

Smart EV Charging: Virtual Synchronous Generator and Phase-Locked Loop Based Control for Efficient V2G and G2V Energy Flow

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Abstract: *The large-scale integration of electric vehicles (EVs) and renewable energy sources is reshaping modern power systems while introducing challenges such as reduced inertia, frequency instability, voltage fluctuations, and peak load stress. Smart electric vehicle charging strategies, including Grid-to-Vehicle (G2V) and Vehicle-to-Grid (V2G) operations, enable EVs to function as flexible distributed energy resources. However, the dominance of power electronic interfaces in EV charging infrastructure reduces natural grid inertia and increases reliance on advanced control strategies. Virtual Synchronous Generator (VSG) control has emerged as an effective grid-forming approach by emulating the dynamic behaviour of synchronous machines, while Phase-Locked Loop (PLL) techniques remain essential for accurate grid synchronization and monitoring. This paper presents a comprehensive review of smart EV charging architectures, V2G and G2V technologies, renewable energy integration, communication frameworks, and power electronic interfaces, with a particular focus on VSG and PLL-based control strategies. Existing research is critically analysed, key challenges are identified, and future research directions for hybrid PLL-VSG control in EV charging systems are discussed.*

Keywords: Smart EV Charging, Vehicle-to-Grid, Grid-to-Vehicle, Virtual Synchronous Generator, Phase-Locked Loop, Renewable Energy Integration, Smart Grid

I. INTRODUCTION

The rapid electrification of transportation has positioned electric vehicles (EVs) as a cornerstone of sustainable energy and mobility solutions. Compared to internal combustion engine (ICE) vehicles, EVs offer significantly higher energy efficiency (85–90%) and substantially lower greenhouse gas (GHG) emissions—approximately 40% less over the vehicle lifecycle [1]. According to the Central Electricity Authority (CEA, 2023), global EV adoption is expected to reach nearly 130 million vehicles by 2030, presenting both opportunities and substantial challenges for power grid infrastructure [2].

Nevertheless, uncontrolled EV charging can impose severe stress on distribution networks, causing peak demand amplification, voltage deviation, and frequency instability. To mitigate these effects, smart charging approaches have been developed that enable controlled, scheduled, and bidirectional power exchange between EVs and the grid. Vehicle-to-Grid (V2G) and Grid-to-Vehicle (G2V) technologies allow EV batteries to operate as distributed energy storage systems (DESS), providing ancillary grid services such as peak shaving, frequency regulation, and renewable energy balancing [3].

However, increased penetration of inverter-based EV chargers results in reduced system inertia, making power grids more vulnerable to disturbances. Virtual Synchronous Generator (VSG) control has emerged as a promising strategy to address this inertia deficiency by replicating synchronous generator (SG) dynamics within power electronic converters.



In parallel, Phase-Locked Loop (PLL) techniques play a critical role in grid synchronization, parameter estimation, and operational mode transitions. The coordinated use of VSG and PLL control is therefore essential for stable and efficient EV-grid interaction [4].

This review paper is organized as follows: Section II discusses the evolution of smart EV charging technologies. Section III covers renewable energy integration with EVs. Section IV examines communication and power electronic infrastructure. Section V reviews PLL techniques. Section VI discusses VSG control strategies. Section VII proposes a hybrid PLL-VSG architecture. Section VIII addresses environmental and lifecycle considerations. Section IX identifies research gaps, Section X outlines future directions, and Section XI concludes the paper.

II. EVOLUTION OF SMART EV CHARGING TECHNOLOGIES

A. Conventional Charging vs. Smart Charging

Conventional EV charging systems typically operate in an uncoordinated and unidirectional manner, often coinciding with residential peak demand periods. This charging behaviour can overload distribution transformers, degrade power quality, and accelerate infrastructure aging. Traditional chargers lack intelligence regarding grid state, pricing signals, or renewable energy availability.

Smart charging strategies introduce intelligent scheduling and communication mechanisms that adapt charging behaviour based on real-time grid conditions, dynamic electricity pricing, and renewable energy availability. Tripathi (2022) compared V2G, Vehicle-to-Home (V2H), and Vehicle-to-Vehicle (V2V) systems, demonstrating that coordinated charging strategies significantly improve grid reliability and defer costly infrastructure upgrades [5]. However, the absence of standardised operational frameworks and viable business models continues to hinder large-scale deployment of smart charging systems.

B. G2V and V2G Operational Principles

Grid-to-Vehicle (G2V) operation focuses on optimized energy absorption by EVs to minimize grid stress during off-peak periods. In contrast, Vehicle-to-Grid (V2G) operation enables EVs to inject stored energy back into the grid during peak demand events or grid contingencies, thereby acting as dispatchable resources [6].

Through these bidirectional mechanisms, EVs can deliver a range of ancillary services including frequency support, voltage regulation, and load balancing. Kumar et al. (2024) demonstrated that V2G and G2V implementations can effectively supplement conventional frequency regulation resources while reducing reliance on fossil-fuel peaking plants [3]. Despite extensive analytical and simulation-based validation, real-world deployment of V2G systems remains limited, constrained by challenges in real-time control, communication latency, battery degradation concerns, and regulatory barriers.

III. RENEWABLE ENERGY INTEGRATION USING EVS

The International Renewable Energy Agency (IRENA, 2023) projects the global share of renewable energy to approach 60% by 2050, driven primarily by rapid expansion of solar photovoltaic (PV) and wind generation capacity [7]. While renewable energy sources (RES) substantially reduce carbon emissions, their intermittent and non-dispatchable nature introduces significant operational uncertainty and challenges for power system balancing.

Electric vehicles, when integrated with smart charging infrastructure, can function as distributed battery energy storage systems (BESS), capable of absorbing excess renewable generation during periods of high supply and low demand, and injecting energy during supply shortfalls. Bidirectional power converters and intelligent dispatch algorithms are critical for enabling this functionality effectively [2].

Sultan et al. (2022) highlighted that robust EV-grid interaction frameworks are essential to prevent voltage and frequency instabilities that may arise from uncoordinated V2G/G2V operations in systems with high RES penetration [8]. The lack of adaptive, real-time control strategies currently limits the effective utilization of EVs as dynamic



renewable energy buffers. Advanced energy management systems (EMS) that incorporate grid state estimation, forecasting, and optimization algorithms are required for reliable EV-based renewable integration.

IV. COMMUNICATION AND POWER ELECTRONIC INFRASTRUCTURE

A. Communication Frameworks

Reliable and secure communication is fundamental to smart EV charging, enabling real-time exchange of grid conditions, charging status, control commands, and pricing information between EVs, charging stations, aggregators, and grid operators. Vehicle-to-Infrastructure (V2I) and Vehicle-to-Vehicle (V2V) communication technologies based on Dedicated Short-Range Communication (DSRC) standards, including IEEE 802.11p and IEEE 1609 protocol families, have been extensively investigated [9].

Biswas et al. (2025) explored the application of these DSRC standards for dynamic V2G coordination and demonstrated that although these technologies support low-latency data exchange, significant challenges related to cybersecurity, scalability, and interoperability with existing grid management systems remain unresolved, particularly in large heterogeneous EV fleets [9]. Emerging technologies such as 5G cellular networks and edge computing are being explored as complementary communication solutions to overcome these limitations.

B. Power Electronic Interfaces

Power electronic converters (PECs) form the technological backbone of smart EV charging infrastructure. Bidirectional DC-AC inverters enable seamless V2G and G2V power flow, while AC-DC rectifiers govern controlled grid energy absorption. Electromagnetic interference (EMI) mitigation techniques and coordinated multi-converter control strategies are essential for maintaining power quality within charging stations and the distribution network [2].

The increasing density of power electronic devices in distribution networks, combined with their non-linear switching behaviour, further emphasizes the need for advanced control strategies. Both VSG and PLL approaches are relevant in this context, addressing frequency synchronization, harmonic suppression, and inertial contribution requirements.

V. PHASE-LOCKED LOOP TECHNIQUES IN EV CHARGING SYSTEMS

Phase-Locked Loop (PLL) techniques are widely employed in grid-connected power electronic converters to accurately estimate the instantaneous grid voltage phase angle, frequency, and magnitude. This information is essential for maintaining phase coherence between the converter output and the grid, enabling stable current injection or absorption during both G2V and V2G operation [10].

In conventional grid-following EV chargers, the PLL acts as the primary synchronization mechanism that governs the control loop reference frame. The Synchronous Reference Frame PLL (SRF-PLL) and the Double Second-Order Generalized Integrator PLL (DSOGI-PLL) are among the most widely implemented architectures, offering varying degrees of robustness under unbalanced and distorted grid conditions [10].

However, under weak grid conditions characterized by high impedance or during rapid V2G power transitions, PLL-based synchronization may experience instability, increased phase tracking errors, and oscillatory behaviour. These limitations become particularly significant in high EV penetration scenarios where multiple charger PLLs interact with each other and with the grid impedance, potentially causing collective instability. Careful PLL design, bandwidth tuning, and adaptive gain scheduling are therefore necessary to ensure robust performance across all operating conditions [4].

VI. VIRTUAL SYNCHRONOUS GENERATOR CONTROL FOR EV CHARGERS

A. Concept and Operational Benefits of VSG

Virtual Synchronous Generator (VSG) control emulates the inertial response, damping characteristics, and frequency droop behaviour of conventional synchronous generators within inverter-based systems. By synthesising virtual inertia and damping through digital control algorithms, VSG-controlled EV chargers can actively participate in primary



frequency regulation and voltage support, thereby enhancing overall grid stability under high renewable energy penetration conditions [11].

Unlike conventional grid-following inverters that rely exclusively on PLL synchronization, VSG-controlled chargers operate as grid-forming devices capable of establishing voltage and frequency references autonomously. This characteristic makes VSG control particularly effective in weak grids or islanded microgrids, where traditional PLL-dominated grid-following strategies may fail to maintain stable operation due to insufficient synchronizing torque [4].

Key implementation features of VSG control applicable to EV chargers include virtual impedance insertion for stable inverter-grid interaction during charging and discharging cycles, anti-windup field current control to improve reliability under grid disturbances, and virtual capacitive coupling mechanisms to reduce harmonic content and improve power quality.

B. VSG-Based V2G Scheduling

Zheng et al. (2025) proposed a VSG-based V2G scheduling framework utilizing virtual synchronization techniques applicable to aggregated EV charging systems [11]. Experimental validation using a low-voltage prototype demonstrated improved transient response during rapid load variations, significant reduction in frequency deviations following grid contingencies, and effective mitigation of power oscillations caused by intermittent EV connection and disconnection events.

Building on principles derived from synchronverter technology, VSG implementations can replace conventional PLL-based synchronization with self-synchronizing mechanisms, reducing overall control complexity while enhancing dynamic grid support capability. This self-synchronizing feature is particularly advantageous during grid fault recovery and black-start operations. Despite these demonstrated advantages, the integration of VSG control into commercial EV charger products and large-scale aggregator platforms remains largely unexplored and represents an important frontier for future development.

VII. HYBRID PLL–VSG CONTROL ARCHITECTURE

Rather than adopting exclusively PLL-based or VSG-based control paradigms, recent research advocates the development of hybrid control architectures that leverage the complementary strengths of both approaches [4]. In the proposed hybrid PLL–VSG framework, the PLL provides accurate grid parameter estimation, phase angle tracking, and operational mode detection under normal grid conditions. Simultaneously, the VSG control subsystem governs power sharing, inertial response emulation, and grid-forming behaviour during grid disturbances, frequency events, or contingency conditions.

This coordinated architectural approach enables smooth and bumpless transitions between grid-following and grid-forming operational modes, improving overall control system robustness under a wide range of grid conditions. The hybrid framework also enhances power quality during both G2V and V2G operations by combining the fast synchronization capability of PLL with the inertial damping provided by VSG.

Key design considerations for hybrid PLL–VSG implementation in EV chargers include bandwidth coordination between the PLL and VSG control loops to avoid adverse interactions, adaptive parameter scheduling based on real-time grid impedance estimation, mode detection logic for reliable switching between grid-following and grid-forming modes, and integration with energy management systems for optimal V2G scheduling. The hybrid approach represents a pragmatic pathway toward deploying grid-supportive EV charging infrastructure without requiring the complete replacement of established PLL-based hardware architectures.

VIII. EFFICIENCY, ENVIRONMENTAL IMPACT, AND LIFECYCLE CONSIDERATIONS

Prabhu et al. (2024) reported that EVs demonstrate energy conversion efficiency of approximately 85–90%, compared to less than 30% for conventional ICE vehicles, resulting in approximately 40% lower lifecycle GHG emissions under



typical charging mix conditions [1]. These efficiency advantages are further amplified when EVs are charged predominantly from renewable energy sources, potentially achieving near-zero operational carbon footprints.

However, comprehensive lifecycle assessment (LCA) studies that account for battery degradation under V2G cycling duty, regional driving patterns, ambient temperature effects on battery performance, and end-of-life battery processing remain limited in scope and geographic coverage. The additional charge-discharge cycles imposed by V2G operation represent a significant concern for battery longevity and must be carefully managed through intelligent charging algorithms and battery state-of-health (SOH) monitoring.

Smart charging strategies incorporating PLL-VSG control can further enhance the environmental profile of EV fleets by maximizing the absorption and utilization of renewable energy during periods of surplus generation, thereby minimizing curtailment losses and reducing reliance on fossil-fuel-based peaking generation capacity. Life-cycle optimized V2G scheduling algorithms that balance grid service revenue with battery degradation costs represent an important area for future research.

IX. LITERATURE REVIEW SUMMARY

Table I presents a consolidated summary of the key contributions identified in the reviewed literature, highlighting technologies employed, principal findings, and persistent research gaps.

TABLE I: Summary of Reviewed Literature on Smart EV Charging and VSG Control

Authors & Year	Key Findings	Technologies/Methods	Research Gaps
Tripathi (2022)	V2G systems can optimize grid support using EVs as mobile storage; highlights business challenges and coordination needs	V2G, V2H, V2V comparison; coordinated charging strategies	Lack of unified V2G business models and lifecycle coordination
Sultan et al. (2022)	Smart grid integration of EVs requires robust frameworks to avoid instability and maximize utility benefits	Systematic literature review; grid-EV interaction models	Limited experimental validation of EV-grid synchronization
IRENA (2023)	RE share projected to reach 60% by 2050; wind and solar to triple	Carbon taxes, PV & wind expansion	Integration of RE with EV charging infrastructure
CEA Report (2023)	EVs projected to reach 130M by 2030; V2G can reduce peak load	Bidirectional inverters, DC-AC conversion, EMI	Real-time control algorithms for dynamic V2G dispatch
Prabhu et al. (2024)	EVs offer 85–90% efficiency vs <30% for ICEs; 40% lower GHG footprint	PEVs, HPEVs, lithium-ion batteries	Lifecycle analysis of EVs under diverse driving conditions
Kumar et al. (2024)	V2G and G2V technologies enhance grid stability and renewable integration; EVs offer frequency regulation and peak shaving	Smart charging, bidirectional flow, grid services	Real-time control and communication protocols for dynamic V2G
Biswas et al. (2025)	V2G supports RE integration, improves grid stability and monetization	PECs, BES, DSRC (IEEE 802.11p, 1609), V2I/V2V	Secure, scalable communication for mobile EVs
Zheng et al. (2025)	V2G scheduling using virtual	VSG control, scheduling	Integration of VSG into



Authors & Year	Key Findings	Technologies/Methods	Research Gaps
	synchronization improves grid stability and reduces transient effects	algorithms, low-voltage prototypes	commercial EV chargers and aggregators

X. RESEARCH GAPS AND CHALLENGES

The comprehensive review of existing literature reveals several critical and unresolved challenges that require focused research attention:

Standardization and Business Models: The absence of harmonized V2G market frameworks, grid codes, and commercially viable business models for EV owners participating in V2G programs remains a primary barrier to widespread deployment. Regulatory structures that compensate EV owners for grid services provided are still nascent in most jurisdictions.

Experimental Validation at Scale: While simulation and small-scale prototype results are promising, comprehensive experimental validation of large-scale EV fleet coordination with realistic grid models and stochastic EV availability patterns is lacking. Hardware-in-the-loop (HIL) and pilot-scale demonstrations are required to bridge this gap.

Weak Grid Stability of PLL-Based Chargers: Grid-following PLL-controlled chargers exhibit inherent stability limitations under high-impedance or weak grid conditions. The proliferation of such devices in distribution networks poses a systemic stability risk that demands coordinated solutions integrating VSG-type grid-forming capabilities.

PLL-VSG Integration: The theoretical and practical challenges of seamlessly integrating PLL and VSG control subsystems—including loop interaction analysis, transition logic design, and stability verification across operational boundaries—remain insufficiently addressed in the literature.

Cybersecurity and Communication Scalability: As EV fleets grow in scale and geographic diversity, ensuring secure, low-latency, and scalable communication between vehicles, charging infrastructure, and grid management systems becomes increasingly critical. Current DSRC-based solutions face limitations in dense urban deployments.

Battery Lifecycle under V2G Duty: Quantitative assessment of battery degradation attributable to V2G participation, and the development of optimized charging protocols that minimize degradation while maximizing grid service value, represent important unresolved research challenges.

XI. FUTURE RESEARCH DIRECTIONS

Based on the identified research gaps, the following priority areas for future investigation are recommended:

- (1) **Adaptive PLL-VSG Coordination for EV Aggregators:** Development of model-based and data-driven adaptive control frameworks that dynamically coordinate PLL and VSG parameters across aggregated EV fleets in response to varying grid conditions and fleet availability.
- (2) **AI-Based Real-Time Parameter Tuning:** Application of machine learning and reinforcement learning techniques for real-time autonomous tuning of PLL bandwidth, VSG virtual inertia, and damping coefficients to optimize performance across diverse grid operating scenarios.
- (3) **Hardware-in-the-Loop and Pilot-Scale Testing:** Systematic HIL testing and controlled pilot deployments of hybrid PLL-VSG smart charger prototypes to validate theoretical advantages under realistic grid conditions and EV usage patterns.
- (4) **Microgrid and Smart City Integration:** Investigation of VSG-enabled EV charging integration within island-capable microgrids and urban smart city energy management architectures, including multi-energy carrier coordination.
- (5) **Grid Code and Standardization Development:** Active engagement with standards bodies to develop grid codes, interoperability standards, and certification frameworks for VSG-enabled EV chargers, facilitating market entry and large-scale adoption.



(6) Lifecycle-Optimized V2G Scheduling: Development of multi-objective optimization algorithms that balance V2G service revenue, battery degradation costs, renewable energy utilization, and grid stability objectives over the EV operational lifetime.

XII. CONCLUSION

This review paper has presented a comprehensive analysis of smart EV charging technologies, encompassing V2G and G2V operational principles, renewable energy integration strategies, communication and power electronic infrastructure, Phase-Locked Loop synchronization techniques, Virtual Synchronous Generator control architectures, and hybrid PLL–VSG frameworks. The critical review of recent literature underscores the transformative potential of smart EV charging in enabling flexible, resilient, and sustainable modern power systems.

VSG control effectively addresses the inertia deficiency and stability challenges arising in inverter-dominated grids, while PLL techniques ensure accurate grid synchronization and enable smooth operational mode transitions. The combined application of PLL and VSG control within a hybrid architecture provides a robust and practically viable framework for efficient EV–grid interaction across the full range of grid operating conditions.

Despite significant research progress, the practical realization of large-scale PLL–VSG-based smart EV charging infrastructure requires sustained effort in experimental validation, standardization, cybersecurity, and lifecycle optimization. Addressing these challenges will be essential for unlocking the full potential of EV fleets as active, grid-supporting resources in the transition toward decarbonized and intelligent energy systems.

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