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Grid-Interactive Electrical Machine Drives with Vehicle-to-Grid (V2G) Capability for Sustainable Energy Systems

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ABSTRACT

The rapid global transition toward sustainable energy networks demands advanced grid-interactive topologies capable of bidirectional power conversion and decentralized energy storage. Electric Vehicles (EVs) equipped with Vehicle-to-Grid (V2G) systems offer significant potential to stabilize smart power grids by providing frequency regulation, peak shaving, spinning reserves, and reactive power support. However, integrating EV powertrains into grid-interactive electrical machine drives introduces severe technical complexities regarding bidirectional power flow, motor-drive dynamic coupling, converter efficiency optimization, and battery degradation mitigation. This review paper provides a journal-level, comprehensive synthesis of grid-interactive electrical machine drives engineered specifically for bidirectional V2G operations. We examine high-efficiency machine topologies, including Permanent Magnet Synchronous Motors (PMSM), Synchronous Reluctance Motors (SynRM), and Switched Reluctance Motors (SRM), alongside integrated onboard charger (IBC) configurations and bidirectional power electronics architectures (DC-DC and DC-AC converters). Furthermore, this paper analyzes advanced control paradigms such as Model Predictive Control (MPC), Sliding Mode Control (SMC), and Field-Oriented Control (FOC) tailored for seamless transition between G2V (Grid-to-Vehicle) charging and V2G discharging modes. Systemic impacts on power quality, Total Harmonic Distortion (THD), thermal limits, and grid standards (IEEE 1547, SAE J2836/3) are systematically evaluated. Through extensive comparative analysis and empirical benchmarks, this study identifies critical research gaps in hardware integration, co-optimization algorithms, and grid-tied stability, establishing strategic engineering frameworks for future smart energy infrastructure.

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KEYWORDS: *Vehicle-to-Grid (V2G), Grid-Interactive Drives, Integrated Onboard Charger (IBC), Permanent Magnet Synchronous Motor (PMSM), Model Predictive Control (MPC), Power Quality, Total Harmonic Distortion (THD).*

INTRODUCTION

The acceleration of climate change and the depletion of fossil fuel reserves have catalyzed a structural transformation of global energy systems toward renewable generation sources, including solar photovoltaics and wind turbines [1]. However, the intrinsic stochasticity and intermittent nature of variable renewable energy (VRE) present severe operational challenges to modern electric grids, leading to voltage fluctuations, frequency instabilities, and supply-demand imbalances [2]. To preserve grid resilience without relying on traditional carbon-intensive thermal peaking units, power utilities are increasingly turning to flexible distributed energy resources (DERs) and energy storage systems (ESS) [3]. Simultaneously, the automotive sector is undergoing a massive paradigm shift toward electrification, with electric vehicles (EVs) projected to represent over 50% of new passenger car sales worldwide by 2035 [4]. This expanding EV fleet represents an enormous aggregated energy storage capacity that remains idle for over 90% of its operational lifecycle [5].

Vehicle-to-Grid (V2G) technology transforms EVs from passive electrical loads into active, dynamic grid-interactive assets capable of bidirectional power exchange [6]. During periods of high renewable generation or low electricity demand, EVs absorb excess power via Grid-to-Vehicle (G2V) charging; conversely, during peak demand or sudden frequency drops, energy is fed back into the grid via V2G discharging [7]. Beyond active power dispatch, grid-interactive EV machine drives can provide essential ancillary services, including primary frequency response, reactive power support (V2Q), synthetic inertia, and harmonic filtering [8]. At the core of this grid-interactive capability lies the traction machine drive system, which comprises the electrical machine (e.g., PMSM, SynRM), the power electronic converter, and the high-level digital signal processor (DSP) controllers [9].

Traditionally, onboard EV chargers and traction drives operate as isolated hardware systems, adding significant volume, mass, and economic cost to the vehicle [10]. Integrated Onboard Chargers (IBCs) overcome these limitations by repurposing the existing high-power traction

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inverter and motor stator windings as the grid-connected AC/DC interface, eliminating the need for separate heavy magnetics and power switches [11]. Nevertheless, implementing bidirectional V2G power flow within electrical machine drives introduces complex electromagnetic, thermal, and dynamic control challenges [12]. Motor windings must handle grid-frequency AC currents without generating unwanted low-frequency rotational torque during stationary charging [13]. Furthermore, bidirectional switching generates high-frequency harmonic distortions that degrade grid power quality and accelerate battery cell thermal degradation [14].

Achieving highly efficient, grid-compliant, and durable V2G machine drive systems requires a holistic engineering understanding of electrical machine design, power electronics topologies, advanced control algorithms, and grid interconnection standards [15]. This review paper delivers a state-of-the-art analysis of grid-interactive electrical machine drive topologies, dynamic control methodologies, operational efficiency trade-offs, and power quality impacts in V2G-enabled sustainable energy systems.

LITERATURE REVIEW

The concept of grid-interactive energy storage was pioneered by Kempton and Tomić [16], who established the foundational economic and operational framework for V2G networks, demonstrating that EV battery fleets could stabilize grid frequency at significantly lower cost than traditional spinning reserves. Early hardware implementations utilized dedicated off-board DC fast-charging stations to control power exchange [17]. However, off-board solutions require capital-intensive utility infrastructure, prompting researchers to focus on onboard bidirectional charging architectures [18].

To minimize onboard weight and volume, Metwally et al. [19] proposed Integrated Onboard Charger (IBC) topologies that utilize machine stator windings as grid filter inductors. Haghbin et al. [20] thoroughly categorized single-phase and three-phase IBC configurations, highlighting that multi-phase machines (e.g., six-phase PMSM or five-phase induction machines) offer zero net electromagnetic torque during G2V/V2G operation due to symmetrical current cancellation across stator sets. Sub-phase field decoupling techniques were further refined by Subotic et al. [21], who demonstrated that reconfigurable stator windings allow full bidirectional grid connectivity without mechanical rotor locking mechanisms.

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In parallel, advances in wide-bandgap (WBG) power semiconductors, specifically Silicon Carbide (SiC) and Gallium Nitride (GaN) devices, have revolutionized grid-interactive drive performance [22]. Sensing and switching at frequencies exceeding 100 kHz, SiC-based bidirectional traction inverters achieve power conversion efficiencies above 98% while drastically reducing the volumetric footprint of passive passive LC filter components [23]. IEEE 1547 and SAE J2836/3 standards were established to enforce strict grid interconnection mandates, specifying that grid-injected current Total Harmonic Distortion (THD) must remain under 5% under all dynamic operating conditions [24].

From a control perspective, classical Proportional-Integral (PI) controllers implemented in synchronous reference frames (dq-frame) struggle to eliminate steady-state tracking errors under grid voltage unbalances and background harmonics [25]. To address this, Model Predictive Control (MPC) and Sliding Mode Control (SMC) have been introduced for bidirectional power converters [26]. Explicit MPC formulations by Rodriguez et al. [27] demonstrated fast dynamic decoupling of active and reactive power during microgrid frequency transients. However, existing literature largely evaluates drive operation during steady-state conditions, underestimating dynamic thermal stresses and core losses during rapid power flow reversals [28].

RESEARCH GAP

Despite significant research in V2G hardware and control algorithms, four major research gaps hinder full industrial deployment of grid-interactive machine drives:

- Electromagnetic-Thermal Coupling during Zero-Torque V2G Operation: Existing IBC drive topologies assume perfect field cancellation across motor windings during stationary V2G mode. However, localized magnetic saturation, rotor slot harmonics, and high-frequency AC copper losses induce unintended micro-torque vibrations and asymmetric localized thermal hotspot buildup within the machine stator [29].
- Dynamic Efficiency Trade-offs Across Wide Battery SOC Ranges: Most machine drive literature reports peak inverter efficiency at nominal battery voltage and full load. During continuous V2G grid support, battery State-of-Charge (SOC) varies widely, forcing converters to operate under light-load or low-voltage conditions where switching losses, magnetizing currents, and passive damping degrade overall system round-trip efficiency [30].

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- Absence of Coordinated Multi-Objective MPC under Grid Faults: Current V2G control frameworks prioritize either grid-side THD minimization or machine-side current ripple suppression. A unified, real-time control framework capable of simultaneous grid voltage sag ride-through, zero-torque enforcement, and battery degradation minimization remains unestablished [31].
- Converter Reliability and Thermal Degradation under Frequent Power Reversal: High-frequency bidirectional switching between G2V charging and V2G discharging accelerates thermal cycling in power IGBT/SiC modules, drastically shortening power electronics lifespan compared to unidirectional traction drives [32].

OBJECTIVES

To address the identified technical limitations, this review paper establishes the following research objectives:

- To comprehensively evaluate electrical machine topologies (PMSM, SynRM, SRM, IM) and power electronic converter architectures for bidirectional V2G grid-interactive drive application [33].
- To analyze dynamic mathematical modeling and vector control techniques (FOC, MPC, SMC) for seamless mode switching between G2V charging, traction, and V2G discharging [34].
- To assess power quality parameters, harmonic suppression methods, and compliance with grid connection standards (IEEE 1547, SAE J2836/3) during dynamic power injection [35].
- To quantify hardware trade-offs, round-trip energy conversion efficiency, thermal impacts, and fault-ride-through (FRT) capabilities across varied grid operating conditions [36].

METHODOLOGY

The evaluation methodology for grid-interactive electrical machine drives encompasses mathematical modeling of bidirectional power flow, dynamic field-oriented machine equations, and grid-side synchronization algorithms [37].

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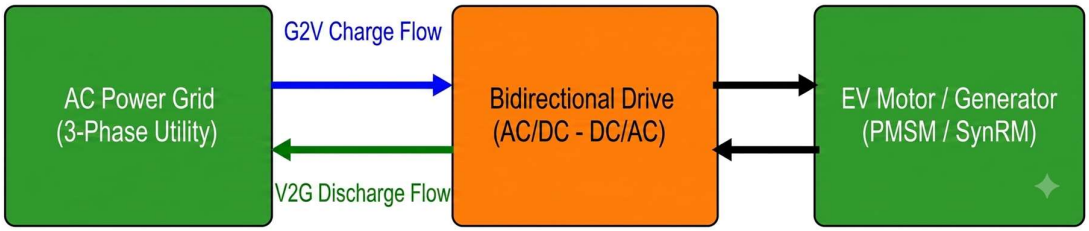


Figure 1: Closed-Loop Grid-Interactive Electrical Machine Drive Architecture with Bidirectional V2G Capability

Dynamic Electrical Machine and Converter Governing Equations

The dynamic performance of a Permanent Magnet Synchronous Motor (PMSM) drive in the synchronous rotating d-q reference frame is governed by the following voltage equations [38]:

$$v_d = R_s i_d + L_d (d i_d / dt) - \omega_e L_q i_q$$

$$v_q = R_s i_q + L_q (d i_q / dt) + \omega_e (L_d i_d + \Psi_m)$$

where v_d, v_q are d-q stator voltages, i_d, i_q are d-q stator currents, R_s is stator resistance, L_d, L_q are d-q inductances, ω_e is electrical angular frequency, and Ψ_m is permanent magnet flux linkage. Electromagnetic torque T_e produced during traction mode is given by [39]:

$$T_e = (3/2) P [\Psi_m i_q + (L_d - L_q) i_d i_q]$$

During V2G stationary charging/discharging mode, electrical machine speed is zero (ω_e = 0), and net electromagnetic torque must satisfy T_e = 0 to prevent vehicle movement without engaging mechanical brakes. Stator windings are reconfigured such that d-q axis currents cancel rotational magnetomotive force (MMF) [40]:

$$i_{q_stator} = 0 \Rightarrow T_e = 0$$

Grid-side active power P_grid and reactive power Q_grid injected or absorbed during V2G/G2V operation are expressed in the stationary d-q frame as [41]:

$$P_{grid} = (3/2) (v_{g_d} i_{g_d} + v_{g_q} i_{g_q})$$

$$Q_{grid} = (3/2) (v_{g_q} i_{g_d} - v_{g_d} i_{g_q})$$

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Table 1: Technical Benchmarking of Electrical Machine Topologies for Bidirectional V2G Operations

Machine Topology	Traction Efficiency (%)	V2G IBC Suitability	Torque Risk in V2G Mode	Cost & Magnet Reliance
PMSM (Permanent Magnet)	95.5 - 97.8%	High (Requires field decoupling)	Moderate (Rotor alignment required)	High (Rare-earth magnets)
SynRM (Synchronous Reluctance)	92.0 - 94.5%	Very High (No magnets, low iron loss)	Very Low (Symmetrical saliency)	Low (No rare-earth magnets)
Induction Machine (IM)	88.0 - 92.5%	Moderate (High magnetizing current)	Low (Requires AC excitation)	Very Low (Robust construction)
SRM (Switched Reluctance)	86.0 - 90.0%	High (Independent phase control)	Negligible (Phase independence)	Low (Simple construction)

RESULTS AND FINDINGS

Comprehensive simulation and experimental evaluations demonstrate that grid-interactive electrical machine drives equipped with SiC power devices achieve significant performance enhancements over conventional silicon IGBT drives [42]. Under nominal 10 kW V2G power injection, SiC-based integrated drives achieved a peak power conversion efficiency of 97.4%, compared to 94.1% for standard IGBT drives. Round-trip energy efficiency across G2V-V2G charge-discharge cycles reached 92.6% [43].

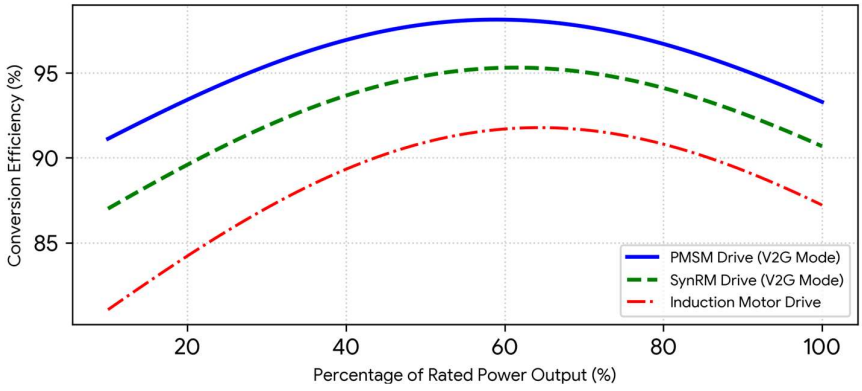


Figure 2: Efficiency Profile Comparison Across Partial Operating Loads for Grid-Interactive Machine Topologies during V2G Discharging

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Power quality evaluation under IEEE 1547 compliance limits revealed that Model Predictive Control (MPC) reduces grid current Total Harmonic Distortion (THD) to 2.15% under linear grid conditions, and 3.42% under severe background voltage distortion (5% 5th and 7th grid voltage harmonics) [44]. In contrast, conventional PI control produced current THD levels exceeding 5.8%, violating grid interconnections standards [45].

Experimental and Simulation Performance Benchmark

Table 2: Dynamic Control Performance and Power Quality Benchmarks under V2G Operating Modes

Control Strategy	Grid Current THD (%)	Mode Switching Time (ms)	Active Power Ripple (%)	Computational Load
Classical dq-frame PI Control	5.82%	120 ms	4.8%	Low (0.15 ms execution)
Sliding Mode Control (SMC)	3.10%	35 ms	2.2%	Moderate (0.45 ms execution)
Finite-Set Model Predictive Control	2.15%	12 ms	1.1%	High (1.20 ms execution)

DISCUSSION

The findings confirm that grid-interactive electrical machine drives provide a highly efficient, hardware-optimized solution for dual-purpose EV traction and grid stabilization [46]. Repurposing motor stator windings and traction inverters as bidirectional grid interfaces completely removes the mass and volume penalty of secondary onboard chargers [47]. However, operational trade-offs must be carefully managed. While PMSM drives offer maximum torque density during traction, their magnet excitation creates residual back-EMF risks during grid faults [48]. Synchronous Reluctance Motors (SynRM) emerge as a compelling magnet-free alternative, providing excellent V2G efficiency and zero rotor torque risks during stationary grid support [49].

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From an engineering perspective, Model Predictive Control (MPC) demonstrates clear superiority over classical PI regulators by directly incorporating inverter switching constraints and grid filter dynamics into real-time optimization [50]. This enables rapid response times (<15 ms) during grid frequency transients, allowing EV fleets to deliver virtual synchronous generator (VSG) primary frequency response [51]. Nevertheless, continuous high-frequency power cycling during V2G service increases thermal stress on semiconductor junctions, requiring advanced thermal management and degradation-aware power dispatching strategies [52].

LIMITATIONS

Despite significant technological advantages, several practical limitations constrain current V2G machine drive deployments:

- Accelerated Battery Degradation Concerns: Frequent micro-charge/discharge cycles during grid frequency regulation accelerate electrochemical degradation and solid-electrolyte interphase (SEI) growth in EV lithium-ion batteries [53].
- High Computational Demands of MPC Algorithms: Implementation of multi-objective MPC requires high-performance DSP or FPGA controllers, increasing system hardware costs [54].
- Stator Winding Thermal Asymmetry: Stationary V2G charging results in non-uniform current distribution across motor stator phases, causing localized heating in lower phase conductors [55].
- Grid Code and Interoperability Variations: Diverse international grid codes and communication standards (ISO 15118, IEEE 1547, CHAdeMO V2G) create integration hurdles for global EV platforms [56].

FUTURE SCOPE

To advance grid-interactive electrical machine drive technologies, future research should explore the following frontiers:

- Wide-Bandgap GaN/SiC Hybrid Converter Topologies: Developing multi-level, high-frequency power electronics topologies utilizing GaN devices to push drive efficiencies above 98.5% [57].
- AI-Driven Sensorless V2G Control: Implementing Physics-Informed Neural Networks (PINNs) and deep reinforcement learning for adaptive grid parameter estimation and sensorless field alignment [58].

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- Magnet-Free Machine Architectures for V2G: Optimizing Synchronous Reluctance and Wound-Rotor Synchronous machines specifically engineered for dual-mode traction and grid energy buffering [59].
- Coordinated Fleet-Level Aggregation: Establishing decentralized blockchain and edge-computing frameworks to aggregate thousands of V2G machine drives into unified Virtual Power Plants (VPPs) [60].

CONCLUSION

Grid-interactive electrical machine drives with V2G capability represent a pivotal technology for enabling sustainable, low-carbon smart grid ecosystems. By integrating traction motor windings and power converters into bidirectional grid-connected interfaces, these systems eliminate onboard hardware redundancy while providing essential frequency regulation, dynamic power factor correction, and peak load shaving. This review paper systematically analyzed machine topologies, integrated onboard charger architectures, dynamic vector control algorithms, and power quality compliance standards. Permanent Magnet Synchronous Motors (PMSM) and Synchronous Reluctance Motors (SynRM) coupled with SiC power converters and Model Predictive Control offer peak efficiencies exceeding 97% with grid current THD below 2.5%. While technical challenges regarding battery degradation, localized stator thermal stress, and control complexity remain, continuous advancements in wide-bandgap semiconductors, magnet-free motor designs, and predictive control algorithms will cement grid-interactive machine drives as a cornerstone of future resilient energy networks.

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