutionary importance of developing semiconductor technologies like SiC and GaN by examining converter classifications, efficiency-enhancement methodologies, and comparative performance trends from recent literature. These gadgets are raising the bar for performance in contemporary power converters, especially when combined with sophisticated digital control methods and bidirectional power flow.

A move toward highly adaptable, intelligent, and application-specific converter designs is indicated by the increasing focus on compactness, thermal optimization, and intelligent integration, especially with artificial intelligence (AI) and Internet of Things (IoT) frameworks. High device prices, heat restrictions in high-density packing, and a lack of consistent platform standards are still issues, though.

7. CHALLENGES AND FUTURE RESEARCH DIRECTIONS

In order to guarantee flexibility across a range of applications, future research should give priority to hybrid converter to-

pologies that integrate the advantages of numerous architectures, sophisticated thermal management materials, AI-optimized control algorithms, and modular, scalable designs. Meeting the growing needs of next-generation RE and transportation systems in terms of performance, dependability, and cost-effectiveness will require addressing these issues.

High-efficiency DC-DC converter technology has advanced significantly, but a number of practical and technological obstacles still prevent their widespread use in EVs and RE systems. Costly materials, temperature restrictions, complicated integration, and a lack of platform standardization are the causes of these difficulties.

7.1 Current Challenges

Devices made of SiC and GaN have made major advancements in thermal performance, efficiency, and switching speed possible. Their production procedures are still expensive, though, which limits their suitability for mass-market uses. For cost-sensitive EV markets and extensive RE deployments, this cost barrier is very important. Thermal management is harder when converter designs get smaller to fit weight and space requirements, particularly in EVs and portable RE systems. Localized hotspots, shorter component lifespans, and possible converter performance derating are all consequences of high power densities.

Adaptive operating capabilities are promising when artificial

intelligence (AI), machine learning, and Internet of Things (IoT)-based control are combined. But this also brings with it problems like slow communication, cybersecurity flaws, and the need for fast digital processors that can be controlled in real time.

Interoperability is made more difficult by the lack of internationally recognized standards for DC–DC converter design, communication protocols, and safety certifications. This restricts the scalability of converters across various systems and raises development costs for manufacturers.

7.2 Future Research Directions

In order to attain high efficiency under a range of load circumstances while preserving low component stress, future designs are anticipated to integrate the benefits of several topologies, such as resonant and non-resonant stages.

Artificial intelligence may be used for energy optimization, defect prediction, and converter parameter self-tuning. Under shifting load and environmental circumstances, this kind of adaptive management may improve performance in real time, save downtime, and increase component lifespan.

Heat dissipation in high-power-density converters may be greatly enhanced by research into phase-change materials, liquid cooling systems, and novel TIMs. The incorporation of nanomaterials, including heat spreaders based on graphene, has the potential to transform compact thermal design. Redundancy, parallel operation, and easier maintenance are made possible by modular DC–DC converters. This strategy is especially pertinent to EV fleets and big renewable installations, where scalability and flexibility are essential.

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