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Bidirectional Converters for Vehicle-to-Grid (V2G) Applications

Rohit S. Bansal, Ayesha K. Pathak, Milan T. Rao
Associate Professor, Assistant Professor
Department of Electric Machine Design
Lady Doak College – Arts & Science Faculty, Madurai
***Email**:Rohitsbansal11@gmail.com, ayeshakpathak6d@rediffmail.com, raomilan1t@yahoo.com*

ABSTRACT

Vehicle-to-Grid (V2G) technology is a transformative method that enables electric vehicles (EVs) to interact with the power grid in a bidirectional way. This paper discusses the role of bidirectional converters in enabling V2G applications, addressing key converter topologies, control strategies, and system challenges. Bidirectional converters are essential to manage power flow from EV batteries to the grid and vice versa, while maintaining power quality, stability, and safety. The review includes comparative analysis of converter types, performance factors, and future directions. Practical implementation concerns and potential improvements are also highlighted. The aim is to provide a comprehensive understanding for researchers and engineers about the present status and future prospects of bidirectional converters in V2G systems.

KEYWORDS: *Bidirectional converters, vehicle-to-grid (V2G), electric vehicles, power electronics, grid integration, energy management, converter topologies.*

INTRODUCTION

Electric vehicles are increasingly important in a sustainable energy future. V2G applications extend the role of EVs beyond transportation — they act as mobile storage units that can inject energy into the grid at times of high demand and absorb energy when there is surplus generation. For this interaction, power electronics interfaces known as bidirectional converters are vital. These converters regulate the direction of power flow between EV batteries and the utility grid, ensuring

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efficient and stable operation. This review explores the technical foundation of bidirectional converters, their application in V2G, limitations, and the research progress.

BACKGROUND AND MOTIVATION

The modern electrical grid is undergoing a major transition due to the rapid growth of renewable energy sources, electrification of transportation, and rising electricity demand. Conventional power systems were originally designed for unidirectional power flow—from centralized generation plants to consumers. However, this structure is increasingly stressed by **peak load conditions**, **variable renewable generation**, and **large-scale charging of electric vehicles (EVs)**. Expanding grid infrastructure to meet these challenges involves high capital investment, long approval timelines, and increased operational costs.

One of the most critical challenges is **peak demand management**. During peak hours, utilities often rely on expensive and carbon-intensive peaking power plants. At the same time, a large number of EVs remain parked for long durations, typically more than 90% of the day. This underutilized battery capacity represents a significant opportunity for grid support if it can be accessed in a controlled and reliable manner.

Another growing concern is the **intermittency of renewable energy sources** such as solar and wind. These sources are highly dependent on weather conditions and often do not align with load demand profiles. For example, solar generation peaks during midday, while residential electricity demand typically peaks in the evening. Without sufficient energy storage or demand-side flexibility, this mismatch can lead to renewable curtailment or grid instability. Vehicle-to-Grid (V2G) systems offer a practical solution by allowing EV batteries to absorb excess renewable energy during low demand periods and supply energy back to the grid when generation drops or demand increases.

The increasing **electrification of loads**, including electric transportation, heating, and industrial processes, further amplifies the need for flexible grid resources. Uncoordinated EV charging can overload distribution transformers, cause voltage fluctuations, and increase losses in the network.

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V2G-enabled EVs, when properly controlled, can act as **distributed energy resources (DERs)** that support voltage regulation, reactive power compensation, and frequency control, particularly at the distribution level.

The motivation for V2G is also driven by **economic and environmental factors**. From the grid operator's perspective, aggregated EV batteries can reduce the need for costly infrastructure upgrades and improve overall grid reliability. For EV owners, participation in V2G programs can generate additional revenue through ancillary services such as frequency regulation and peak shaving. Environmentally, V2G facilitates higher penetration of renewable energy and reduces reliance on fossil-fuel-based reserve generation.

At the heart of all these functionalities lies the **bidirectional power converter**. Bidirectional DC–DC converters manage energy exchange between the EV battery and the DC link, accommodating wide voltage variations while protecting battery health. Bidirectional DC–AC converters ensure compliant interaction with the utility grid by providing synchronization, power quality control, and safe islanding operation. These converters must operate efficiently in both charging and discharging modes, respond rapidly to grid commands, and comply with stringent grid codes.

In summary, the background and motivation for V2G technology stem from the growing need for **grid flexibility, renewable integration, and cost-effective energy management**. Bidirectional converters serve as the key technological enablers that transform EVs from passive loads into active grid-supporting assets, making them an essential component of future smart grids.

BIDIRECTIONAL CONVERTER TOPOLOGIES

Bidirectional power converters form the core interface between electric vehicle batteries and the electrical grid in V2G systems. Their primary function is to enable controlled and reversible power flow while ensuring high efficiency, safety, and compliance with grid standards. Based on the power conversion stage, these converters are generally classified into **bidirectional DC–DC converters** and **bidirectional DC–AC converters**. Each category plays a distinct role in the overall V2G architecture.

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1. Bidirectional DC–DC Converters

Bidirectional DC–DC converters act as the first stage of power processing in most V2G systems. They connect the EV battery, which typically operates at a relatively low and variable DC voltage, to a high-voltage DC link or intermediate bus. This stage is essential for voltage level matching, current regulation, and battery protection during both charging (grid-to-vehicle) and discharging (vehicle-to-grid) modes.

One of the simplest and widely studied topologies is the **bidirectional buck–boost converter**. In charging mode, it operates as a buck converter to step down the DC-link voltage to a suitable battery charging level. In discharging mode, it works as a boost converter, elevating the battery voltage to the DC-link level. The main advantages of this topology are its simple structure, low component count, and ease of control. Due to these features, buck–boost converters are often used in low- to medium-power EV applications and experimental V2G setups. However, when a wide battery voltage range is involved, the converter may suffer from reduced efficiency, higher current stress on switches, and increased ripple, which can affect battery life and thermal performance.

The **bidirectional Cuk converter** is another topology that has gained attention due to its inherent ability to provide continuous input and output currents. This characteristic significantly reduces current ripple at the battery terminals, which is beneficial for improving battery lifespan and reducing electromagnetic interference. In V2G applications, smooth current profiles are particularly important because frequent charge–discharge cycles are involved. Despite these advantages, the Cuk converter requires more passive components, including inductors and capacitors, which increase system size, cost, and control complexity. Additionally, the presence of energy transfer through a capacitor makes the design and stability analysis more challenging, limiting its use mainly to specialized or research-oriented systems.

For higher power levels and safety-critical applications, **bidirectional isolated DC–DC converters** are commonly employed. These converters incorporate high-frequency transformers

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to provide galvanic isolation between the EV battery and the grid-side DC link. Isolation is often mandated by safety standards to protect users and equipment from electrical faults. Popular isolated topologies include the dual active bridge (DAB), full-bridge, and half-bridge converters. Among these, the dual active bridge is especially suitable for V2G systems because it allows soft switching over a wide load range, leading to high efficiency and reduced switching losses. Isolated converters also enable higher voltage gain and better scalability, making them suitable for fast charging stations and high-capacity EV batteries. However, their drawbacks include increased circuit complexity, higher cost, and more demanding control requirements.

In summary, the selection of a bidirectional DC–DC converter topology depends on several factors such as power rating, voltage range, safety requirements, efficiency targets, and system cost. While non-isolated converters are preferred for compact and cost-sensitive applications, isolated converters dominate in high-power and grid-compliant V2G systems where safety and reliability are critical.

Table 1: Comparison of Bidirectional DC–DC Topologies

Topology	Isolation	Complexity	Efficiency	Use Case
Buck-Boost	No	Low	Medium	Small EV battery systems
Cuk	No	Medium	Medium-High	Reduction of ripple required
Isolated Converter	Yes	High	High	Safety-critical, high power systems

2. Bidirectional DC–AC Converters

Bidirectional DC–AC converters are a critical stage in V2G systems, as they enable the interaction between the EV's DC battery system and the AC utility grid. These converters are responsible not only for converting DC power into AC during vehicle-to-grid operation, but also for rectifying AC power from the grid during grid-to-vehicle charging. In addition to bidirectional power flow, they must ensure compliance with grid codes related to voltage quality, frequency regulation, harmonic distortion, and safety.

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In V2G operation, the DC–AC converter typically functions as a **grid-connected inverter**, synchronizing its output with the grid voltage and frequency. This synchronization is essential to ensure seamless power exchange without causing disturbances or instability. Control strategies such as current-controlled voltage source inverter (VSI) schemes and phase-locked loops (PLL) are commonly used to achieve accurate synchronization and dynamic response.

One of the most commonly used topologies in bidirectional DC–AC conversion is the **full-bridge inverter**. This topology consists of four controlled switches arranged in an H-bridge configuration. During charging mode, the inverter operates as an active rectifier, converting AC grid power into DC for battery charging. During discharging mode, it functions as an inverter, supplying sinusoidal AC current back to the grid. The full-bridge inverter is widely adopted due to its simple structure, mature control techniques, and relatively low cost. It is particularly suitable for low to medium power V2G applications, such as residential chargers and small commercial systems. However, at higher power levels, full-bridge inverters tend to suffer from increased switching losses and higher harmonic distortion, which may require bulky filters to meet grid standards.

To overcome these limitations, **multilevel inverter (MLI) topologies** have been increasingly explored for V2G applications. Multilevel inverters generate output voltage waveforms with multiple discrete voltage levels, which closely approximate a sinusoidal waveform. Common MLI configurations include the neutral-point-clamped (NPC), flying capacitor, and cascaded H-bridge inverters. The key advantage of multilevel inverters is their ability to significantly reduce total harmonic distortion (THD) while operating at lower switching frequencies. This results in improved efficiency, reduced electromagnetic interference, and smaller filter requirements.

In the context of V2G, multilevel inverters are especially attractive for high-power charging stations and fast-charging infrastructure, where power quality and efficiency are critical. They also distribute voltage stress across multiple semiconductor devices, allowing the use of lower-rated switches and improving system reliability. However, these benefits come at the cost of increased circuit complexity, higher component count, and more sophisticated control algorithms. Balancing

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capacitor voltages, ensuring equal power sharing, and maintaining stable operation under bidirectional power flow remain challenging tasks in multilevel inverter designs.

Overall, the choice between full-bridge and multilevel bidirectional DC–AC converters depends on application requirements such as power rating, efficiency, cost, and grid compliance. While full-bridge inverters remain popular for simpler and lower-power V2G systems, multilevel inverters are gaining attention as a scalable and high-performance solution for future large-scale V2G integration.

CONTROL STRATEGIES FOR BIDIRECTIONAL CONVERTERS

Effective control is essential for the reliable operation of bidirectional converters in vehicle-to-grid (V2G) applications. These converters must handle frequent transitions between charging and discharging modes while maintaining stable voltage, controlled current, and high power quality. Unlike conventional unidirectional chargers, V2G converters operate under varying grid conditions and battery states, which makes their control more challenging. Therefore, advanced control strategies are required to ensure fast dynamic response, stability, and compliance with grid standards.

1. Pulse Width Modulation (PWM)

Pulse Width Modulation (PWM) is the most widely used control technique in bidirectional power converters due to its simplicity, flexibility, and proven reliability. In PWM-based control, the switching devices are driven by pulses whose duty cycle is adjusted to regulate the output voltage or current. In bidirectional DC–DC converters, PWM enables smooth transition between buck and boost modes depending on the direction of power flow.

For V2G applications, PWM is commonly combined with **inner current control loops** and **outer voltage or power control loops**. The current control loop ensures accurate regulation of charging and discharging currents, which is crucial for protecting the battery and meeting grid requirements. The outer loop determines the reference values based on operating conditions such as battery state-

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of-charge (SoC), grid demand, or pricing signals. This cascaded control structure provides good stability and is relatively easy to implement using digital controllers.

In bidirectional DC–AC converters, sinusoidal PWM (SPWM) and space vector PWM (SVPWM) are frequently used. These techniques allow the inverter to produce high-quality sinusoidal currents with low harmonic distortion. However, PWM-based control can result in higher switching losses, especially at high switching frequencies. As V2G power levels increase, these losses can affect efficiency and thermal performance, motivating research into alternative or optimized modulation techniques.

2. Model Predictive Control (MPC)

Model Predictive Control (MPC) has emerged as an advanced control strategy for bidirectional converters due to its ability to handle multi-variable systems and constraints. MPC uses a mathematical model of the converter to predict its future behavior over a short time horizon. Based on these predictions, an optimization algorithm selects the best switching state that minimizes a predefined cost function.

In V2G systems, MPC is particularly attractive because it can directly consider constraints such as maximum current limits, voltage bounds, and switching losses. By evaluating multiple future switching possibilities, MPC can achieve faster dynamic response compared to conventional PWM-based controllers. This is especially useful during sudden grid disturbances or rapid transitions between charging and discharging modes.

Another advantage of MPC is its ability to reduce current ripple and switching losses without the need for additional modulation stages. However, the main drawback of MPC is its high computational burden. Implementing MPC in real-time requires powerful digital signal processors or field-programmable gate arrays (FPGAs). Additionally, the accuracy of MPC depends heavily on the precision of the system model, and parameter variations can degrade performance if not properly compensated.

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3. Voltage and Frequency Regulation Methods

In grid-connected V2G operation, maintaining proper voltage and frequency synchronization is a fundamental requirement. Bidirectional DC–AC converters must inject or absorb power in a way that supports grid stability rather than disrupting it. To achieve this, converters rely on synchronization and regulation techniques that align their output with the grid.

A commonly used approach is the **phase-locked loop (PLL)**, which continuously tracks the grid voltage phase and frequency. The PLL provides reference signals for current control, ensuring that injected currents are in phase with grid voltage for active power exchange, or appropriately shifted for reactive power support. Advanced PLL designs, such as second-order generalized integrator (SOGI-PLL), are often used in V2G systems to improve performance under distorted or unbalanced grid conditions.

In addition to PLL-based synchronization, **droop control** and **grid-supportive control strategies** are employed in some V2G applications. These methods allow the converter to adjust its power output in response to grid frequency or voltage deviations, effectively mimicking the behavior of conventional generators. Such capabilities enable EVs to participate in frequency regulation and voltage support services, particularly in weak or islanded grids.

Overall, the choice of control strategy depends on system complexity, power rating, and performance requirements. While PWM-based control remains the industry standard due to its simplicity, advanced techniques like MPC and adaptive voltage–frequency regulation are gaining attention for future large-scale and smart grid-integrated V2G systems.

V2G SYSTEM ARCHITECTURE

The architecture of a Vehicle-to-Grid (V2G) system defines how electric vehicles interact with the power grid in a safe, reliable, and coordinated manner. Unlike conventional charging systems, V2G architecture enables **bidirectional power flow**, real-time communication, and intelligent control. A typical V2G system is composed of several tightly integrated subsystems, including the

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EV battery, bidirectional power converter, control unit, communication interface, and the grid connection point.

At the core of the system is the **EV battery**, which acts as an energy storage element. Modern EV batteries operate over a wide voltage range and are sensitive to overcurrent, overvoltage, and excessive cycling. Therefore, battery management systems (BMS) are integrated to monitor parameters such as state-of-charge (SoC), state-of-health (SoH), temperature, and allowable charge–discharge limits. These parameters directly influence how much power can be exchanged with the grid at any given time.

The **bidirectional power converter** serves as the electrical interface between the EV battery and the grid. It typically consists of a DC–DC conversion stage connected to a DC–AC inverter stage. The DC–DC converter regulates battery current and adapts the battery voltage to the DC-link level, while the DC–AC converter synchronizes with the grid and manages power quality. This modular architecture allows flexible operation under different grid conditions and supports both charging and discharging modes with high efficiency.

A **control unit** governs the overall operation of the V2G system. It processes information from the battery management system, grid conditions, and user preferences to determine the appropriate operating mode. During periods of low grid demand or excess renewable generation, the control unit commands the converter to operate in charging mode, drawing power from the grid to charge the EV battery. Conversely, during peak demand or grid contingencies, the controller enables discharging, allowing stored energy in the EV battery to be injected back into the grid. The control unit also ensures smooth transitions between modes and prevents unsafe operating conditions.

The **communication interface** is a key component that differentiates V2G systems from conventional EV chargers. Communication standards such as **ISO/IEC 15118**, along with protocols like OCPP (Open Charge Point Protocol), enable secure and standardized information exchange between the EV, charging station, and grid operator. Through this interface, the grid operator can send control signals related to power setpoints, pricing, and grid support requirements. At the same time, the EV can communicate its availability, battery status, and user-

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defined constraints. This two-way communication ensures coordinated operation and user acceptance.

Finally, the **grid connection** links the V2G system to the utility network, typically at the distribution level. Protective devices such as relays, circuit breakers, and isolation mechanisms are included to ensure compliance with safety and grid codes. Filters and protection circuits are also used to limit harmonics, suppress transients, and prevent unintentional islanding.

In summary, the V2G system architecture integrates power electronics, control, communication, and grid infrastructure into a unified framework. By intelligently coordinating these components, V2G systems transform EVs from passive loads into active grid assets capable of supporting energy management, grid stability, and renewable integration.

CHALLENGES IN BIDIRECTIONAL CONVERTER IMPLEMENTATION

Although bidirectional converters present potential benefits, several challenges persist:

1. Efficiency and Losses

Power conversion involves switching and conduction losses. High-efficiency designs require optimized semiconductor devices, which add cost.

2. Thermal Management

High power handling causes heat generation. Adequate cooling techniques are necessary to ensure reliability over long term.

3. Grid Stability and Power Quality

Large scale V2G injection may affect grid stability. Harmonic suppression and reactive power control are necessary for compliance with grid codes.

4. Battery Degradation

Frequent cycling from V2G participation can influence battery lifetime. Control strategies must balance grid services without heavily degrading battery health.

APPLICATIONS OF BIDIRECTIONAL CONVERTERS IN V2G

V2G applications enable several advantages:

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1. Peak Shaving

Discharging during peak grid demand can ease stress on generation units and reduce operational costs.

2. Frequency Regulation

Instantaneous response of bidirectional converters supports frequency regulation, stabilizing grid frequency during fluctuations.

3. Renewable Energy Integration

EVs can absorb surplus from solar or wind generation, serving as buffer storage and reducing renewable curtailment.

CASE STUDIES AND PRACTICAL DEPLOYMENTS

Several pilot projects worldwide have experimented with V2G technology:

- Community-based V2G demonstrations showed the feasibility of aggregated EV storage for grid support.
- Commercial fleets used bidirectional charging for reducing electricity bills through time-of-use arbitrage.
- Microgrid projects leveraged EV batteries to maintain islanded operation during grid outages. These deployments show technical viability but also highlight economic and regulatory barriers.

FUTURE DIRECTIONS

Advances in wide-bandgap semiconductors (like SiC and GaN) promise higher efficiency and reduced size of converters. Research is also ongoing on:

- **AI-based adaptive control** for better dynamic response.
- **Standardization of communication protocols** to enable seamless V2G across brands.
- **Economic models** that provide incentives for EV owners to participate in V2G.

Integration with renewable energy and smart grid frameworks will grow as technology matures.

CONCLUSION

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Bidirectional converters are key enablers for V2G applications. They bridge the gap between EV batteries and the utility grid by enabling controlled, efficient, and reliable power flow. While several converter topologies and control strategies have been proposed, practical challenges such as efficiency, battery wear, and grid compliance remain. However, with technological advancement and supportive policies, V2G systems are expected to become more mainstream, contributing significantly to grid resilience and renewable integration.

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