

Isolated Bidirectional Flyback Converter in EV Charging and V2G Systems: A State-of-the-Art-Review

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Abstract

The growing adoption of electric vehicles (EVs) and the potential of Vehicle-to-Grid (V2G) technology underscore the importance of efficient and reliable isolated bidirectional DC-DC converters in EV charging systems. The market for EVs is expanding at an exponential rate due to the worldwide trend towards sustainable transportation, with electric mobility emerging as a crucial way to lower carbon emissions and rely less on fossil fuels. This review examines the current state and advancements of isolated bidirectional converters, specifically highlighting flyback converter topology in the context of EV charging and V2G applications. Beginning with the operating principles and advantages of isolation in bidirectional power transfer, the paper analyzes recent trends, including innovations in efficiency, compact design, and sophisticated control techniques. Key implementation challenges such as thermal management, regulatory compliance, and cost considerations are addressed, with an emphasis on their impact on scalability. The review also explores promising future directions, such as the integration of AI-driven control strategies, compatibility with smart grids, and the use of wide-bandgap materials like GaN and SiC to enhance converter performance and support high-speed charging. This article aims to provide a comprehensive overview of isolated bidirectional converters' role in advancing EV charging infrastructure and strengthening the integration of renewable energy sources within the grid.

Keywords: Electric vehicles, BESS, grid frequency regulation, autonomous control, power grid stability

INTRODUCTION

The global shift towards sustainable transportation is driving exponential growth in the electric vehicle (EV) market, with electric mobility emerging as a key solution to reduce carbon emissions and dependence on fossil fuels [1]. As EV adoption accelerates, so does the demand for an efficient, fast-charging infrastructure, which is critical for supporting widespread EV usage. This need has spurred advances in bidirectional DC-DC converter technology, particularly within EV charging systems.

Bidirectional converters not only enable efficient power transfer between the grid and EVs but also facilitate the emerging vehicle-to-grid (V2G) paradigm, which promises to integrate EVs as mobile energy storage units capable of stabilizing the grid [2].

Electrical isolation is a critical aspect of bidirectional converters in EV infrastructure. Isolation provides a physical barrier that separates high-voltage and low-voltage sections, significantly enhancing safety and reliability during high-power bidirectional energy transfers [3]. This protection is essential, given the high voltages involved in EV batteries and charging systems, which can otherwise

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present substantial safety risks to users and sensitive components [4]. Additionally, isolation plays a role in mitigating electrical noise and improving the overall system performance, particularly under varying load conditions [5].

This review examines the current state of isolated bidirectional DC-DC converters and explores advances in design and control techniques. Focusing specifically on the flyback converter topology, a promising architecture for EV charging and V2G applications, we aim to assess its advantages in terms of compactness and ease of integration [6]. Innovations in converter design have made significant strides in enhancing efficiency, reducing thermal stress, and enabling compact and scalable designs suitable for high-power applications [7]. This review also highlights the challenges in implementation, including thermal management, compliance with regulatory standards, and cost-effectiveness, all of which affect scalability [8]. An overview of the considered system is shown in Figure 1.

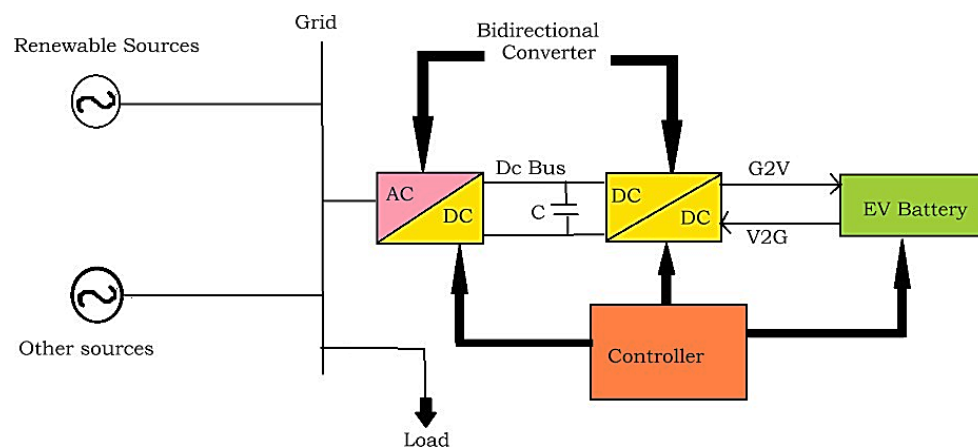


Figure 1. Overview of the considered system.

Finally, we discuss future trends that could further enhance converter performance, such as AI-driven control mechanisms, integration with smart grid infrastructures, and adoption of wide-bandgap materials such as gallium nitride (GaN) and silicon carbide (SiC). These materials enable higher switching frequencies, increased efficiency, and potential for rapid, high-power charging [9]. By providing a comprehensive overview of isolated bidirectional converters in EV systems, this review aims to highlight their critical role in supporting efficient EV infrastructure and advancing sustainable energy integration with the grid [10–14].

BACKGROUND ON EV CHARGING AND V2G TECHNOLOGY

EV Charging Infrastructure

The rapid growth of EVs has pushed the development of diverse EV charging infrastructures to meet varying energy demands and charging speeds. Broadly, EV charging methods are classified based on the type of current used, and whether the charging equipment is onboard or offboard. Alternating current (AC) charging is commonly available through residential and public charging stations and typically requires an onboard charger within the EV to convert AC power to the DC power necessary to charge the battery. AC charging is generally slower and more suitable for long-duration charging sessions, such as overnight residential charging, owing to the lower power output levels ranging from 1.4 to 22 kW.

In contrast, direct current (DC) fast-charging bypasses the vehicle's onboard charger and directly provides high-voltage DC power to the battery, thereby significantly reducing the charging time. DC fast chargers are found in commercial or dedicated charging stations and offer higher power levels, often between 50 kW and 350 kW, making them ideal for quick recharging. The DC fast-charging infrastructure, such as that governed by standards like CCS, the combined charging system (CCS), and CHAdeMO, is instrumental in providing rapid charging options, especially on highways or in urban areas with high EV traffic density.

Additionally, EV chargers are either onboard, meaning integrated within the vehicle, or offboard, which are standalone external units. Onboard chargers are limited by space and weight considerations, often making them suitable only for lower power levels such as AC Level 1 or Level 2 charging. Offboard chargers, however, are larger and more powerful and are commonly used in DC fast-charging stations because of their capability to support high-power charging directly to the vehicle's battery.

Vehicle-to-Grid (V2G) Technology

Vehicle-to-grid (V2G) technology leverages the stored energy in EV batteries as a grid resource, enabling bidirectional power flow between the vehicles and the electrical grid. V2G allows EVs not only to draw power from the grid for charging but also to return power during periods of high demand or grid instability. This bidirectional flow plays a vital role in stabilizing the grid, offering demand response capabilities, and supporting renewable energy integration.

In essence, V2G technology enables EVs to act as mobile energy storage units, providing ancillary services such as frequency regulation, peak shaving, and load balancing. For instance, during peak demand periods, EVs connected to a V2G-enabled system can discharge stored energy to alleviate grid stress and return to charging during off-peak hours, when demand and electricity costs are lower. This capability can support grid operators by enhancing grid resilience and reducing the need for expensive energy reserves.

Moreover, because renewable energy sources such as solar and wind generate variable outputs, V2G-capable EVs can store excess energy and release it when generating dips, thus fostering a more sustainable and flexible energy system.

Role of Isolated Bidirectional Converters

In EV charging and V2G applications, isolated bidirectional DC-DC converters are fundamental for ensuring safe and efficient power transfer. These converters manage the bidirectional energy flow between EV batteries and the grid or other energy storage systems, with isolation playing a crucial role in terms of safety and reliability. Isolation provides galvanic separation between the high-voltage side connected to the grid and the low-voltage side linked to the EV battery, significantly reducing the risk of electric shock or damage due to fault currents. This is particularly important in high-power applications, where unintentional leakage currents can compromise user safety and system integrity.

In addition, isolated bidirectional converters are optimized to handle the bidirectional nature of V2G applications, facilitating seamless transitions between the charging and discharging modes. By supporting bidirectional energy flow, these converters enable EVs to participate dynamically in grid services, thereby increasing their utility beyond mere transportation. Another benefit of isolation in these converters is the mitigation of electrical noise, enhancement of the reliability of the converter under varying load conditions, and improvement of the overall system efficiency [15–18].

Emerging advancements such as wide-bandgap materials (e.g., GaN and SiC) have further enhanced the performance of these converters by enabling higher switching frequencies and improved efficiency. These materials are particularly relevant in high-speed charging applications, where reduced energy losses and better thermal management are critical. Consequently, isolated bidirectional converters are positioned as a cornerstone technology for future EV charging infrastructure that aims to support both conventional and V2G functionalities, strengthen grid resilience, and support a more sustainable energy ecosystem [19, 20].

FUNDAMENTALS OF ISOLATED BIDIRECTIONAL CONVERTERS

Isolated bidirectional DC-DC converters are essential in EV systems, particularly for integrating the V2G functionality. By isolating the high- and low-voltage sides, these converters enhance safety and support bidirectional power flow, enabling EVs to both charge from and discharge to the grid.

Types of Isolated Bidirectional Converters

Several topologies are widely used for isolated bidirectional converters in EV applications, each with unique characteristics tailored to the specific power and efficiency requirements. Key types include:

1. *Flyback converters*: The flyback converter is a straightforward, cost-effective topology that is often used for low-power applications. It is suitable for bidirectional operation using a single switch on both sides of the transformer, and it is compact, making it ideal for onboard chargers. However, its efficiency decreases at higher power levels because of significant losses in the transformer and other components.
2. *Dual active bridge (DAB) converters*: DAB converters are highly efficient and capable of handling high-power, making them suitable for fast-charging applications in EVs. DAB converters use two active H-bridge circuits on each side of the transformer, enabling efficient bidirectional power transfer with controlled soft switching, which minimizes switching losses. This topology supports high-frequency operations and is increasingly used in high-power EV charging and V2G systems.
3. *Resonant converters*: Resonant converters, such as the LLC resonant converter, operate at variable frequencies and achieve high-efficiency through zero-voltage or zero-current switching techniques. They are well-suited for applications requiring high-efficiency and low electromagnetic interference (EMI). Although resonant converters offer excellent performance at high-power, their design is complex, which can increase cost and make control more challenging compared to other topologies.

Working Principle of Flyback Converters

The isolated bidirectional flyback converter operates based on transformer isolation, in which energy is transferred between the primary and secondary windings during different phases of operation. In a flyback converter, a transformer with an air gap stores energy in its core. Basic operation involves two main modes: charging (from grid to battery) and discharging (from battery to grid).

1. *Charging mode (powering the battery)*: During the initial phase of charging, a switch on the primary side of the transformer is activated, allowing the current to flow through the primary winding, thereby storing energy in the core of the transformer, as shown in Figure 2.

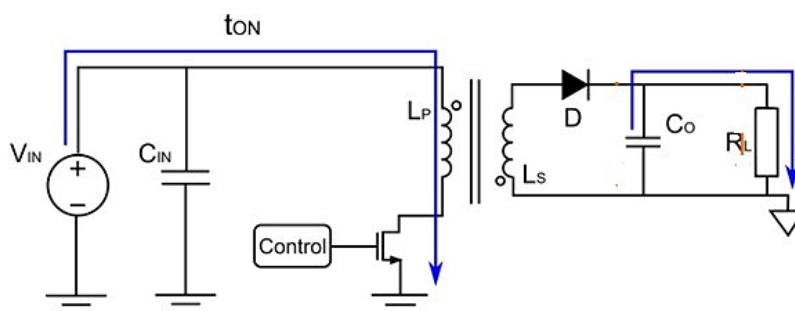


Figure 2. Flyback converter during the charging period.

When the switch is turned off, the magnetic field in the core collapses, releasing energy through the secondary winding, which subsequently charges the battery. This process is repeated rapidly to maintain continuous power flow, allowing efficient battery charging at the required voltage level.

2. *Discharging mode (feeding power to the grid)*: In the discharge phase, the energy stored in the EV battery flows from the secondary side to the primary side of the converter, reversing the charging process, as shown in Figure 3. By activating the switch on the secondary side, the stored energy in the battery is transferred back through the transformer to supply power to the grid, enabling the V2G functionality. A comparison of various features is presented in Table 1.

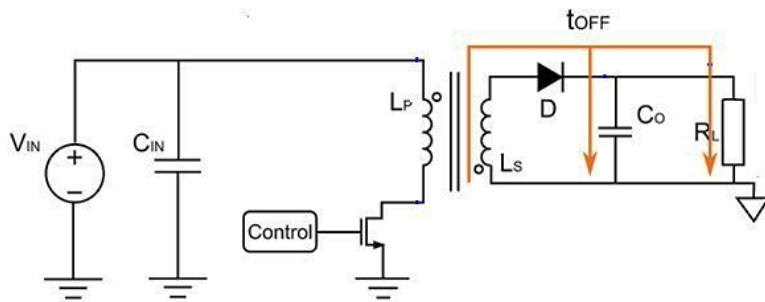


Figure 3. Flyback converter during the discharging period.

Table 1. Comparison table with regards to various features.

Features	Flyback converter	Dual active bridge (DAB)	Resonant converter
Efficiency	Moderate efficiency decreases at higher power levels due to transformer losses and hard switching.	High efficiency, especially at high-power levels, due to soft switching and lower losses.	High-efficiency through zero-voltage or zero-current switching; low EMI.
Power rating	Suitable for low-power applications (10s to 100s of watts); limited scalability due to thermal constraints.	Ideal for medium to high-power (kW range); widely used in fast-charging systems.	Medium to high-power (kW range); suitable for applications needing low EMI.
Cost	Low cost; fewer components and simpler design.	Higher cost due to complex circuitry and components (H-bridges).	Moderate to high cost, depending on the complexity and control requirements.

The flyback converter's simplicity and reduced component count make it a practical choice for lower power applications; however, it faces limitations in efficiency and thermal management as the power levels increase. This topology also includes key components, such as rectifiers, transformers with gapped cores, and control circuits that regulate energy flow based on the current mode.

COMPARATIVE ANALYSIS

Each isolated bidirectional converter topology has its advantages and limitations, which influences its suitability for specific applications within EV charging infrastructure.

Efficiency Improvements

Efficiency is critical in isolated bidirectional converter design for EV charging applications. Recent advances focus on minimizing power losses and improving conversion efficiency. One prominent approach involves *soft-switching techniques* such as zero-voltage switching (ZVS) and zero-current switching (ZCS). Soft switching reduces switching losses and EMI by ensuring that power transistors switch on or off at zero-voltage or current, significantly lowering heat dissipation. This technique, often applied in dual active bridge (DAB) converters, enhances performance at high-power levels, making it a popular choice for EV fast-charging.

Another area of development is *transformer design*. Researchers are exploring core materials that reduce hysteresis and eddy current losses, such as ferrite cores for low-power applications, and amorphous or nanocrystalline cores for high-power systems. Optimizing winding techniques, such as interleaved and layered winding configurations, also reduces leakage inductance and improves power transfer efficiency.

The use of *advanced semiconductor materials*, particularly wide-bandgap materials, such as Gallium Nitride (GaN) and SiC, is also driving efficiency improvements. GaN and SiC devices can operate at higher voltages and temperatures than traditional silicon-based transistors, making them suitable for

high-frequency operation with reduced switching losses. These materials enable more compact designs and higher thermal tolerances, making them ideal for converters in fast-charging stations.

Table 2 provides a comparison of the primary types of isolated bidirectional converters utilized in EV charging and V2G applications, including Flyback, Dual Active Bridge (DAB), and resonant converters.

Table 2. Comparative analysis.

Complexity	Simple; easy to control and integrated with low-power applications	Complex; requires precise control for soft-switching operation	Moderate to high complexity; frequency control necessary for optimal performance
Switching Frequency	Low to moderate; limited by transformer design	High; enables a compact design and better power density	High; wide frequency range possible, enhancing efficiency
Applications	Onboard charging and lower power V2G applications	Offboard chargers, high-power EV fast-charging, and V2G	Medium to high-power charging; suitable for applications prioritizing low EMI
Thermal Management	Limited thermal efficiency; less suited for high-power use	Effective thermal management due to soft switching	Good thermal performance with resonant components
Isolation	Transformer-based, ensuring safety but adding bulk at higher power	Transformer-based isolation; designed for high-power without compromising efficiency	Transformer-based, supports efficient energy transfer and low EMI

Power Density Enhancements

Increasing the power density of isolated bidirectional converters is essential to satisfy space constraints in both onboard and offboard EV charging systems. A higher power density allows converters to deliver more power without increasing their physical footprint. A primary strategy for enhancing the power density is *high-frequency operation*. Operating at higher frequencies enables the use of smaller magnetic components, such as transformers and inductors, which reduces the overall size of the converter. Wide-bandgap devices, such as GaN and SiC, also support high-frequency operation without sacrificing efficiency, allowing for a more compact and efficient design.

Advanced Cooling Methods

Advanced cooling methods are another focus area, as managing heat dissipation becomes challenging at higher power densities. Innovative cooling solutions, such as liquid cooling, direct-contact heat sinks, and thermally conductive materials, help dissipate heat more effectively, ensuring that the components maintain optimal operating temperatures. Direct-contact cooling and liquid-cooling techniques are increasingly used in fast-charging applications to handle the high-power output required without increasing the thermal stress on the components.

Furthermore, *3D packaging techniques* are being explored to achieve more compact designs. By stacking components vertically, 3D packaging minimizes space requirements, enhances thermal management, and reduces parasitic inductance, which is critical in high-frequency applications.

Control Strategies

Control strategies play a vital role in optimizing bidirectional energy flow in isolated converters. Recent advances have focused on improving the stability, responsiveness, and flexibility of these systems. *Digital pulse-width modulation (PWM)* is one of the most widely used control methods, allowing precise control over switching cycles, thus improving efficiency and reducing power losses. Digital PWM is particularly effective for managing rapid transitions in the power flow between the charging and discharging modes in V2G applications.

More sophisticated control approaches such as *predictive control* and *adaptive control* are gaining popularity. Predictive control methods leverage model-based algorithms to forecast the system behavior

and adjust switching patterns, accordingly, resulting in faster response times and improved accuracy. This is especially useful in high-power applications, where the load conditions frequently fluctuate. On the other hand, adaptive control automatically adjusts control parameters based on real-time operating conditions, allowing converters to maintain optimal performance under varying load and voltage conditions. This adaptability is crucial for handling the dynamic nature of V2G applications, in which bidirectional power flow and rapid switching are essential.

In addition, *AI-driven control algorithms* have emerged as a promising trend for bidirectional converters. Machine learning techniques can optimize the control settings in real-time, making converters more responsive to grid demands, environmental conditions, and load variations. AI-driven control is expected to play a key role in future smart grid applications, where EVs will need to interact seamlessly with renewable energy sources and support demand response services.

Integration with Renewable Energy Sources

Integrating isolated bidirectional converters with renewable energy sources, such as solar and wind, enhances the sustainability of EV charging. By connecting EV chargers to renewables, isolated bidirectional converters help balance fluctuations in the renewable energy output. For instance, during periods of high solar generation, EVs can be charged directly, or excess energy can be stored in EV batteries for later use or grid support via V2G systems. This approach helps stabilize the grid and improve the reliability of renewable energy systems.

Advanced converters designed for renewable integration typically incorporate *Maximum Power Point Tracking (MPPT)* algorithms to optimize the power extraction from renewable sources. MPPT algorithms adjust the converter's operating point to match the optimal power output of the solar or wind source and maximize efficiency. Moreover, the use of high-efficiency bidirectional converters allows for flexible energy management strategies such as peak shaving and load balancing, which are essential for integrating EVs into renewable energy systems.

The development of smart grid-compatible converters is also accelerating, with converters being equipped to communicate with grid operators. This enables dynamic interactions between EVs and the grid, supporting demand response, frequency regulation, and energy storage applications. As the penetration of renewable energy in the grid increases, the role of isolated bidirectional converters in efficiently managing power flow and ensuring stability becomes even more critical.

In summary, the ongoing advancements in efficiency, power density, control strategies, and renewable integration have positioned isolated bidirectional converters as key enablers for sustainable and flexible EV charging systems. These innovations will support the broader adoption of V2G technology, grid stability, and effective renewable energy utilization.

Challenges in Implementing Isolated Bidirectional Converters for EV Charging and V2G

Isolated bidirectional converters play a vital role in EV charging and V2G applications; however, their implementation presents specific challenges in areas such as thermal management, safety compliance, energy flow control, and cost efficiency. Table 3 provides an in-depth look at these challenges and some potential solutions.

Thermal Management

Thermal management is a significant concern in bidirectional converters because of the high heat generated during charging and discharging cycles. In high-power applications, heat accumulation can compromise the performance of key components, such as semiconductors and transformers, thereby impacting the overall system reliability. *Advanced cooling techniques* are essential to address this issue. For example, liquid cooling is highly effective at dissipating heat in compact designs, and thermally conductive materials, such as SiC, can endure high temperatures and improve cooling efficiency.

Table 3. Challenges and potential solutions.

Challenge	Description	Potential solutions
Thermal management	High-power operation in bidirectional converters generates significant heat, which, if not managed effectively, can reduce converter efficiency and lead to component failure.	Advanced cooling techniques, such as liquid-cooling and direct-contact cooling, and the use of thermally conductive materials to dissipate heat more effectively
Isolation and Safety standards	Isolation is essential to prevent electrical hazards, especially at high voltages, and to comply with safety regulations. Standards such as Underwriters Laboratories (UL), International Electrotechnical Commission (IEC), and International Society of Automotive and Aerospace Engineers (SAE) require strict isolation measures in EV systems.	Compliance with safety certifications and use of high-quality insulation materials to ensure compliance with Underwriters Laboratories (UL), International Electrotechnical Commission (IEC), and International Society of Automotive and Aerospace Engineers (SAE) standards for both onboard and offboard applications
Bidirectional energy management	Managing bidirectional power flow can be challenging, as improper control may lead to grid instability, energy losses, or even damage to the EV battery and grid infrastructure.	Advanced control strategies such as predictive control, adaptive control, and AI-based algorithms dynamically adjust energy flow and prevent grid instability.
Cost and scalability	Implementing converters in large-scale charging infrastructure is expensive, especially with high-quality components for isolation and control, and high-power systems can be difficult to scale affordably.	Use of cost-effective materials, modular designs that allow for scalability, and high-efficiency components to reduce long-term operational costs

Isolation and Safety Standards

Compliance with safety and isolation standards, such as UL (Underwriters Laboratories), International Electrotechnical Commission (IEC), and Society of Automotive Engineers (SAE) regulations are essential for bidirectional converters in EV systems. These standards ensure that the converters are adequately isolated to prevent electrical hazards. *Isolation techniques* such as reinforced insulation and the use of safety-rated transformers are critical to meet these standards. Ensuring compliance involves integrating high-quality isolation components, which can raise costs but is essential for safety.

Bidirectional Energy Management

Effective bidirectional energy management is necessary to prevent issues such as grid instability and excessive wear of EV batteries. *Advanced control algorithms*, including predictive control and AI-based adaptive control, have been developed to handle real-time variations in the load and grid demand. These control methods help maintain a stable energy flow between the grid and the EV, allowing for smoother transitions between charging and discharging while optimizing energy efficiency.

Cost and Scalability

The cost of implementing high-performance bidirectional converters on a large-scale can be prohibitive, particularly for public EV charging stations. High-quality components needed for isolation, thermal management, and control increase the initial costs, while scalability remains a challenge because of the infrastructure required. *Modular converter designs* that allow scalability and *cost-effective materials* can help alleviate some of these issues. In addition, high-efficiency designs can reduce operational expenses, making widespread implementation more feasible over time.

In summary, addressing these challenges requires a multifaceted approach that incorporates advanced cooling, strict adherence to safety standards, sophisticated control strategies, and cost-effective and scalable solutions. These improvements are essential to make isolated bidirectional converters viable and reliable for large-scale EV charging and V2G applications.

CONCLUSION AND FUTURE SCOPE

This review explores the critical role of isolated bidirectional converters in EV charging systems and Vehicle-to-Grid (V2G) applications. Key technological advancements have been identified, including

improvements in efficiency through soft-switching techniques, the adoption of wide-bandgap materials, and innovative transformer designs that enhance power density. Moreover, the integration of advanced control strategies, such as digital PWM and AI-driven algorithms, has shown promise in managing bidirectional energy flow and optimizing operational performance.

Despite these advancements, several challenges persist in the implementation of such converters. Effective thermal management remains a critical concern, particularly in high-power applications, where heat dissipation can significantly affect performance and reliability. Compliance with stringent safety standards, such as those set by the UL, IEC, and SAE, poses additional hurdles that necessitate robust isolation techniques.

Furthermore, the complexity of bidirectional energy management systems and the need for cost-effective, scalable solutions for the widespread adoption of charging infrastructure present ongoing challenges that require continued research and innovation.

Several areas of research warrant further exploration to enhance the capabilities of isolated bidirectional converters in EV charging and V2G contexts.

1. *Emerging control algorithms*: Investigating next-generation control strategies that leverage artificial intelligence and machine learning can provide significant benefits. Adaptive algorithms capable of real-time optimization based on varying grid conditions and EV demands can improve the stability and efficiency of energy transfer.
2. *Novel transformer designs*: Research on advanced transformer designs, including the use of amorphous or nanocrystalline materials, may further reduce losses and improve the thermal performance of converters. Innovations in transformer architectures, such as hybrid or planar transformers, could also contribute to achieving higher power densities.
3. *Thermal management techniques*: Developing new thermal management solutions that incorporate phase-change materials or advanced liquid-cooling methods could significantly enhance the reliability of high-power converters. In addition, integrating thermal management into the design phase may yield compact and efficient systems.
4. *Integration with smart grids*: As the energy landscape evolves, exploring how isolated bidirectional converters can be integrated with smart grid technologies is vital. Research could focus on enhancing communication protocols among EVs, chargers, and the grid, ensuring seamless interaction for optimal energy distribution and demand response.
5. *Cost reduction strategies*: Finally, research aimed at identifying cost-effective materials and manufacturing processes will be crucial for promoting the scalability of isolated bidirectional converters in public and private charging infrastructures. Evaluating the lifecycle costs and benefits of different technologies will inform future implementation decisions.

In conclusion, while isolated bidirectional converters present significant opportunities for enhancing the EV charging infrastructure and V2G applications, addressing the identified challenges and pursuing innovative research avenues will be essential for realizing their full potential. Continued collaboration between academia, industry, and regulatory bodies will foster the development of advanced solutions that not only improve the performance of these systems but also contribute to a more sustainable energy future.

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