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SURVEY

Electric Vehicle Integration With Grid-Forming Capability in Renewable-Powered Microgrids: A Survey and Future Perspectives

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ABSTRACT In recent years, electric vehicles (EVs) are increasingly recognized as flexible energy resources that can provide ancillary services to renewable energy sources-based microgrids (MGs), particularly when operated under grid-forming (GFM) control techniques. However, realizing this potential requires developments across several layers, including EV charger architectures, storage systems coordination, and hierarchical MG control. This paper brings these developments together. It reviews recent advancements in hybrid energy storage systems, converter topologies for on-board and off-board EV chargers, advanced control and energy management systems, vehicle-to-grid implementations, and EV-interactive MG operation. It also provides a comparative assessment of three proposed GFM-based EV-MG integration schemes in terms of GFM resource availability, active power exchange capacity, efficiency, infrastructure cost, and ancillary service potential. Major open research challenges and promising directions are discussed at the end.

INDEX TERMS Electric vehicle charging, grid-forming control, microgrids, vehicle-to-grid, renewable energy sources.

I. INTRODUCTION

In response to the global shift toward sustainable energy, renewable energy sources (RESs)-based microgrids (MGs), which integrate local generation, energy storage systems (ESSs), and controllable loads under an intelligent control scheme, are being increasingly used. MGs can operate either connected to the main grid or in islanded mode, seamlessly transitioning between the two modes [1], while supporting autonomous functions such as black-start [2], islanding detection [3], and resynchronization with the grid after disturbances. Another defining feature is the scalability, with deployments ranging from small-scale or building-level systems, commonly referred to as nanogrids [4], to much larger installations designed for residential [5], industrial [6], railway power systems [7], maritime [8], and space applications [9].

In this evolving domain, the increasing use of electric vehicles (EVs) introduces both opportunities and challenges for MG operation. With global EV sales exceeding 17 million in 2024 [10], uncontrolled charging can overload local grids and reduce power quality. When integrated with RES-powered MGs, EV charging stations (EVCSs) can influence system stability and flexibility, extending beyond simple energy consumption. Advanced on-board and off-board charging topologies, along with intelligent energy management systems (EMSs), allow for coordinated charging schedules, bidirectional grid-to-vehicle (G2V) and vehicle-to-grid (V2G) operation, and improved storage lifetime.

However, the increasing interaction between RES-based MGs and EV charging systems requires the use of power electronic interfaces, which makes it difficult for conventional grid-following (GFL) control techniques to operate effectively, especially under weak grids or islanded conditions. Grid-forming (GFM) control has emerged as a major solution, allowing inverters to establish voltage and frequency references autonomously, while providing fast dynamic response, robust frequency damping, and black-start capability [11], [12], without requiring phase-locked loops (PLLs) or external grid reference signals.

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Given the current research interest in the aforementioned subjects, this paper synthesizes developments in RES-based MGs, EV charging systems, and advanced control schemes, highlighting the role of GFM control techniques and EV charging integration architectures in enhancing the performance of EV-integrated MGs. Furthermore, the paper proposes solutions to increase RES penetration in EV charging systems and to better leverage EV charging infrastructure to enhance MG operation. The rest of the paper is organized as follows: Section II introduces the recent developments in RES-based MGs, covering typical AC, DC, hybrid MG architectures, RES integration, hybrid energy storage system (HESS) solutions (with a focus on battery-supercapacitor HESS), and classification of advanced control techniques. Section III details advancements in EV charging systems, including EV charger classifications, state-of-the-art on-board charger (OBC) and off-board charger (OFBC) converter topologies (with comparative double-stage summaries), EMSs for EV-MG integration, and V2G solutions in both AC and DC MGs. Section IV presents the advancements in GFM control within the context of EV-integrated MGs, reviewing recent GFM-based EV-MG integration solutions in literature, as well as specific architectural schemes for integrating GFM-controlled EVs into RES-based MGs. Section V outlines open research challenges and future directions. And finally, Section VI concludes the paper.

II. RECENT DEVELOPMENTS IN RES-BASED MGS

Practical MGs are best realized as integrated systems in which energy sources, storage devices, and loads are interfaced via power conversion and protection hardware and managed by hierarchical control and communication systems.

The ongoing transition from large synchronous generators to power electronics-dominated converters has motivated extensive research and development on wide-bandgap semiconductor technologies, modular multilevel converter topologies, and GFM control techniques, to ensure stable and reliable MG operation [13]. Such evolution has shifted the attention from centralized toward decentralized and distributed control schemes, which align more closely with the modular and uncertain nature of highly RES-penetrated MGs, while reducing the overall control complexity and communication needs [14], [15].

Another important evolution is the transformation of EVs from passive loads to MG-interactive components that provide ancillary services at the converter and MG levels [16], while also contributing to EMSs [17].

A. MG ARCHITECTURES OF INTEREST

The configuration of MG determines its operational characteristics and complexity for specific applications. Each configuration presents various advantages and challenges that must be carefully considered. Block diagrams of the typical structures of AC, DC, and hybrid MGs are depicted in Fig. 1.

Among existing configurations, AC MGs remain the most mature and widely used configuration due to their compatibility with the existing AC power infrastructure and the availability of standardized protection and power-electronic interfaces. AC MG control approaches are based on GFL, GFM, and grid-supporting (GS) technologies [18].

Now, alongside the continued use of two-level voltage source converters, modular multilevel converters are increasingly explored in medium- and high-power MG applications. These architectures reduce voltage stress on individual devices, improve waveform quality and enable scalability through submodule and parallel connectivity, while optimizing current sharing and system efficiency [19]. Despite these advances, AC MGs still face challenges such as synchronization during grid reconnection [18], fast voltage and frequency regulation under high penetration of inverter-based resources [20], circulating currents in parallel inverters [21], and harmonic distortion from power electronic converters and nonlinear loads [22].

DC MGs are gaining attention for their efficiency advantages, as they eliminate redundant DC-AC conversion for local renewables, storage units, and EVs. From an architectural perspective, a DC MG can be either unipolar or bipolar [23]. Unipolar DC MGs use a two-wire configuration that provides a single DC voltage level, whereas bipolar DC MGs introduce a neutral conductor, allowing for multiple DC voltage levels within the same system.

In low-voltage systems, PV, storage, and loads are typically interfaced with the DC bus by using non-isolated bidirectional DC-DC converters, such as buck/boost and interleaved converters, due to their simplicity and high efficiency [24]. Isolated bidirectional topologies, particularly the dual active bridge (DAB) and its variants, have received significant attention in recent years because of their galvanic isolation and excellent suitability for high-power EV charging applications [25]. Recent studies emphasize modular swarm-based designs [26] that enable organic scaling from single-home PV systems to interconnected multi-MGs while maintaining safety and stability across increasingly demanding voltage levels and power capacities. However, DC MGs must address voltage regulation issues under constant power loads, fault protection under non-zero crossing currents, and grounding/EMC trade-offs [24], [27].

Hybrid MGs connect AC and DC buses using interlinking converters (ILCs), resulting in more flexible power flow, isolation, and improved power quality. Modern ILC designs, including multi-port and partially-rated topologies [28], allow for direct connection of multiple resources, reduce converter ratings, and improve fault tolerance. Hybrid MGs maximize flexibility by connecting AC and DC sources and loads, which reduces conversion stages and improves efficiency, but they require complex control and protection schemes, as well as higher costs due to ILCs.

B. RES INTEGRATION

Currently, photovoltaic (PV) energy is regarded as one of the most promising RESs, alongside wind turbine (WT) energy, not only due to its continuous decline in cost, but also because

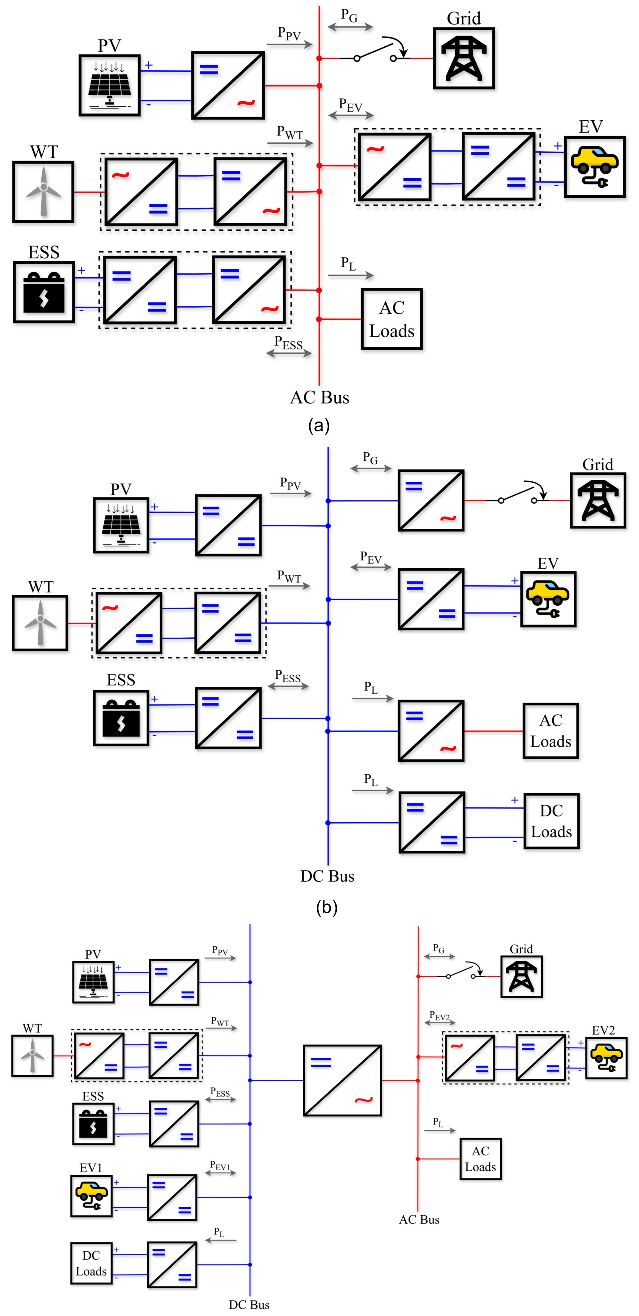


FIGURE 1. Typical structure of a RES-based MG: (a) AC, (b) DC, (c) Hybrid.

of its strong alignment with net zero emission targets and 100% renewable scenarios by 2050 [29]. However, using PV panels as a single source is not practical, and thus MGs that integrate multiple sources are commonly implemented, as they can handle the intermittency. A case study in this regard is shown in [30], where a hybrid system consisting of diesel, wind, PV, EVs is used, noting that EVs can act as both flexible loads and distributed storage units when coordinated under the EMS. Likewise, authors in [31] demonstrate that integrating fuel cells into an islanded wave-PV MG allows the system to respond effectively to unexpected environmental conditions, while sustaining continuous power delivery.

Looking at the most recent research trends, advanced forecasting and control techniques are becoming more essential for RES integration in MGs. Fuzzy logic (FL) controllers [32], model predictive control (MPC) [33], and AI-based forecasting [34] are being used to handle the multi-timescale variability in daily solar and wind production. These methods aim to minimize forecast error and maintain both economic dispatch and operational stability.

C. ADVANCED ESS FOR MGS

ESSs in MGs have evolved from passive energy buffers into active components that participate in voltage and frequency regulation in both grid-connected and islanded modes [1], while also reducing operational costs by shifting renewable energy to high-value periods [35].

To avoid excessive oversizing and fast degradation associated with single-technology storage, HESSs are increasingly being used in recent MG developments. Among various configurations, battery-supercapacitor HESSs [36], [37], [38], [39], [40], [41] have received particular attention due to their complementary characteristics, where the high-energy battery manages slow and sustained energy transfers, while the high-power supercapacitor absorbs fast and transient power fluctuations. Other HESS configurations, such as battery-hydrogen [42] and battery-flywheel systems [43], have also been investigated in the literature.

The integration of HESS with RES-based MGs requires advanced control and optimization techniques combined with robust EMS algorithms. Table 1 summarizes recent works on battery-supercapacitor HESS integration. Coordinated control using FL, genetic algorithm, MPC, and droop-based EMSs, has been widely used to address fast power balancing and voltage stability in AC and DC MGs.

TABLE 1. Comparative summary of recent battery-supercapacitor HESS solutions for MG applications.

Ref.	MG Type	RES	Control Technique	Performance Gains
[36]	DC	PV	FL controller	Effective power sharing; uncertainties handling.
[37]	DC	PV	“Pontryagin’s Minimum Principle”-based EMS	Longer HESS lifetime; cost savings.
[38]	AC	PV + WT	Two-layer control (MPC-based + FL)	Power fluctuation mitigation; longer HESS lifetime.
[39]	DC	PV	Decoupled control (k-type lead compensator and nonlinear PI)	Improved voltage regulation; faster transient response; longer HESS lifetime.
[40]	DC	Fuel cell	Modified droop-based EMS	Dynamic power sharing; bus voltage regulation.
[41]	DC	Wave	Genetic algorithm	Optimal cost and sizing; longer HESS lifetime; peak power handling.

The optimal sizing and placement of ESSs in MGs must include frequency stability constraints beyond economic criteria, with rate-of-change-of-frequency (RoCoF), frequency nadir, and steady-state deviation considered in planning. In [44], a mixed-integer linear programming (MILP) method, combined with a discretized swing equation model, is used to ensure that battery ESS deployments meet nadir, RoCoF, and steady-state frequency limits while optimizing system performance. The impact of battery ESS placement on fast frequency response is investigated in [45], where mitigation of frequency nadir and RoCoF events is achieved by integrating a location-dependent weighting term into a distributed controller based on the "Alternating Direction Method of Multipliers". Further evidence that optimal ESS sizing and placement enhance grid stability and resilience is provided in [46], where a metaheuristic approach based on the "Binary Grey Wolf Optimizer" is used.

D. ADVANCED MG CONTROL TECHNIQUES

The MG concept is increasingly seen as a multi-layered architecture, where physical power conversion and distribution are coordinated by real-time control loops and supervisory energy management functions [47]. An MG's hierarchical control architecture is based on three control layers, primary, secondary, and tertiary, that operate at different time scales [15]. At the primary level, inverter controllers use local measurements to regulate voltage and frequency and enable decentralized power sharing, typically through droop-, virtual synchronous machine (VSM)-, or virtual oscillator control (VOC)-based schemes in AC MGs, and V-I droop control in DC MGs [48].

While primary control is simple and robust, it introduces steady-state deviations in voltage and frequency. Secondary control operates on a slower timescale to compensate for these deviations and restore nominal operating points. It is commonly implemented using centralized or distributed architectures, where centralized schemes provide accurate restoration but require reliable communication, whereas distributed approaches, such as consensus-based algorithms, rely on each inverter communicating only with its neighbors in order to achieve global control objectives.

Above the secondary layer, tertiary control addresses coordination and economic objectives by computing optimal power references for distributed energy resources (DERs), storage units, and loads using optimization-based techniques such as optimal power flow [49], convex programming [50], and MILP formulations [51].

Within this hierarchical MG control architecture, several advanced control schemes have been proposed to overcome the limitations of conventional linear controllers. Nonlinear techniques such as sliding mode control (SMC), disturbance-observer-based control, data-driven control, MPC, direct power control, and passivity-based control have been applied to provide superior multi-objective handling, dynamic performance, and disturbance rejection capabilities compared to linear approaches [52]. Advanced controllers have also been shown to improve converter robustness and control bandwidth when replacing conventional cascaded PI structures, with model-based and data-driven methods offering complementary benefits in handling uncertainties and V-I coupling constraints [53].

A clear trend in recent literature is the increasing use of AI and data-driven control approaches due to uncertainties in loads and RES generation, with artificial neural networks (ANNs), FL, and support vector machines being applied in forecasting, energy management, and converter-level control tasks [47].

Accordingly, advanced MG control techniques can be classified into three major groups: model-based control, VOC, and smart control, as depicted in Fig. 2.

1) MODEL-BASED CONTROL

Model-based control techniques depend on physical or mathematical representations of converters, storage units, and loads, making them great choices for ensuring stability, handling constraints, and multi-objective optimization in terms of voltage, frequency, and power quality.

Among these techniques, MPC is widely used due to its ability to forecast system behavior, including predicted load demand, RES generation, and energy costs, while integrating a feedback mechanism that enhances robustness against uncertainty and forecast errors. Since MG management involves both continuous dynamics, such as ESS charging/discharging rates, and discrete decisions, such as the ON/OFF states of DERs or controllable loads, MPC is typically formulated through an MILP method [54], which allows efficient solution with commercial solvers without the need for complex heuristics or decomposition methods.

Beyond centralized, long-term economic optimization, MPC has been applied in real-time distributed control for heterogeneous DERs to reduce frequency deviations, while optimizing the operational cost of controllable devices [55]. In the same secondary level, a distributed MPC technique is used in [56] to regulate DC voltage and maintain accurate power sharing between energy storage units, considering physical voltage bounds and addressing communication delays through an improved formulation.

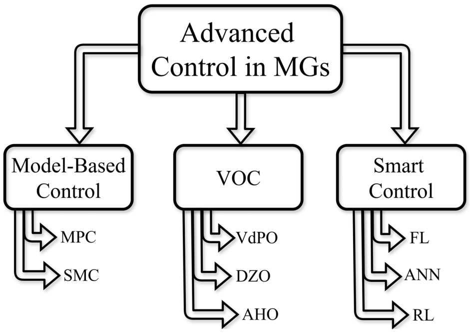


FIGURE 2. A classification of advanced control techniques in RES-based MGs.

On the other hand, SMC is a nonlinear control technique that basically pushes system states toward a predefined sliding surface and maintains them there despite disturbances or parametric uncertainties.

In islanded MGs, an adaptive SMC design is applied in [57], for voltage regulation to mitigate load-induced nonlinearities and external disturbances from heterogeneous, uncertain loads, using sliding surfaces defined by proportional, integral, and derivative terms of the voltage error, combined with tracking and switching components to ensure robust tracking. The suggested control technique in [58] uses a cascaded structure, where the SMC operates in the inner loop to provide fast and robust regulation while implementing a fixed switching frequency, which is often challenging in conventional SMC techniques.

At the secondary control level, SMC with predefined stability is used in [59] to restore frequency in a low-inertia heterogeneous power system that integrates VSM-based GFM storage converters and GFL WT converters. This ensures predefined stability, but the main trade-off is the added design complexity.

2) VIRTUAL OSCILLATOR CONTROL

VOC variants, including the Van der Pol oscillator (VdPO), the dead-zone oscillator (DZO), and the Andronov-Hopf oscillator (AHO), are time-domain models in which a GFM inverter is controlled to behave like a self-sustained electrical oscillator. By integrating these dynamics directly into the controller, the inverter establishes voltage waveforms, synchronizes with parallel-connected units, and shares power through local interactions, without the need for phasor calculations or communication networks [60]. These capabilities make VOC more suitable for low-inertia MGs than droop-based schemes.

In a foundational work [61], the VdPO was introduced as a weakly nonlinear oscillator that can be used to achieve stable inverter operation in islanded MGs using its inherent synchronization properties. By coupling an LC resonator with a negative conductance and a cubic voltage-dependent current source, the VdPO provides robust terminal voltage dynamics that link directly to active and reactive power outputs. Moreover, the VdPO shows local exponential stability, with small-signal analyses confirming the stability of the high-voltage equilibrium and robustness to disturbances and parameter variations.

Recent work in [62] enhances VdPO performance through the integration of inner proportional multi-resonant controllers for better sinusoidal tracking and selective harmonic compensation, as well as PI-based power-limiting mechanisms to enforce active/reactive power limits while maintaining balanced load sharing. A new VdPO is presented in [63], which is applied in hybrid MGs to manage power sharing among PV, WT, and HESS sources, exploiting its decentralized operation and fast dynamic response.

An important contribution to VOC-based GFM control is presented in [64], where the DZO was introduced as the primary mechanism to achieve communication-free synchronization of parallel inverters. The DZO's structure is similar to that of the VdPO and includes a passive RLC resonator combined with piece-wise constant nonlinearity [60]. Furthermore, the DZO guarantees global asymptotic synchronization, with sufficient stability conditions independent of network size and load, alongside the limit-cycle stability and robustness [64].

The AHO improves upon limitations of earlier VOC variants by producing a perfectly sinusoidal limit cycle and enabling fully dispatchable P/Q [65]. Its dynamics allow relationships for $P - \omega$ and $Q - V$ control, allowing AHO parameters to be tuned to meet transient response and steady-state regulation requirements.

Recent developments address conventional AHO limitation, where P and Q controls are coupled, by introducing dynamic voltage references with integral corrections to track P/Q references simultaneously without steady-state errors [66], [67]. In single-phase MGs, an AHO control implementation has been proposed [68], where the oscillator's state variables provide voltage amplitude and frequency references for parallel inverters, achieving communication-free synchronization, robust load sharing, and fast transient response. The work in [69] integrates a quasi-PR controller into the AHO's input current loop to provide virtual inertia and damping, resulting in reduced RoCoF and power overshoot in islanded and grid-connected modes, respectively.

The transient stability improvement for AHO under grid faults is realized in [70], by adding a voltage magnitude term, which changes the reactive power droop coefficient from decreasing to increasing. This modification reduces grid voltage sags, increases the stable operating region, and enables the converter to stabilize in an overdamped state. To compensate for inverter non-idealities such as dead-time effects and device voltage drops, authors in [71] introduce a dual-loop structure, where the AHO provides the primary voltage reference regulated by an outer PI voltage loop, and an inner PI current loop, ensuring accurate voltage and current tracking, while preserving $Q - V$ droop characteristics.

3) SMART CONTROL

Smart control classification includes FL, ANN, and reinforcement learning (RL), as they provide capabilities beyond classical model-based or VOC-based schemes. These techniques are increasingly integrated with other control methods and applied across hierarchical MG layers, making them highly relevant for future MG applications. However, these advantages come with trade-offs in terms of higher computational complexity, training effort, and high sensitivity to data quality and generalization.

FL does not require complex mathematical models and allows for adaptive handling of nonlinear MG dynamics via rule-based parameter tuning. Applications of FL control include MG EMSs, where inputs such as battery state of charge (SOC) deviation and power imbalance are used to determine the output charge/discharge current via fuzzy rules [72]. Beyond EMS applications, FL has been extended to MG dynamic control, where it is used to dynamically adjust the inertia and damping parameters of VSMs [73], [74].

More recent studies integrate FL with advanced control schemes, such as FL-MPC for distributed secondary frequency and voltage regulation, where FL dynamically adjusts cooperative control coefficients [75], and FL-based tuning of VOC parameters to maintain voltage regulation and reduce total harmonic distortion (THD) under variable load conditions [76].

ANN are data-driven models capable of learning nonlinear input-output relationships from historical or synthetic data, making them suitable for MGs with diverse RESs and uncertain grid conditions.

A major trend in recent MG research is using ANN to replicate the optimal actions of computationally expensive controllers, such as MPC [77], [78], [79]. In [77], an ANN-based current controller for a single-phase grid-connected inverter is developed, where the ANN is trained offline using data from a supervisory MPC scheme and deployed in real time, significantly reducing calculations. This online computational reduction is also achieved in [78], where an ANN-based MPC is applied for a three-phase islanded inverter, resulting in fast voltage and current control under various load conditions. Similarly, the work in [79] introduces a physics-informed ANN current controller trained using PI-generated datasets, which achieves better transient performance compared to MPC and PI controllers. In [80], feed-forward ANNs are trained as surrogate models for conversion losses and integrated into an MILP-based tertiary optimization scheme, enabling optimization of hybrid MG variables such as DC-link voltage.

Beyond surrogate modeling, ANNs are increasingly used directly in control loops, including ANN-based vector control enhanced by Approximate Dynamic Programming for grid-connected inverters [81] and ANN-based virtual impedance control for bidirectional converters with online weight adaptation to maintain droop stability under unknown line impedances [82]. At higher hierarchical layers, ANN-based load power forecasting is integrated into droop control in [83] to support distributed secondary frequency control, eliminating the need for real-time frequency measurements.

RL views MG control as a sequential decision-making problem in which an agent learns optimal policies via interaction with the environment, without the need for system models. This capability makes RL particularly attractive for RES-based MGs with long-term coupling between control actions and system states.

At the primary control level, direct deep RL is applied for current control of a three-phase grid-connected inverter, as presented in [84], where RL agent learns an optimal control policy from raw data, achieving enhanced static and dynamic responses compared to traditional PI or MPC controllers. In [85], Proximal Policy Optimization is used to train deep RL agents for tuning PI gains in GFM and GFL inverters, resulting in reduced transient overshoot and shorter settling times during disturbances. RL is also used to optimize MPC weighting factors, integrating THD and voltage tracking errors into the reward function to enhance voltage quality [86].

At the tertiary level, a centralized RL technique based on the ‘‘state-action-reward-state-action’’ algorithm is proposed in [87] for joint scheduling of an EV-integrated MG, where the agent minimizes total operational cost under intermittent RES generation and complex operational constraints with higher computational efficiency, compared to MPC and deep Q-network methods. Another relevant work in [88] proposes an integrated deep ANN and Monte Carlo RL technique for multi-MG energy management, in which RL optimizes retail pricing signals and reduces the peak-to-average load ratio.

Having established the advanced control and energy management basis for robust RES-based MG operation, the analysis now moves from the grid/MG-level perspective to the EV charging infrastructure that enables and further enhances such interactions.

III. ADVANCES IN EV CHARGING STATIONS

There is a clear progression of EV architectures based on the degree of electrification, ranging from hybrid EVs and plug-in hybrid EVs to fully electric configuration. The energy storage itself can also be hybridized, with batteries complemented by supercapacitors [89], [90]. Such hybridization mitigates the limitations of batteries, particularly their relatively low power density and degradation under high transient loads. These trends directly influence charging requirements and grid interaction characteristics, motivating the need for advanced charging and control techniques.

In the following, the recent advances in EV charging infrastructure will be discussed, focusing on EV charger types, power electronic converter topologies, EV-grid/MG interactions, and advanced control and EMSs.

A. EV CHARGER CLASSIFICATIONS

EV battery chargers can be classified based on several factors including installation type (on-board or off-board), charging levels (level 1–4), and power source type (AC/DC) [91]. OBCs convert AC to DC within the vehicle, while OFBCs do this externally, supplying DC directly to the battery. In terms of power levels under European standards [92], level 1 (slow) charging uses single-phase at 16–32A, providing up to 7.4kW. Level 2 (semi-fast) uses either single-phase or three-phase (at 16–63A and can deliver up to 44kW). Level 3 (fast) supplies DC up to 600V at 50–350kW. An emerging level 4 class targets 800–1000V and power above 400kW [91], representing the ultra-fast DC charging.

However, the aforementioned factors are closely interrelated rather than fully independent. For example, AC chargers are on-board and typically operate at level 1 or level 2, whereas DC chargers are off-board and correspond to level 3

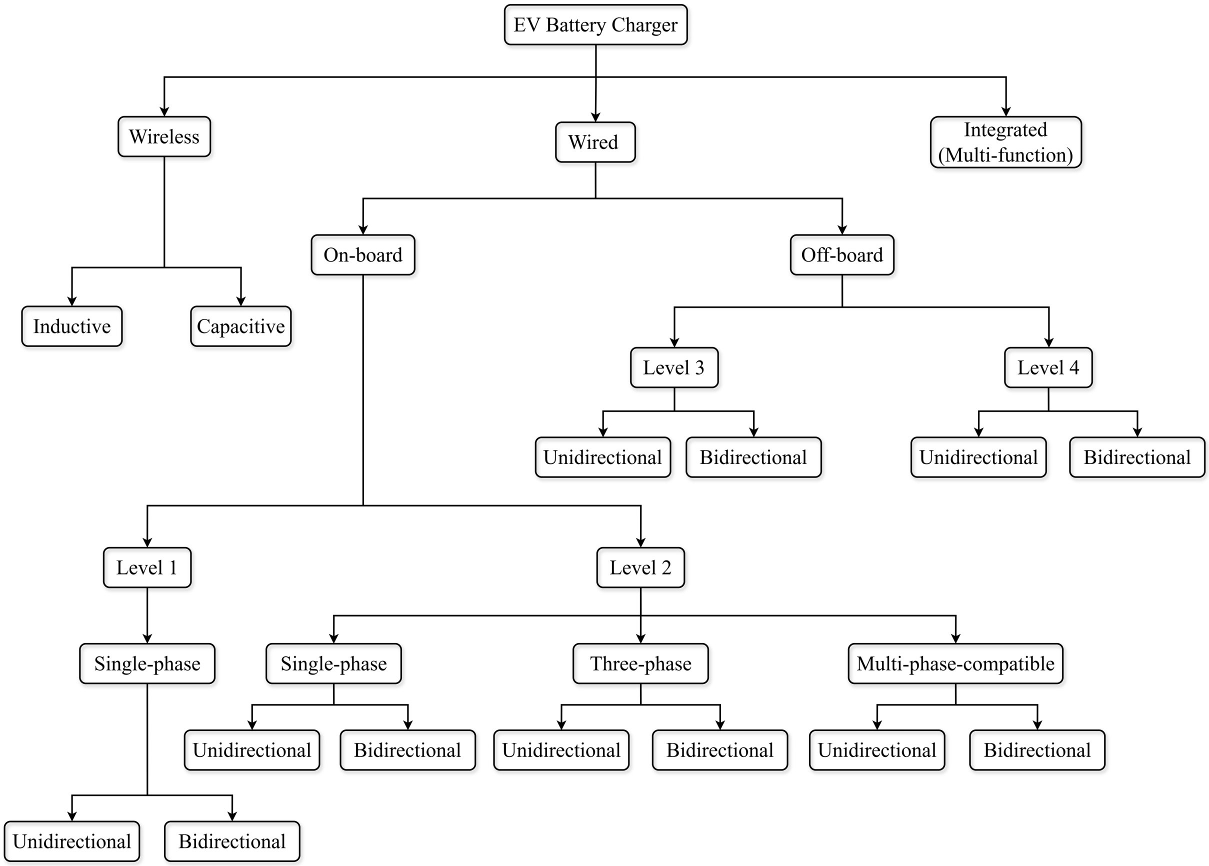


FIGURE 3. **A unified classification of emerging EV chargers.**

or level 4 charging. To better represent interconnections, a unified classification is proposed in Fig. 3.

A relevant factor to the EV charger classification is the power-flow direction, where chargers may be unidirectional or bidirectional. Bidirectional capabilities can exist in both OBCs [93], [94] and OFBCs [95], [96], with their functionality determined by the design of the power converter topology and associated control techniques. Recent advances in wide-bandgap devices and high-density magnetic components now allow compact and high-efficiency bidirectional OBCs capable of supporting vehicle-to-everything (V2X) functions, including V2G, and vehicle-to-home (V2H) [93]. On the other hand, bidirectional OFBCs provide higher power ratings and are ideal for grid services, as they can provide fast response to grid demands and operate across all $P-Q$ quadrants [95]. Recent advances in bidirectional OFBCs include multifunctional topologies with unified control techniques [96], achieving fast dynamic response with seamless and fast G2V/V2G transitions, while maintaining low current THD.

All the previously discussed power transfer techniques are considered wired (conductive), whereas wireless charging is based on power transfer via inductive or capacitive coupling [97]. Resonant inductive power transfer is the most preferred wireless charging method due to its high efficiency, safety, and suitability for practical short-range applications. Recent advances enhance wireless EV charging by integrating wireless power transfer, OBCs, and auxiliary power functions into a single compact system [98]. This design reduces weight, cost, and complexity by sharing magnetic components and power electronics, while maintaining high power density.

Another important factor in EV charger classification is the AC phase, with advanced OBCs increasingly support both single- and three-phase operation. Recent designs achieve full-range, high-efficiency operation without extra components, enabling seamless switching between single- and three-phase grids [92], [94].

B. EMERGING TRENDS IN EV CHARGER ARCHITECTURES FOR SEAMLESS MG INTEGRATION

Advanced power-electronic converter topologies are being introduced to optimize the performance in both OBCs [93] and OFBCs [99]. Growing charging power demands and power limitations imposed by grid operators are pushing the development of configurations that integrate RESs and ESSs directly into EV charging infrastructures.

As illustrated in Fig. 4, local resources can be interfaced either on the AC side of OBCs and OFBCs, or directly at the DC bus of OFBCs, allowing for higher charging power levels, improved efficiency, and increased operational flexibility. AC-side RES and ESS integration allows local compensation for grid power consumption, reduces peak demand, and participates in MG-level energy management without modifying the internal charger architecture.

On the other hand, the DC-side integration in OFBCs reduces the redundant conversion stages and facilitates higher charging power densities. This configuration also enables enhanced coordination between local storage and charging dynamics, which is very important in fast-charging applications under constrained grid connections.

These EV charging architectures provide a practical means to better exploit local generation and storage for EV charging, without requiring major modifications to existing MG configurations. By enabling ancillary services such as voltage regulation and reactive power support, they enhance the MG operation. These architectures can also be deployed across residential, commercial and large-scale EV facilities. These features make them promising solutions for the GFM-based EV-MG integration schemes analyzed in Section IV.

From an architectural perspective, OBCs and OFBCs are generally realized using either single-stage or double-stage structures, where the decoupling of AC-DC and DC-DC functions in the latter structures offer simple design and control [145], which motivates our focus in the following analysis. Table 2 presents a concise comparison of the EV OBCs and OFBCs, detailing AC-DC and DC-DC configurations, V2G capability (i.e. bidirectional power flow in both conversion stages), major functional enhancements beyond control, and corresponding performance gains across the most recent literature.

1) CONVERTER TOPOLOGIES IN OBCS

Common AC-DC stages include a variety of power factor correction (PFC) topologies [100], [101], [102], [103], [104], ranging from traditional diode-bridge designs to adaptive and interleaved bridgeless totem-pole or full bridge architectures, which enhance power quality, reduce component size, and improve reliability for high-voltage battery systems.

Isolated DC-DC stages often use DAB [94], [105], non-inverting buck-boost [106], series resonant (SR) [103], series-parallel resonant (SPR) [100], [101], [104], or push-pull converters [102], offering galvanic isolation, wider voltage conversion ratio, soft-switching, and higher power density, while advanced control techniques further optimize efficiency, minimize leakage currents, and support bidirectional V2G operations.

Single-stage OBCs have been also investigated in the literature for reduced component count and enhanced power density, with recent solutions integrate active power decoupling directly into the converter structure [107], [108].

2) CONVERTER TOPOLOGIES IN OFBCS

Advanced PFC converters are also used in the AC-DC stage of OFBCs [109], [110], [111]. The Vienna rectifier (VR) is used in high-power OFBs due to its ability to achieve near-unity power factor, low current distortion, and minimized semiconductor voltage stress via a split DC-link structure [112], [113]. Recent work [112] has combined VRs with stacked DAB converters, enabling reduced switching losses and compact designs suitable for ultra charging applications. Moreover, VRs have been integrated as low-frequency unfolders in quasi single-stage [113], transferring high-frequency current shaping and voltage regulation to modular DC-DC stages, which allows for filter-less grid interfacing, removal of bulky DC-link capacitors, and straight-forward scalability to higher power levels.

In the DC-DC conversion stage of advanced OFBCs, the DAB converter remains the dominant topology, with recent research emphasizing multilevel topologies [114] and modular stacking [112]. Advanced control strategies enhance DAB-based OFBs for grid-interactive operation, with modified direct power control schemes facilitating fast

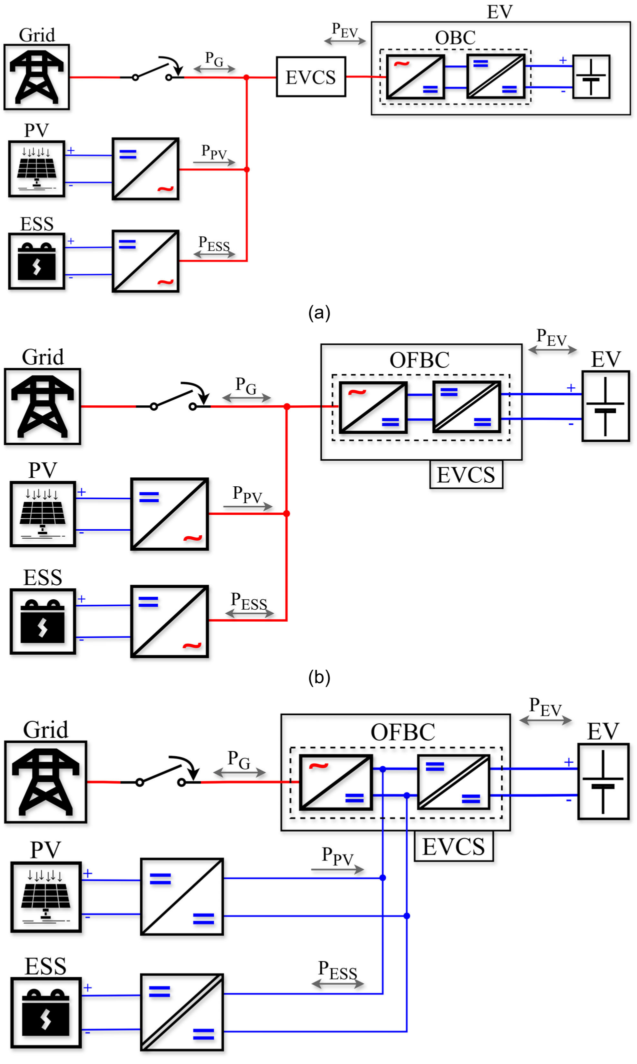


FIGURE 4. Advanced EV chargers: a) AC-side RES-integrated OBC, b) AC-side RES-integrated OFBC, c) DC-side RES-integrated OFBC.

TABLE 2. Comparative summary of recent OBC and OFBC converter topologies (double-stage).

EV Charger	Ref.	AC-DC Stage	DC-DC Stage	V2G Capability	Enhancement	Performance Gains
OBC	[94]	Differential rectifier (buck-boost)	DAB converter	Yes	Universal multi-phase operation without extra power components.	Almost unity power density; higher peak efficiency; low THD.
	[100]	Interleaved bridgeless totem-pole PFC converter	CLLC SPR converter	Yes	Dynamic phase adjustment.	High peak efficiency; wide voltage range.
	[101]	PFC converter	CLLC SPR converter	Yes	An integrated transformer design; soft start technique with no extra components.	Ultra-wide voltage range; high power density; high peak efficiency.
	[102]	Diode-bridge rectifier with front-end boost converter	Push-pull converter	No	None	Almost unity power factor; low THD.
	[103]	Inverter PFC	LC SR converter	No	None	Reduction of common-mode leakage current; volume Reduction (smaller magnetic area than LLC).
	[104]	Half-bridge PFC converter	CLLC SPR converter	Yes	Dual stacked switches configuration.	High DC voltage compatibility; full soft switching; high V2G efficiency.
	[105]	Single-phase rectifier	DAB converter	Yes	None	Second-order harmonic ripple reduction; superior dynamic response and stability.
	[106]	Three-leg voltage source inverter	Non-inverting Buck-Boost Converter	Yes	Integrated design with Permanent Magnet Synchronous Motor windings (as input filter) in the AC-DC conversion; active power decoupling.	Almost unity power factor; low DC-link ripple; low grid current THD in both G2V and V2G.
OFBC	[96]	Single-phase active rectifier	DAB converter	Yes	None	Unity power factor; high peak efficiency; low THD.
	[109]	Three-phase three-level boost PFC converter	Dual-output CLL SR converter	No	H5 bridge reconfiguration for charging 400V and 800V batteries.	High overall efficiency; low THD.
	[110]	Three-phase PFC converter	LLC SPR converter	No	Modular structure with reconfigurable output (series or parallel relay).	High efficiency; ultra-wide output voltage range.
	[111]	Bridgeless boost-buck PFC converter	PSFB converter	No	Reconfigurable secondary side of PSFB converter using only one relay and a filter capacitor branch.	Ultra-wide output voltage range; unity power factor; high average efficiency; low current THD.
	[112]	Three-level VR	DAB converter	No	Utilization of 600V GaN transistors and 1200V SiC diodes.	High peak efficiency; ultracompact power density.
	[113]	Three-phase VR-based unfolder	Two isolated current source converters	No	Filter-less grid connection (converter input inductance as grid filter).	High power factor; low THD; high efficiency.
	[114]	Three-phase voltage source converter	Three-level DAB converter	Yes	None	Reduced voltage and current stresses; low cost and compact due to three-level topology; high efficiency; low THD.

dynamic response and stable bidirectional V2G operation within a single hardware platform [96].

Compared with DAB-based DC-DC conversion solutions, resonant converters offer a wider soft-switching region, making them especially attractive for multi tens of kilowatt systems operating over large voltage conversion ratios [109], [110]. Reconfigurable resonant topologies, such as H5 bridge CLL SR converters [109], further enable flexible excitation of individual resonant tanks, supporting wide output voltage ranges while maintain zero voltage switching (ZVS). Another topology used in the isolated DC-DC stage of OFBCs is the phase-shifted full-bridge (PSFB) converter, due to its structural simplicity, and capability to achieve primary-side ZVS, with reconfigurable designs now capable of supporting voltage ranges from 120V to 900V by adapting secondary-side connections, maintain high efficiency across low-, medium-, and high-voltage operating conditions [111].

Single-stage OFBCs have been developed using dual-output transformers [115] and Swiss-rectifier modules [116] to achieve compact and efficient charging architectures.

C. EV-MG INTERACTION AND CONTROL

Recent research highlights the advancing role of EVs within MGs, where coordinated charging and bidirectional power exchange are used to enhance operational flexibility, stability, and economic performance. Recent advancements in EMSs and V2G operation within AC and DC MGs are reviewed in the following.

1) ADVANCED EMS IN EV-INTERACTIVE MGS

Recent advancements in EMSs for EV-interactive MGs focus on optimization-based systems that increasingly use online approaches, mainly MPC [117] and Adaptive Equivalent Consumption Minimization (AECM) [118], which continuously optimize power flows, battery SOC and fuel or electricity usage under real-time constraints, offering higher adaptability than offline approaches. Integration with intelligent transportation systems and V2X communication further enhances EMS capabilities by providing real-time predictive information for vehicle power demand, cooperative driving, and coordinated V2G/G2V interactions [118].

To further enhance MG coordination, hierarchical EMS structures allocate power among aggregated EVs using SOC-weighted techniques, reducing SOC dispersion and preventing overcharging, while innovative hardware solutions, such as electric drive-reconstructed OBCs that integrate driving and charging functionalities to lower cost and improve V2G/G2V efficiency [17].

In a recent work [119], a transformer-based predictive EMS uses real-time traffic data to improve power allocation in fuel-cell and battery systems, achieving up to 4.6% operational economy improvement compared to conventional predictive methods. In addition, HESS managed via bidirectional OFBCs decouple fast and slow dynamics, using DC-link capacitors for virtual inertia and the EV battery for long-term frequency support, while simultaneously enabling full V2G functionalities including voltage regulation, reactive power support, and harmonic mitigation [120].

Deep RL has emerged as a smart approach for EMSs in EVs, addressing the limitations of conventional EMS such as poor real-time performance and limited generalization [121]. Hierarchical deep RL architectures, such as Deep Deterministic Policy Gradient combined with vehicle-level AECM technique, enable integrated speed planning and energy management for connected hybrid EVs, simultaneously optimizing fuel consumption, battery SOC, emissions, and car-following objectives, outperforming traditional Q-learning and deep Q-network methods under both standardized and real-world driving cycles [122]. To ensure safe and feasible operation, physics-informed exploration techniques combined with prioritized experience replay guide deep RL agents toward physically realizable actions, eliminating the need for separate safety layers while improving learning speed and energy efficiency [123].

2) V2G SOLUTIONS FOR EV-MG INTEGRATION

Recent studies on V2G-capable EVs in AC MGs focus on distributed MPC for coordinated voltage and frequency support [124], [125]. In [124], a non-iterative peer-to-peer distributed MPC scheme enables real-time voltage regulation via aggregated EV chargers with low computational burden and robustness to communication latency in wide-area low-voltage networks. Extending this concept to networked MGs, the work in [125] integrates a non-intrusive battery surrogate model into distributed MPC to enhance frequency nadir and recovery performance, while maintaining robustness against parameter uncertainties and topology variations.

In low-inertia islanded AC MGs, V2G-capable EVCSs can actively support frequency stability by combining MPC with virtual inertia emulation [126]. An MPC-VSM technique allocates charging power across EVs based on their SoC and target energy, ensuring grid frequency stability while limiting unnecessary battery cycling. Beyond steady-state operation, recent work has addressed the critical challenge of maintaining V2G functionality during grid disturbances [127]. By integrating virtual inertia behavior into an MPC technique and accounting for positive and negative sequence components, GFL-controlled EV inverters can effectively suppress double-frequency power oscillations caused by unbalanced faults and stay connected during voltage sags.

A major research direction focuses on direct DC charging and DC-bus stabilization under fast and stochastic charging dynamics, with the work in [128] shows that integrating an additional voltage control loop into bidirectional DC-DC converters effectively limit DC-bus deviations during rapid EV charging transients. Similar voltage control challenges are addressed in [129], showing that SMC achieves faster settling and eliminates overshoot in low-voltage DC charging systems.

Beyond local control, an MILP-based day-ahead scheduling model is introduced in [130], that accounts for DC cable losses, to ensure realistic scheduling and economic feasibility in large charging infrastructures. In a related direction, a hierarchical MPC technique combined with an EV power allocation layer is used in [131], allowing DC MGs to act as energy routers that maximize PV self-consumption while ensuring that EVs reach their target SoC by departure. In bipolar DC MGs, the voltage imbalance caused by large EV penetration is addressed in [132], through distributed coordination based on a voltage unbalance factor, achieving excellent efficiency and improved voltage quality.

Further advancing, intelligent and data-driven control techniques are emerging to handle uncertainty and operational complexity in DC V2G systems [133], [134]. In [133], ANNs integrated with terminal SMC technique is used to improve PV voltage reference tracking under fast irradiance changes. Also, deep learning-based demand forecasting combined with metaheuristic optimization is applied in [134] to anticipate charging peaks and actively coordinate EV participation in DC MGs.

The developments in advanced MG-integrated EV chargers introduce the question of how these systems operate under GFM control, which is addressed in detail in the next section. Particular attention is given to various structural realizations of this integration, which are evaluated with respect to power capacity, implementation cost, efficiency, and continuous MG support capability.

IV. RECENT PROGRESS IN GFM CONTROL FOR RES-BASED MGS WITH EV INTEGRATION

Multiple GFM control techniques are compared in [135], highlighting that VOC can achieve self-synchronization from arbitrary initial conditions without explicit power calculations and PLLs. The work also highlights various applications of GFM control in RES-based MGs across both generation and load sides, including stabilizing inverters of wind, PV, and storage units, allowing EVCSs to support weak or offshore grids, and regulate islanded MGs.

In the following, recent advances in leveraging GFM control to integrate EVs into RES-based MGs are discussed.

A. GFM-BASED SOLUTIONS FOR EV-INTERFACED MGS

For clarity, Fig. 5 illustrates a generic EV-MG interfacing configuration, where the charger's inverter is controlled by droop-based, VSM-based, or VOC-based techniques. Recent developments within this scope are summarized in Table 3.

1) DROOP-BASED TECHNIQUES

Recent works in droop-based GFM control for EV-interfaced MGs are reported in [136], [137], [138], [139], [140], [141], and [142], demonstrating the capability of EV chargers to provide frequency and voltage regulation, inertia emulation, black-start support, and reliable V2G/V2H operation under islanded and disturbed conditions. Advanced droop variants further improve transient stability, circulating current mitigation, and parallel EV coordination without a primary voltage source, confirming droop-based GFM as a practical and scalable solution for multi-EV MG operation.

2) VSM-BASED TECHNIQUES

Major contributions in VSM-controlled EV chargers are reported in [143], [144], [145], [146], [147], and [148], demonstrating enhanced inertial emulation, fault support, coordinated primary and secondary frequency control, and adaptive inertia tuning for low-inertia MGs. Integration with MPC and FL control enables multi-objective optimization, that balances grid support with battery lifetime and user charging requirements, while consensus-based cooperative VSM schemes demonstrate scalable and communication-based coordination among multiple EV chargers in community MGs.

3) VOC-BASED TECHNIQUES

Major developments of VOC techniques that are relevant for EV-interfaced MGs are provided in [149], including unified VOC, inertia-enhanced AHO, and damping-enhanced AHO. The damping-enhanced AHO technique shows superior performance in grid-connected V2G under disturbances and islanded V2H during outages, providing well-damped power responses with negligible oscillations compared to inertia-enhanced AHO.

TABLE 3. Examples of recent developments in EV-MG integration with GFM control.

GFM Control	Ref.	Enhanced Technique	MG Operation	Performance Gains
Droop	[136]	Secondary control	Grid-connected & islanded	Sustains isolated grids; enables black-start re-energization.
	[137]	Dual-loop feedforward decoupling	Grid-connected & islanded	High V2G efficiency; fast DC-link stabilization.
	[138]	None	Grid-connected	High reduction in RoCoF; enhanced FRT stability.
	[139]	Augmented frequency support	Grid-connected	Superior mitigation of frequency nadir.
	[140]	Virtual impedance	Islanded	Limited voltage and frequency deviations; reduced settling.
	[141]	Nested-loop scheme	Grid-connected & islanded	Robust frequency regulation during unsymmetrical faults and grid outages.
	[142]	P-Q decoupling	Grid-connected & islanded	Robust power sharing in parallel EV operation.
VSM	[143]	Virtual two-phase system	Grid-connected & islanded	Elimination of double-frequency power oscillations.
	[144]	P-Q decoupling	Grid-connected	Reducing current stress.
	[145]	Two-stage auxiliary frequency regulation	Islanded	Elimination of steady-state frequency deviations; short adjustment time with small overshoot during load disturbances.
	[146]	Active power feedback)	Grid-connected	Effective suppression of RoCoF; optimized inverter stability during active power reference fluctuations.
	[147]	FL controller	Grid-connected	Effective peak shaving and valley filling.
	[148]	Consensus-based cooperative adaptive virtual inertia	Islanded	Robust operation of multi-EV chargers; suppresses power oscillations.
VOC	[149]	Feedforward damping	Grid-connected & islanded	Reducing power overshoot.

B. PROPOSED SOLUTIONS FOR EV-MG SYNERGY FEATURING GFM CONTROL

Building on the topologies discussed in Fig. 4, this subsection discusses how GFM-based EV chargers can be architecturally integrated within RES-powered MGs. In particular, attention is given to how different charger integration ways influence the availability of GFM resources, charging/discharging power capability, the extent to which the EVCS can be used as an active MG asset, the energy conversion efficiency, and the associated infrastructure cost. From this perspective, Fig. 6 depicts three representative schemes that are expected to dominate future RES-based charging implementations, while their comparative characteristics are summarized in Table 4.

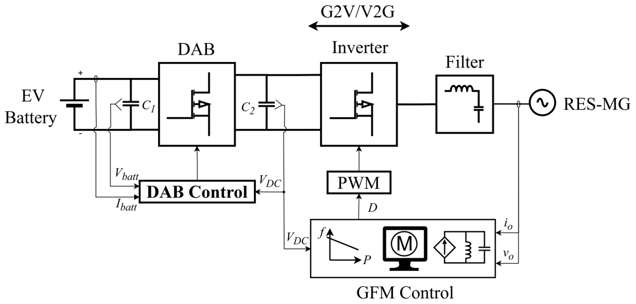


FIGURE 5. Generic representation of EV-MG integration based on GFM control.

To provide a structured comparison, several assessment factors relevant to GFM-based EV-MG operation are established and analyzed, as outlined in the following.

1) GFM RESOURCE AVAILABILITY

This factor captures whether the GFM voltage source capability is continuously sustained or dependent on the physical presence of the EV.

2) ENERGY CONVERSION EFFICIENCY

This factor evaluates the extent to which the EV charger architecture affects conversion stages and associated losses along with the power flow between the MG, the RES/ESS, and the EV battery.

3) EV-MG INFRASTRUCTURE COST

This captures the additional infrastructure cost associated with realizing the scheme at the EVCS level. This is mainly centered around the DC/AC interfacing requirements.

4) ACTIVE POWER EXCHANGE CAPACITY

This reflects the achievable charging and discharging power levels supported by each scheme, directly related to EV availability, its SOC-related constraints, EVCS topology, and RES connectivity.

5) ANCILLARY SERVICE POTENTIAL

This one captures the ability of the charger to support MG operation beyond active power transfer, even in the absence of connected EVs. Such support includes reactive power support and other power quality enhancement functions.

6) EV-MG SUPPORT EFFECTIVENESS

It is an aggregate indicator used to reflect how an EV charging system can be used as an active MG asset under GFM control.

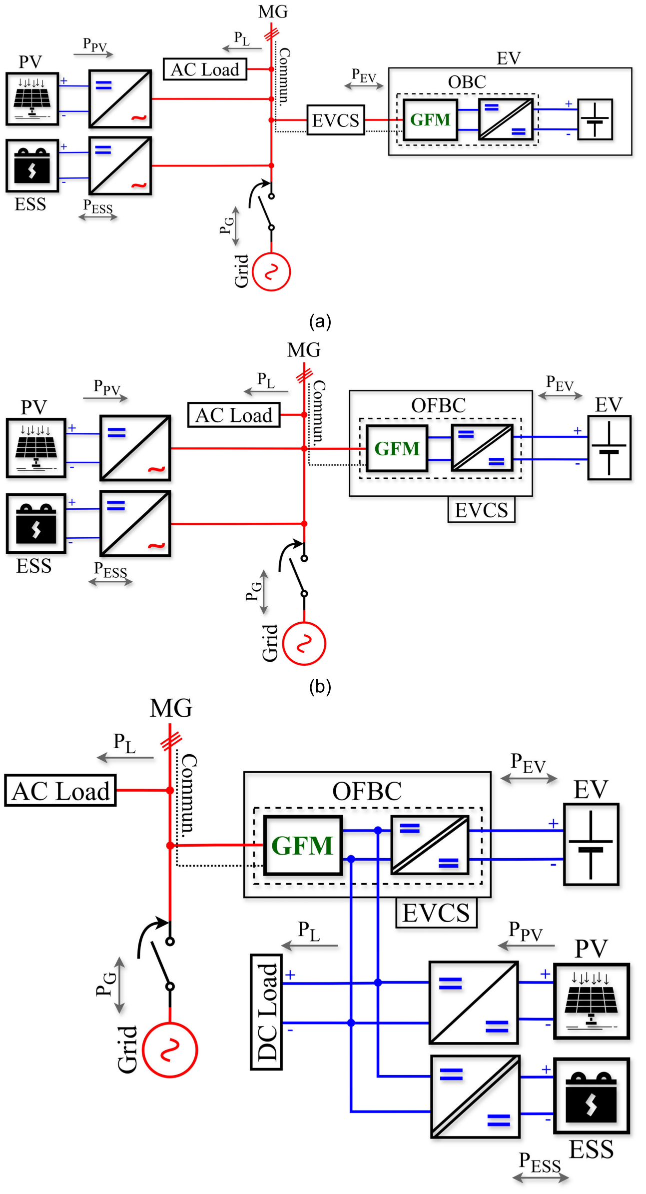
The first scheme, shown in Fig. 6(a), represents a typical OBC integration, in which the GFM control is applied to the inverter stage during periods when the EV is connected to a RES-powered MG through the EVCS. From efficiency perspective, this scheme follows conventional DC-AC conversions for integrating RES and ESS into the MG. The EV battery interfacing is handled within the vehicle, with the EVCS acting mainly as a connection point. Therefore, no significant infrastructure cost is required. Also in this scheme, GFM capability is discontinuous and directly depends on the EV connection, since both the DC bus and the GFM inverter are integrated within the EV. As a result, the ancillary services are related to EV availability, limiting the overall contribution of this scheme, despite its suitability for residential and workplace charging contexts.

The second scheme, shown in Fig. 6(b), considers an OFBC interfaced with a RES-powered MG, where the charger-side inverter operates in GFM mode. Here, the EVCS must be equipped with dedicated off-board power conversion hardware, which increases the installation cost. Regarding efficiency, the DC-AC conversion stages are still required in the MG side, so there is no improvement over the OBC case. Compared to OBC-based solutions, this scheme allows for higher charging power levels and decouples grid support functions from EV hardware constraints, so that the GFM inverter can provide reactive power compensation and enhanced power quality independently of the connected EVs. However, in the absence of an EV, sustained GFM operation is limited, due to the lack of a DC bus interface, thus reducing the overall effectiveness of this scheme.

The third scheme, shown in Fig. 6(c), integrates RESs and ESSs directly into the DC bus of the OFBC. This reduces the power conversion losses associated with redundant DC-AC stages, but it does not considerably reduce the implementation cost, as PV and storage units are interfaced through dedicated DC-DC converters. The cost-effectiveness can be further improved using multiport active bridge configurations where local DC sources are arranged within single-stage isolated structure. Furthermore, this DC-side integration fundamentally changes the role of the charger, transforming it into a continuously available GFM resource regardless of EV presence. PV generation and stationary storage can maintain DC bus interface, allowing for continuous ancillary services, while EVs act as flexible loads or storage resource when connected. Overall, this scheme provides the highest EV-MG support effectiveness.

TABLE 4. Comparative assessment of EV-MG integration schemes under GFM control.

Assessment Factor	Scheme (a)	Scheme (b)	Scheme (c)
1. GFM Resource Availability	Low	Low	High
2. Energy Conversion Efficiency	Medium	Medium	High
3. EV-MG Infrastructure Cost	Low	High	Medium
4. Active Power Exchange Capacity	Low	High	High
5. Ancillary Service Potential	Low	High	High
6. EV-MG Support Effectiveness	Low	Medium	High



(a)

(b)

(c)

FIGURE 6. EV charging schemes for MG operation under GFM control: (a) OBC with AC-connected RES and ESS, (b) OFBC with AC-connected RES and ESS, (c) OFBC with DC-connected RES and ESS.

V. OPEN RESEARCH CHALLENGES AND PROSPECTS

Motivated by the increasing penetration of EVs and RESs, and by the need for resilient, flexible, and grid-supportive MGs, EV-integrated MGs with GFM control are advancing quickly. Based on the comparative analyses and insights developed throughout this survey, several observations and future directions emerge, highlighting opportunities to transform EV-interfaced MGs from isolated energy assets into continuously available, intelligent, and controllable GFM resources, as follows:

- HESS configurations provide compact solutions for combining long-term and short-term storage, but optimal coordination of multiple storage layers under dynamic EV charging remains an open challenge. Integrating optimization-based EMS with adaptive learning techniques (e.g. RL or physics-informed ANNs) can enhance V2G operation, reduce battery degradation, and enhance the overall system flexibility (see Table 1).
- The increasing interest in DC MGs is motivated by their higher efficiency and compatibility with EV charging systems, with direct charging from local RESs becoming increasingly advantageous. However, protection and fault isolation remain less mature than in AC MGs, and further work is needed to develop fast and reliable solutions for EV-interactive DC MGs.
- Advanced control techniques are currently the focus of extensive research, with the trade-off between performance and complexity becoming increasingly apparent. Real progress is expected from smart hybridization and well-considered arrangement of control functions across hierarchical layers. At the primary level, VOC-based GFM control, particularly the damping-enhanced AHO demonstrates superior transient behavior, but its sensitivity to network parameters (e.g. grid impedance) and varying EV availability requires adaptive techniques. Promising directions include integrating AHO with FL-based online tuning or learning-based models that dynamically reject disturbances. At secondary and tertiary layers, MPC and similar model-based schemes remain effective for slower timescales, while RL, especially when integrated with physics-informed ANNs, shows potential for decision-making, V2G/G2V coordination, and multi-MG operation, without increasing the computational burden in the primary control loop.
- The integration of EV charging systems with DC MGs represents a highly promising direction for GFM-controlled operation, as it enables faster charging rates (e.g. exceeding the grid limit of 22kW up to 50kW or more), while the same DC MG interface can support bidirectional V2G operation. While OBCs are suitable for residential and workplace charging, their dependence on the physical presence of EVs and relatively lower power ratings limit their value as grid-support assets. On the other hand, OFBCs with DC-connected RES and ESS, as proposed in Fig. 6(c), maintain the GFM inverter active even when no EVs are connected, transforming an EV parking lot into a continuously available resource capable of supporting stable and resilient islanded MG operation whenever required.

VI. CONCLUSION

This paper has presented an overview of the evolving intersection between RES-based MGs and EV integration, with a particular focus on GFM control-based integration architectures, giving researchers and engineers a practical reference for current developments.

The survey has revealed that the successful integration of EV charging systems and GFM control capabilities in

RES-based MGs depends on both physical and control architectures. Converter topologies and hierarchical control schemes must handle the stochastic nature of renewable generation, and grid- and EV-side behaviors. Beyond passive load operation, EVs equipped with advanced bidirectional chargers and advanced GFM control techniques can actively provide virtual inertia, voltage and frequency regulation, and autonomous services (e.g. black-start) for weak or islanded operation.

Our analysis has indicated a clear trend toward HESSs to separate fast and slow dynamics. Also, promising research directions include the hybridization of control schemes across hierarchical layers, such as the damping-enhanced AHO with FL- or learning-based models at the primary level, and MPC with RL or physics-informed ANNs at the secondary and tertiary levels. Moreover, it is identified that OFBC architectures with DC bus interfaces offer a robust solution for RES-based MGs, enabling direct, efficient, and high-power charging from local DC sources, with continuous GFM functionality provided in a cost-effective manner, regardless of the EV connection status.

The main contributions of this paper can be summarized as follows:

- A comparative summary of recent battery-supercapacitor HESS solutions and their control and optimization techniques was provided, clarifying performance gains and optimal sizing/placement challenges.
- A discussion on the latest MG control techniques, classified into model-based, VOC, and smart control, was presented, followed by discussion of each group and how they address the high-RES and high-EV conditions.
- The paper has reviewed EV chargers, focusing on features that can be leveraged to actively integrate EVs into RES-based MGs, considering both OBCs and OFBCs.
- Recent GFM-based EV-MG integration solutions were analyzed, including droop-, VSM-, and VOC-based techniques. The comparative analysis of the GFM-based EV-MG integration across three architectures has shown that the OFBC with DC-connected RES provides the highest overall EV-MG support effectiveness.

Looking ahead, several challenges remain, including adaptive GFM tuning under fast EV dynamics, coordinated control across multiple hierarchical layers, and robust EMSs capable of managing multi-EV systems. Future research should focus on hybrid learning-based techniques, interoperable DC MG protection, and enhanced integration of RESs, HESSs, and GFM-controlled EV resources into DC MGs.

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