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Bidirectional Power Converter Topologies for Vehicle-to-Grid (V2G) and Grid-to-Vehicle (G2V) Systems: A Comprehensive Review

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Abstract: The accelerating global transition toward renewable energy integration and sustainable transportation has positioned Vehicle-to-Grid (V2G) and Grid-to-Vehicle (G2V) technologies as pivotal enablers of smart grid evolution. This review paper provides a critical synthesis of recent advances in bidirectional power converter topologies, control methodologies, and grid interface strategies developed between 2021 and 2026. The examination encompasses converter architectures ranging from three-phase full-bridge rectifiers and PWM inverter configurations to DC-DC converter designs tailored for both Light-Duty Vehicles (LDVs) and Heavy-Duty Vehicles (HDVs). Particular emphasis is placed on Phase-Locked Loop (PLL)-based control schemes, CC-CV battery management protocols, Total Harmonic Distortion (THD) compliance with IEEE 519 standards, and the performance advantages observed through parallel battery (multi-EV) operation. Key findings indicate that well-designed bidirectional charger topologies can achieve THD values well below the 5% threshold mandated by IEEE standards—as low as 0.93% under parallel battery operation—while maintaining stable DC-link regulation and responsive mode transition. The paper further addresses emerging challenges including battery degradation from frequent cycling, anti-islanding protection requirements, and the integration of Cyber-Physical Systems (CPS) for remote monitoring. Future directions encompassing standalone inverter architectures, monetization frameworks for V2G services, and renewable energy co-optimization are also identified.

***Keywords*:** Vehicle-to-Grid (V2G), Grid-to-Vehicle (G2V), bidirectional power converters, Phase-Locked Loop (PLL), Total Harmonic Distortion (THD), electric vehicles (EVs), smart grid, DC-DC converters, PWM inverters, battery management.

1. Introduction

The convergence of electrified transportation and renewable energy generation has fundamentally reshaped the discourse around grid stability and energy storage. Electric vehicles (EVs), once regarded solely as mobile loads, are now recognized as distributed energy resources capable of bidirectional power exchange with the utility grid. The V2G paradigm allows EVs to inject stored energy back into the grid during peak demand periods, while G2V operations enable controlled charging during periods of low demand or excess renewable generation [1,2].

Statistical analyses suggest that personal EVs remain parked for approximately 22 hours daily on average, representing an underutilized storage asset of significant magnitude. As EV penetration continues to climb globally—with projections indicating hundreds of millions of EVs on the road by 2030—the aggregate storage capacity available to grid operators becomes substantial enough to meaningfully influence grid frequency regulation, voltage stability, and renewable energy curtailment reduction [3,4].

However, realizing these potential demands careful attention to power electronics design. Bidirectional charger systems must satisfy a complex matrix of requirements: achieving high conversion efficiency across both charge and discharge directions, maintaining low harmonic distortion in grid-injected currents, executing rapid and seamless mode transitions, complying with electromagnetic compatibility (EMC) regulations, and preserving battery health through controlled cycling profiles [5,6].

The literature from 2021 to 2026 reflects intense research activity across these dimensions. Converter topologies have evolved from simple diode-bridge rectifier arrangements toward sophisticated multi-stage bidirectional architectures employing IGBTs and MOSFETs with advanced gate-drive control. Simultaneously, control strategies have advanced from basic proportional-integral (PI) regulators to adaptive and intelligent controllers capable of handling grid disturbances, unbalanced load conditions, and multi-EV coordination [7,8].

This review systematically examines these developments, drawing on 25 high-impact publications spanning 2021 to 2026. The paper is organized as follows: Section 2 reviews converter topology classifications; Section 3 addresses control strategies and PLL implementations; Section 4 examines battery management and charging protocols; Section 5 discusses harmonic performance and grid compliance; Section 6 explores multi-EV parallel operation; Section 7 identifies challenges and future research directions; and Section 8 presents conclusions.

2. Converter Topology Classifications and Architectures

2.1 AC-DC Front-End Converters

The AC-DC interface stage forms the primary boundary between the utility grid and the EV charging system. For three-phase applications—characteristic of public fast-charging infrastructure and fleet depot installations—the three-phase full-bridge converter topology has emerged as the dominant architecture due to its favorable harmonic profile and bidirectional capability [9]. The six-pulse bridge configuration, employing six controllable switching devices (typically IGBTs), produces output voltages with significantly reduced ripple compared to three-pulse midpoint alternatives, while eliminating DC components from transformer secondaries—a critical advantage for preventing core saturation in grid-connected transformers [10].

Recent investigations have demonstrated that replacing conventional thyristors with fully controllable devices (IGBTs or MOSFETs) in the bridge configuration unlocks true bidirectional power flow without the commutation constraints inherent to thyristor-based designs. Sinusoidal Pulse Width Modulation (SPWM) applied to the bridge switches enables precise control of both active and reactive power injection, with unipolar switching schemes at 10 kHz demonstrating effective harmonic suppression when combined with LCL grid filters [11,12].

Single-phase topologies retain relevance for residential and light-duty charging applications. Toroidal converter configurations and bridgeless PFC rectifiers have been reported to achieve efficiencies exceeding 97% in unidirectional configurations, with bidirectional extensions incorporating regenerative snubber circuits to recapture switching losses [13].

2.2 DC-DC Converter Stages

The DC-DC conversion stage interfaces the DC-link bus with the variable-voltage EV battery pack. For Light-Duty Vehicles (LDVs), where battery pack voltages typically range from 200V to 400V, the two-quadrant (Type-C chopper) topology employing complementary MOSFET pairs provides smooth bidirectional current control. The effective power rating of 3.3 kW typical for residential LDV charging can be achieved with compact magnetics operating at switching frequencies of 10 kHz or higher [14].

Heavy-Duty Vehicle (HDV) applications demand substantially higher power ratings—22 kW and above—necessitating robust converter designs with carefully engineered filter inductors and DC-link capacitors. The full-bridge two-quadrant converter for HDV integration incorporates thyristor-controlled rectifier stages for AC-DC conversion cascaded with IGBT-based chopper stages for DC-DC regulation, providing the power handling capability and thermal performance required for commercial vehicle charging [15].

Isolated bidirectional DC-DC converter topologies, including Dual Active Bridge (DAB) converters, have attracted considerable research attention since 2021 for their galvanic isolation, wide voltage conversion ratio, and inherent soft-switching characteristics. DAB converters operating with phase-shift modulation can achieve zero-voltage switching (ZVS) across substantial load ranges, contributing to efficiency improvements particularly relevant for high-power V2G discharge cycles [16].

2.3 Integrated and Multi-Port Topologies

Emerging multi-port converter architectures accommodate simultaneous integration of EV battery systems, photovoltaic (PV) arrays, and grid connections within a single power conversion stage. Such configurations reduce component count and power conversion losses compared to cascaded single-port approaches, enabling direct PV-to-vehicle (PV2G) power flows without intermediate AC conversion [17]. Quadratic bidirectional DC-DC converters extending voltage conversion ratios beyond what conventional non-isolated topologies can achieve have been proposed for V2G applications where large voltage differentials exist between grid DC-link and battery terminals [18].

A comparative summary of the major converter topologies discussed is presented in Table 1, highlighting their key characteristics, applications, and advantages.

Table 1: Comparative Analysis of Converter Topologies for EV Charging Systems

Converter Stage	Topology	Key Devices	Power Range	Key Features	Applications
AC-DC	Three-phase full-bridge (six-pulse)	IGBTs/MOSFETs	> 20 kW	Low harmonic distortion, bidirectional capability, no DC transformer saturation	Fast charging stations, fleet depots
AC-DC	Single-phase bridgeless PFC	MOSFETs	< 5 kW	High efficiency (>97%), reduced conduction losses	Residential EV charging
DC-DC	Two-quadrant (Type-C chopper)	MOSFETs	~3.3 kW	Smooth bidirectional current control, compact design	Light-duty EVs
DC-DC	Full-bridge converter (HDV)	IGBTs + Thyristors	> 22 kW	High power handling, thermal robustness	Heavy-duty EV charging
DC-DC (Isolated)	Dual Active Bridge (DAB)	IGBTs/MOSFETs	Medium–High	ZVS operation, galvanic isolation, high efficiency	V2G, high-power systems
Multi-Port	PV-Grid-EV integrated converters	Mixed (IGBTs/MOSFETs)	Variable	Reduced conversion stages, multi-source integration	PV-assisted EV charging
DC-DC	Quadratic bidirectional converter	MOSFETs	Variable	High voltage gain, wide conversion ratio	Advanced V2G systems

3. Control Strategies and Phase-Locked Loop Implementation

3.1 PLL-Based Grid Synchronization

Accurate grid synchronization is a prerequisite for compliant bidirectional power exchange. The Phase-Locked Loop (PLL) controller has established itself as the standard synchronization mechanism in grid-connected converters, with the Synchronous Reference Frame PLL (SRF-PLL) being particularly prevalent in three-phase V2G systems. The SRF-PLL operates by transforming three-phase voltages from the stationary ABC frame through the stationary alpha-beta frame (via Clarke transformation) to the rotating dq0 synchronous reference frame (via Park transformation) [9,19].

In the dq frame, grid synchronization is achieved when the q-axis voltage component (Vq) is regulated to zero through a PI controller whose output generates the angular frequency (ωt) signal. This ωt signal subsequently produces the Sin(ωt) and Cos(ωt) reference signals corresponding to active and reactive current components, respectively. PI controller gains require careful tuning—typical values of (Kp=10, Ki=50,000) have been demonstrated to provide adequate bandwidth for grid frequency variations while rejecting voltage harmonics [20].

The current control loop in the dq frame operates on the transformed grid currents (Id, Iq). The active current reference (Idref) is derived from DC-link voltage regulation, with the outer voltage loop PI controller (Kp=0.5, Ki=5) generating the active current demand that an inner current PI controller (Kp=25, Ki=500) tracks. The reactive current reference (Iqref) is set to zero for unity power factor operation or adjusted deliberately for reactive power compensation services [21].

3.2 Advanced Control Methodologies

Model Predictive Control (MPC) frameworks applied to V2G converters have demonstrated superior dynamic response compared to conventional PI-based schemes, particularly during transient conditions such as sudden load changes or mode transitions between V2G and G2V operation. Finite Control Set MPC (FCS-MPC) directly selects switching states to minimize a cost function combining current tracking error and switching frequency, eliminating the modulation stage and enabling inherent harmonic optimization [22].

Adaptive fuzzy and neural network-based controllers have been investigated for scenarios characterized by nonlinear battery dynamics and variable grid impedance. Adaptive Feed-Forward SOGI-DRC (AFF-SOGI-DRC) control architectures have been reported to significantly improve power quality metrics in renewable energy-based EV charging stations operating under grid disturbance conditions [7]. Interval Type-2 Fuzzy Logic controllers applied to shunt converters in EV charging schemes have demonstrated enhanced robustness to parametric uncertainties compared to their Type-1 counterparts [3].

3.3 Mode Transition and Autonomous Operation

The ability to transition seamlessly between V2G and G2V modes without interrupting grid synchronization represents a critical performance criterion for practical deployment. Toggle-switch-controlled mode transition schemes implemented in Simulink models demonstrate that the PLL controller can re-synchronize current references within a few cycles of the 50 Hz grid frequency when abrupt mode changes occur [9,19]. During V2G operation, the current reference is set positive (+30 A), maintaining grid voltage and current in phase (zero phase displacement) to inject active power. G2V mode employs a negative reference (-30 A), producing 180° phase displacement that draws power from the grid into the battery.

Battery charging and discharging controllers employing PI regulators (Kp=0.005, Ki=10) with duty cycle limiters (0 to 0.95) interface directly with the DC-DC PWM generator, providing smooth current tracking with minimal overshoot. Battery controller response measurements confirm settling times below 0.1 seconds for both V2G and G2V mode initiations, and rapid re-stabilization following abrupt mode changes [20].

A consolidated comparison of the control strategies, parameters, and operational characteristics is presented in Table 2.

Table 2: Comparative Analysis of Control Strategies for V2G Converter Systems

Control Category	Technique	Key Parameters	Functional Role	Performance Characteristics	Application Context
Grid Synchronization	SRF-PLL	Kp = 10, Ki = 50,000	Phase and frequency tracking	High accuracy, harmonic rejection	Three-phase grid-connected V2G
Current Control	dq-frame PI control	Inner: (Kp = 25, Ki = 500)	Tracks Id and Iq currents	Fast response, stable tracking	Grid-side converters
Voltage Control	DC-link PI control	Outer: (Kp = 0.5, Ki = 5)	Regulates DC-link voltage	Maintains power balance	Bidirectional converters
Predictive Control	FCS-MPC	Cost function-based	Direct switching control	Fast dynamic response, reduced switching losses	High-performance V2G systems
Intelligent Control	Fuzzy Logic (Type-2)	Rule-based	Handles nonlinearity	High robustness to uncertainty	Variable grid conditions
Adaptive Control	AFF-SOGI-DRC	Adaptive gains	Power quality enhancement	Improved disturbance rejection	Renewable-integrated EV charging
Mode Transition	Toggle-based control	±30 A reference	V2G/G2V switching	Fast resynchronization (< cycles)	Real-time operation
Battery Control	PI + Duty limiter	Kp = 0.005, Ki = 10	Charging/discharging control	Settling time < 0.1 s	Battery management interface

4. Battery Management and Charging Protocols

4.1 Charging Method Comparison

The three fundamental charging methods—Constant Voltage (CV), Constant Current (CC), and Combined CC-CV—each present distinct trade-offs in battery capacity utilization, charging speed, and potential for battery degradation. CV charging, while straightforward to implement, risks high initial current surges that can induce crystal structure damage in lithium-ion cathode materials. CC charging avoids initial current spikes but results in suboptimal capacity utilization as terminal voltage rises toward the cutoff level without the final balancing phase [23].

The CC-CV method, universally adopted for lithium-ion chemistry in V2G applications, begins with constant current charging until the cell voltage reaches its upper cutoff threshold, then transitions to constant voltage regulation while current naturally declines to a minimum termination level. This protocol enables full capacity utilization while preventing overcharge conditions. For V2G bidirectional operation, the discharge phase mirrors the CC protocol, with current held at a controlled negative reference until SOC decrements to a defined lower limit [24].

4.2 Battery Degradation Considerations

A persistent concern in V2G deployment is the accelerated battery degradation resulting from increased charge-discharge cycle frequency. Lithium-ion cells exhibit capacity fade governed by both calendar aging (time-dependent electrolyte decomposition and SEI layer growth) and cycle aging (mechanically induced particle cracking and active lithium inventory loss) [25]. V2G operation superimposes additional shallow discharge-charge cycles onto the primary transportation usage cycle, potentially advancing calendar aging through elevated average SOC and temperature exposure.

Recent electrochemical modeling studies have investigated the net impact of V2G participation on battery lifetime, with findings indicating that smart V2G strategies operating within carefully defined SOC windows (20%-80%) and constraining discharge rates below 0.5C can limit additional capacity fade to acceptable levels while still providing economically valuable grid services. Optimal V2G scheduling algorithms that minimize battery degradation while maximizing grid service revenue represent an active research frontier [23,25].

5. Harmonic Performance and Grid Compliance

5.1 IEEE 519 Standards Compliance

Total Harmonic Distortion (THD) of the grid-injected current constitutes the primary power quality metric by which V2G converter designs are evaluated for grid compliance. IEEE Standard 519-1992 (and its 2014 revision) establishes maximum THD limits of 5% for current injected at the Point of Common Coupling (PCC) for systems above 1 kV. Compliance with this threshold is essential for regulatory approval of V2G equipment and for protecting sensitive grid-connected loads from harmonic interference [9,20].

Experimental and simulation results from single-battery V2G-G2V topology implementations demonstrate THD values of approximately 2.45% at the fundamental frequency of 50 Hz with a 22.36 A fundamental component—well within the IEEE 519 limit. The harmonic spectrum confirms dominant harmonic content at orders corresponding to the PWM switching frequency sidebands, which the LCL filter (5mH – 30μF – 5mH) effectively attenuates [11].

5.2 THD Improvement Through Parallel Operation

A particularly significant finding from recent research is the substantial THD reduction achievable through parallel operation of multiple EV batteries—effectively simulating multiple EVs connected simultaneously to a common DC bus through individual DC-DC converter subsystems. Parallel battery V2G-G2V operation has been reported to reduce THD from 2.45% (single battery) to 0.93% (parallel batteries), with a corresponding increase in fundamental current magnitude from 22.36 A to 67.14 A [9].

This improvement is attributable to the interleaving effect between multiple DC-DC converters operating with phase-shifted PWM carriers, which partially cancels harmonic components at the fundamental switching frequency and its sidebands. The phenomenon echoes the well-established harmonic reduction principles of multi-pulse rectifier configurations, extended here to the DC-DC converter stage. As EV fleet penetration grows and multi-vehicle charging scenarios become commonplace, this harmonic improvement effect represents an inherent advantage of scale in V2G infrastructure [17,21].

5.3 LCL Filter Design and Impact

The LCL filter topology—comprising a converter-side inductor, a shunt capacitor, and a grid-side inductor—provides superior high-frequency attenuation compared to simple L or LC configurations, enabling effective switching harmonic suppression without requiring prohibitively large passive component values. The resonant frequency of the LCL filter must be positioned appropriately between the grid fundamental frequency and the PWM switching frequency to avoid resonance excitation. Active damping strategies applied through modification of the current controller reference signal offer resonance suppression without the power dissipation penalty of passive damping resistors [12,22].

6. Multi-EV Parallel Operation and Grid Impact

6.1 Parallel Battery Architecture

The extension of single-EV V2G topology to accommodate multiple vehicles connected in parallel to a shared DC bus represents a critical scaling step toward commercially viable V2G aggregation. In parallel architectures, each EV battery interfaces with the common DC bus through a dedicated bidirectional DC-DC converter subsystem, while a single three-phase bidirectional AC-DC converter manages the grid interface. Independent current controllers for each battery allow differentiated charging and discharging profiles based on individual vehicle SOC, departure schedules, and user preferences [15,21].

Simulation results for parallel three-EV configurations show that the aggregate grid current amplitude increases proportionally with the number of participating vehicles, while DC-link voltage regulation remains stable through the shared voltage control loop. The DC-link capacitor sizing (5600 μF in studied implementations) must account for the higher ripple current contributions from multiple switching converter stages operating simultaneously [19,20].

6.2 Grid Impact and Smart Charging Coordination

Large-scale uncoordinated EV charging presents documented risks to distribution grid infrastructure, including transformer overloading, voltage deviation at residential feeders, and demand peak amplification. Coordinated V2G-G2V scheduling algorithms capable of distributing EV charging across off-peak periods—typically overnight when residential demand is minimal—while aggregating discharge capacity to support peak morning and evening demand periods, can substantially mitigate these risks [4,16].

Vehicle-to-Home (V2H) and Vehicle-to-Building (V2B) extensions of V2G technology create localized energy management opportunities that reduce reliance on grid-scale coordination. An EV battery discharged to support household loads during grid outages or peak tariff periods provides direct economic value to the vehicle owner while concurrently reducing grid demand [6,17]. Hierarchical energy management systems coordinating multiple EVs within a fleet depot environment have demonstrated the ability to jointly optimize V2G service delivery, battery lifetime, and transportation readiness constraints [15].

7. Challenges, Emerging Technologies, and Future Directions

7.1 Current Technical Challenges

Despite demonstrable progress in converter performance and control sophistication, several technical barriers continue to impede widespread V2G commercialization. Anti-islanding protection—detecting and isolating the V2G converter from a de-energized grid segment to prevent backfeed hazards to utility workers—remains an area where standardization is incomplete, with active impedance-injection and passive frequency-shift detection methods each exhibiting trade-offs between detection speed and nuisance tripping rate [13,22].

Power factor correction across the full operating range of bidirectional converters, particularly during light-load discharge conditions in V2G mode, challenges conventional controller designs optimized for rated power operation. DC current injection into the grid—capable of saturating distribution transformer cores—must be maintained below 0.5% of the rated output current per IEEE 1547 requirements, necessitating careful DC offset compensation in the current control loop [10,19].

Battery SOC estimation accuracy directly influences V2G scheduling decisions and battery protection algorithms. Extended Kalman Filter (EKF) and Sigma-Point Kalman Filter (SPKF) approaches applied to equivalent circuit battery models have demonstrated SOC estimation errors below 2% under dynamic V2G cycling profiles, though computational demands increase substantially for temperature-dependent model parameterization [25].

7.2 Wide Bandgap Semiconductor Integration

Silicon Carbide (SiC) MOSFET and Gallium Nitride (GaN) transistor technologies are progressively entering commercial V2G charger designs, enabling switching frequencies an order of magnitude higher than conventional silicon IGBT designs while simultaneously reducing conduction and switching losses. The higher junction temperature capability of SiC devices (175°C vs. 125°C for Si) enables more aggressive thermal management designs with reduced heatsink mass—a significant advantage for on-board vehicle charger applications constrained by weight and volume [14,24].

SiC-based three-phase bidirectional chargers operating at 100 kHz switching frequency have been reported with power densities exceeding 10 kW/L, compared to 1-2 kW/L for conventional Si IGBT designs at 10-20 kHz. The reduced filter size enabled by higher switching frequencies also contributes to system miniaturization. However, electromagnetic interference (EMI) challenges intensify at higher switching frequencies, requiring careful PCB layout and filter design to maintain conducted and radiated EMC compliance [13].

7.3 Cyber-Physical Systems Integration

The integration of Cyber-Physical Systems (CPS) with V2G infrastructure creates transformative possibilities for remote monitoring, predictive control, and large-scale fleet coordination. CPS architectures leveraging Internet of Things (IoT) communication protocols enable real-time SOC reporting, dynamic tariff response, and demand-response participation without requiring physical intervention at charging points [5,8].

Cybersecurity considerations are paramount in CPS-enabled V2G deployments, as communication network vulnerabilities could enable malicious actors to manipulate EV charging patterns in coordinated fashion, creating artificial demand spikes or disrupting grid-stabilizing V2G discharge services. Cryptographic authentication protocols adapted from industrial control system security standards are being evaluated for V2G communication interfaces [8].

7.4 Future Research Directions

The path forward for V2G technology encompasses several high-priority research areas. Standalone inverter architectures capable of supporting unbalanced and nonlinear loads—common in residential and commercial environments—extend V2G utility beyond grid-connected operation to off-grid and microgrid applications. Multi-functional on-board chargers integrating G2V, V2G, Vehicle-to-Home (V2H), and active filtering capabilities within a single power stage maximize the value extracted from the vehicle's power electronics investment [17,18].

Regulatory and market framework development represents an equally important frontier. Monetization policies enabling EV owners to receive compensation for V2G grid services—frequency regulation, spinning reserve, peak shaving—must be designed to ensure that the economic returns justify battery wear costs while incentivizing participation. Several electricity market operators have initiated V2G pilot programs with aggregated EV fleets, and the lessons emerging from these deployments will shape the regulatory landscape for the decade ahead [2,6].

8. Conclusion

This review has examined the state of the art in bidirectional power converter topologies and control strategies for V2G and G2V applications, drawing on the most recent literature from 2021 to 2026. The evidence collectively demonstrates that well-designed V2G systems, employing three-phase full-bridge AC-DC converters with LCL grid filters and bidirectional DC-DC converter stages controlled by PLL-based current controllers, are capable of meeting IEEE 519 harmonic distortion requirements, maintaining stable DC-link regulation, and executing rapid mode transitions between charging and discharging operations.

The THD performance improvements observed in parallel multi-EV configurations—from 2.45% in single-battery operation to 0.93% with parallel batteries—represent a compelling argument for aggregated V2G deployment, as harmonic performance improves naturally with fleet scale. DC-link voltage control maintaining regulation within ±1% of the 800V reference under both V2G and G2V steady-state conditions, and successful re-synchronization within milliseconds of abrupt mode transitions, confirm the technical maturity of PLL-controlled bidirectional converter architectures.

Ongoing challenges in battery degradation management, anti-islanding protection, wide-bandgap semiconductor integration, and cybersecurity for CPS-enabled deployments continue to drive research activity. The convergence of increasingly capable power electronics, advanced control algorithms, and emerging regulatory frameworks positions V2G technology on the threshold of large-scale commercial deployment. As renewable energy penetration accelerates and EV adoption reaches mass-market scale, V2G-capable EVs are poised to become indispensable assets in the transition to a sustainable, resilient electricity system.

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