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Review article

Electric vehicle integration in microgrid: Hierarchical control, emerging technologies, and future directions

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ABSTRACT

The convergence of electric vehicles (EVs) into microgrids (MGs) rapidly alters modern power networks' structure and management frameworks. As EVs gain global prominence, their incorporation into MGs introduces complexities due to their unpredictable charging patterns, mobility, and potential to function as bidirectional energy storage systems using vehicle-to-grid (V2G) technology. Traditional hierarchical control structures, consisting of primary, secondary, and tertiary levels, must be adapted to manage the interactions among EVs, distributed energy resources (DERs), and variable loads. This review paper presents a comprehensive overview of hierarchical control approaches for MGs incorporating EVs, addressing fundamental concepts, recent technology breakthroughs, and increasingly evident obstacles. The investigation methodically examines key components of each control layer, including frequency and voltage stabilization, power sharing, optimal dispatch, and market-oriented coordination. Significant emphasis is placed on enabling technologies, such as artificial intelligence (AI), machine learning (ML), and multi-agent systems (MAS), which facilitate the development of more autonomous, predictive, and decentralized control architectures. The paper also discusses the supplementary function of EVs in conjunction with renewable resources. It outlines the necessity for regulatory standards, communication protocols, and cybersecurity to provide scalable and interoperable MG solutions. Future research directions highlight the adoption of AI-based control strategies, the development of peer-to-peer energy trading mechanisms, the deployment of blockchain-enabled transaction frameworks, and the design of resilience-oriented MG architectures. This review is a valuable resource for researchers, engineers, and policymakers. It

Abbreviations: EVs, Electric vehicles; MG, Microgrid; MGCC, Microgrid central controller; G2V, Grid-to-vehicle; V2G, Vehicle-to-grid; V2H, Vehicle-to-home; EVGI, Electric vehicle grid integration; EVCS, Electric vehicle charging station; EVCs, EV chargers; AC, Alternating current; DC, Direct current; RES, Renewable energy sources; FC, Fuel cell; PV, Photovoltaic; WT, Wind turbine; ESS, Energy storage system; BEVs, Battery electric vehicle; BMS, Battery management system; CC, Constant current; CV, Constant voltage; CC-CV, Constant current-constant voltage; CP-CV, Constant power-constant voltage; PCC, Point of common coupling; SC, Super capacitor; DERs, Distributed energy resources; MPPT, Maximum power point tracking; SoC, State of charge; DC-DC, Direct current-direct current; NIBDCs, Non-isolated bidirectional converters; DoD, Depth of discharge; SOH, State of health; MPC, Model prediction control; PLL, Phase locked loop; FLL, Frequency locked loop; PWM, Pulse width modulation; EMS, Energy management system; MAS, Multi-agent system; AI, Artificial intelligent; FDA, Flow direction algorithm; SMC, Sliding mode control; SPVA, Searching peak and valley algorithm; FIS, Fuzzy inference system; DOA, Dollmaker optimization algorithm; SBNN, Spatial bayesian neural network; PSO, Particle swarm optimization.

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synthesizes current information and identifies research gaps, facilitating the optimal utilization of EVs in advancing sustainable, adaptable, and intelligent MG systems.

1. Introduction

The world's renewable energy capacity grew unprecedentedly during the past decade, according to a report published in 2022 by the Renewable Energy Policy Network for the 21st Century (REN21) (Hassan et al., 2024). The seventh United Nations Sustainable Development Goal (SDG7) to "ensure access to affordable, reliable, sustainable, and modern energy for all" by 2030 mirrors the global recognition of this significance (Gielen et al., 2019). This vast expansion validates the worldwide transition to cleaner and greener energy sources, spurred by technology, the environment, and facilitating policies (Bakhsh et al., 2024). Integrating small-scale generating systems such as solar photovoltaics, microturbines, fuel cells, wind turbines, and energy storage systems into low-voltage distribution systems will result in an active power system (Hassan et al., 2023). These power sources, which are referred to as distributed generators (DGs), possess decentralized generation capacity (Twaisan and Barışçı, 2022). Gathering several DG units together can create a Microgrid (MG) system, which resolves the issues created by DG unit high penetration and enables us to apply DG systems on a large scale (Han et al., 2017). One of the most crucial components of MG is energy storage systems, as they bring reliability and stability to the system (Elalfy et al., 2024). The MGs may not generate enough energy to meet the load requirements in certain instances while also producing excess energy in some other cases. Storage of excess energy through batteries for later use during deficiencies is a remarkable feat of technology. An example of an energy storage system is an EV battery. Electric vehicles have garnered significant attention recently due to their environmentally friendly nature and energy storage advantages (Sudhakar and Kumar, 2022). The high-power, high-energy battery pack of EVs provides their propulsion with high efficiency. In addition, EVs can serve as dynamic loads or energy storage systems (ESS) in the power network (Waseem et al., 2025). The vehicle-to-grid (V2G) concept is affected by the control strategy and service requirements of the aggregation of EVs (Eltohamy et al., 2025). Electric vehicles (EVs) are active components in the power network and can easily be integrated into MG planning processes (Singh et al., 2024). This enhances the MG's technical and economic indicators.

EVs can significantly contribute to the power grid by eradicating harmonics, offering reactive power, decreasing peak demand, and providing ancillary services (Sarda et al., 2024). The lack of a proper V2G operation strategy has led to future energy management issues for microgrids. The 10% penetration of EVs under the G2V operation results in a 17.9% increase in the daily peak load. The 20% penetration of EVs leads to a rise in the peak load by as much as 35.8% (Shokouhmand and Ghasemi, 2022). Additionally, an uncoordinated V2G mode leads to inefficient and unreliable network operation. Therefore, it is necessary to implement a plan that balances demand and generation over the planning period (Vishnuram and Alagarsamy, 2024). Overall, electrical vehicle grid integration (EVGI) has presented the electrical grid with significant challenges and benefits, as shown in Fig. 1.

EVs assist in MG energy management by acting as energy storage during surplus times from the grid, G2V, and feeding the grid when required (Micari and Napoli, 2024). EV batteries can also balance the power shortage caused by the intermittent renewable energy sources in the MG (Shi and Guo, 2023). V2G technology enables the real-time monitoring and control of electric vehicle-to-grid power transfer, thereby enhancing economic operation, profitability, and reducing carbon emissions. V2G power exchange is primarily classified as unidirectional and bidirectional modes (Abdelfattah et al., 2024). V2G unidirectional chargers are standard EV chargers utilized to charge EVs in a single direction without reversal. A bidirectional V2G mode is an advanced form of EV charger that facilitates power flow in both directions (Habib et al., 2018).

An electric vehicle can take power from the electrical grid for charging and can return energy to the grid when it's not being utilized. The bidirectional power transmission capability benefits both the grid and EVs. A bidirectional charger is a power backup in blackouts and enables home charging capability (Elma et al., 2022). Among the many advantages of bidirectional over traditional unidirectional charging is increased efficiency and reliability in business operations and energy consumption (Al-Amayreh et al., 2025). Bidirectional energy flow can significantly enhance the flexibility and stability of MG systems, particularly those with intermittent renewable energy resources such as PV panels (Tang et al., 2021). Enormous advantages over traditional grid-connected stations make solar-powered electric charging stations (EVCS) one of the key enablers in constructing a sustainable energy system (Mohini et al., 2025). These stations are not just cost-saving but also reduce environmental footprint, enabling the use of solar energy in bulk amounts. More and more institutions, private hospitals, and offices have installed such stations, thus enhancing the popularity of solar energy (Daramola et al., 2023). Using photovoltaic electricity for charging electric vehicles will reduce CO_2 emissions from fossil fuel-fired power plants and reduce energy consumption on the electrical grid. PV-integrated EV networks can be utilized in grid-connected systems to achieve higher efficiency during operation. During an outage, EVs may be charged using photovoltaic power. In addition to reducing peak demands and improving the stability of MGs with PV generation and V2G technology, these technologies can also assist in lessening peak loads (Attou et al., 2021). PV-powered electric vehicle charging stations can enhance MG stability; however, other issues exist (Khan et al., 2024a). Fig. 2 illustrates a typical scenario involving MGs with PV generation and electric vehicle charging.

In certain instances, the MG load exceeds the contractual power due to the charging of electric vehicles. Another situation is the inefficient use of the extra solar cells. This study emphasizes how important it is to have an EMS that manages MG and EV units (Salvatti et al., 2020). Optimally, it becomes clear. However, some challenges face efficient energy flow management in V2G and G2V-enabled PV-based microgrid systems. The intermittent character of solar energy, which depends on meteorological phenomena, creates uncertainty in power production,

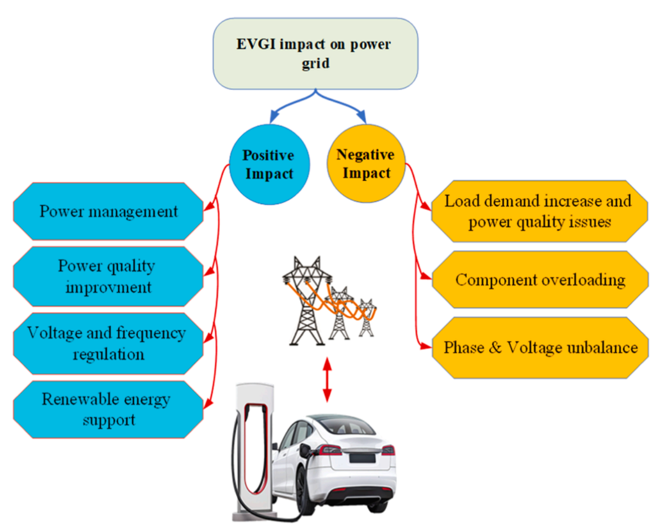

Fig. 1. Positive and negative impact of EV grid integration (Alrubaie et al., 2023).

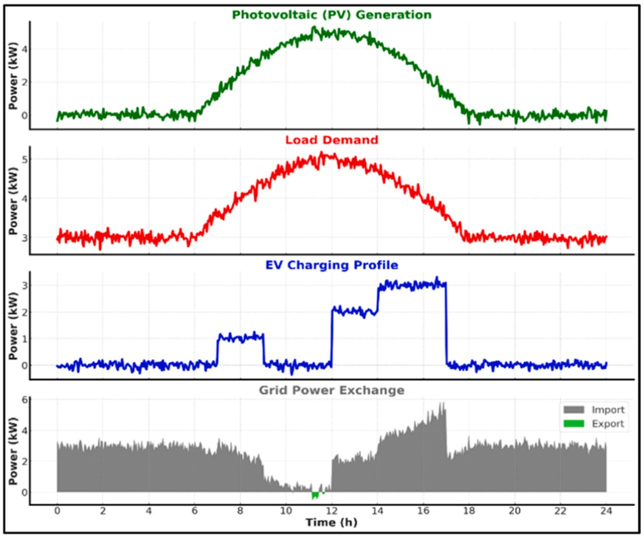

Fig. 2. EV charging impacts the demand for an MG (Salvatti et al., 2020).

making it impossible to predict and control the energy supply accurately. Ensuring stable voltage and frequency levels in the microgrid, particularly in cases of bidirectional power flow, requires advanced control systems. Recently, an assessment of renewable energy systems has been developed to supply electric vehicle charging points, aiming to reduce greenhouse gas emissions from the transportation sector (Alhuyi Nazari et al., 2024). The coupling is designed to enhance the utilization of both technologies, thereby amplifying the environmental and economic benefits of the overall process.

1. Renewable energy generation can decrease EVs' reliance on fossil fuels and facilitate genuine carbon reduction.
2. EVs can assist in addressing the intermittent challenges associated with renewable energy sources and contribute to lowering the expenses related to energy storage systems.
3. The integrated system allows for using renewable energy from EVs on-site, reducing the issues associated with connecting them directly to the public grid.
4. EVs receive on-site charging from renewable distributed power sources. This approach decreases the need for long-distance transmission of electric energy, thereby minimizing power loss associated with lengthy transmission processes. Consequently, investigating systematic charging and discharging management strategies of EVs, along with their energy storage capabilities, can enable the provision of ancillary services to the grid, including voltage regulation, spinning reserve, load shifting, peak shaving, load leveling, and support for intermittent power supply (Wu et al., 2022). The main contribution of this review article includes:

- Conducts a systematic classification and critical evaluation of electric vehicle charging station (EVCS) topologies within MGs, highlighting design principles, operational benefits, and practical limitations.
- Provides a comprehensive assessment of the roles of EVs in V2G technology, including ancillary services, frequency and voltage regulation, active and reactive power support, and facilitation of renewable energy integration.
- Identifies and analyzes the major barriers to large-scale V2G implementation, such as high infrastructure investment, interoperability and standardization issues, and battery degradation, while synthesizing strategies proposed in recent research to address these challenges.
- Investigates hierarchical control optimization across the primary, secondary, and tertiary layers to improve energy management, dynamic stability, and coordinated operation of EV into MG.
- Outlines future research directions, emphasizing the development of scalable and decentralized control architectures, AI- and ML-enabled optimization approaches, blockchain-secured peer-to-peer energy trading, and resilience-oriented microgrid design.

The rest of this work is structured as follows. Section 2 delineates the charging station within the microgrid. Section 3 elucidates the strategies for controlling the charge of electric vehicle batteries. Section 4 covers the classification of DC-DC bidirectional converters appropriate for electric vehicle applications. Section 5 elucidates the advantages of the V2G mechanism. Section 6 addresses the modifications of the V2G, while Section 7 elucidates the mechanism of the PV-powered EV charger. Section 8 presented the hierarchical control strategies. Section 9 addresses the design of EMS for EV applications, while Section 10 presents the primary future direction of the system. Finally, Section 11 presents the principal conclusion of the review strategies.

2. Charging stations in microgrids

An EVCS in MG system combines EVs, renewable energy sources (such as solar and wind power), and the primary grid to enable quick, affordable, and efficient charging. Among the many benefits of such integration are low carbon emissions, lower electricity costs, improved power supply reliability when there is a grid failure, and easy integration of EVs with the power network (Mukherjee and Gupta, 2015). By efficiently controlling electricity usage, such integration is designed to optimize renewable energy sources, buffer against fluctuations in energy demand, and reduce the risk of overloading power grids (Ramkumar et al., 2025).

An EVCS can have a DC or an AC MG system as a building block. As shown in Fig. 3, multiple DC chargers in the DC MG type of EV charging station are all paralleled to a shared DC bus, and a high-power AC/DC converter is used as the interfacing power converter between the DC system and the main AC grid (Wu et al., 2022). A DC microgrid-enabled EV charging system enables multiple EVs to be charged at low cost and high speed. The system offers higher efficiency than traditional AC charging, making it easier to integrate solar and wind energy. The small and efficient design of DC MG-enabled EV charging stations meets the needs for numerous deployments in rural and urban areas (Saxena and Deepa, 2020). As illustrated in Fig. 4, every EV charger in an AC

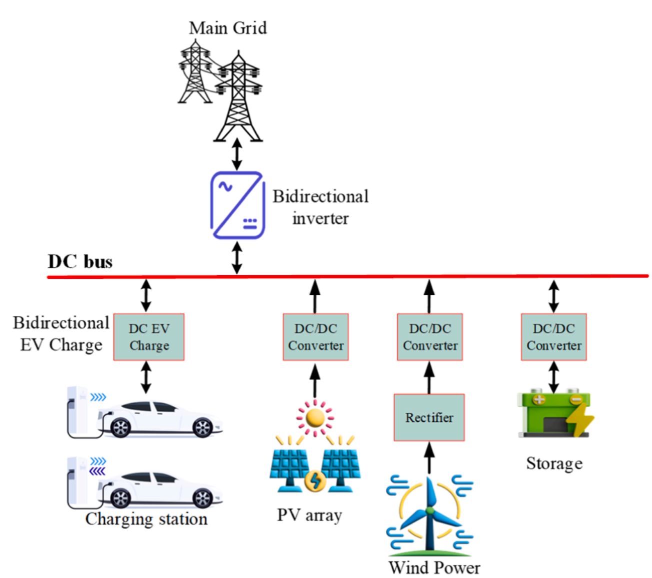

Fig. 3. The architecture of DC-EVCS (Kumar et al., 2023).

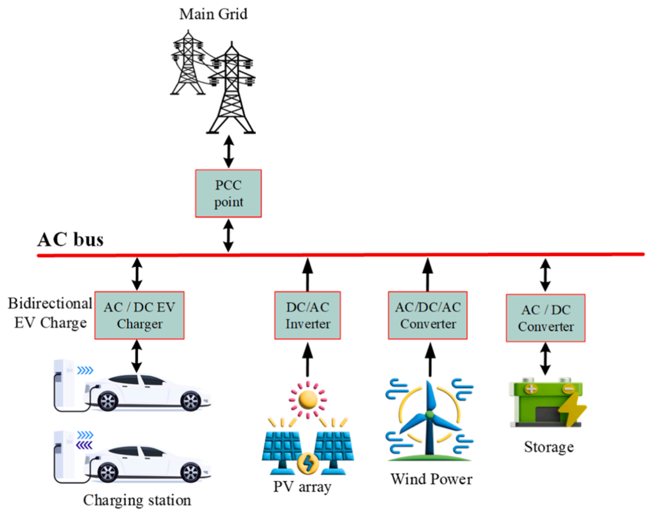

Fig. 4. The architecture of AC-EVCS (Kumar et al., 2023).

MG-type EV charging station consists of an isolated AC/DC power converter connected to the standard AC bus. Because the EV battery, renewable energy resources, and local ESS are all DC load sources connected directly to the DC bus, the AC/DC conversion stages can be reduced at the charging stations (Sharma et al., 2020). Fewer conversion steps enable the DC charging station to provide a more cost-effective and efficient way of integrating DC loads into the local network and renewable energy systems. Conversely, the production cost of AC charging stations can be lower due to their lower charging power (Rafi and Bauman, 2020). Consequently, the preferred public charging outlets currently are AC charging stations. Advancements in AC technology and the development of commercially feasible charging apparatus have enhanced AC charging stations. Nonetheless, the AC charging station has a maximum charging capacity of 19.2 kW, making it appropriate for slow-charging applications. The DC charging station offers an appealing alternative due to its reduced conversion processes, enhanced efficiency, and accelerated charging speed (Arena et al., 2024). The DC power architecture can also enable widespread renewable generation and extensive energy storage.

3. EV battery charging strategies

Lithium-ion batteries have gained more importance in electric vehicles as they have high energy density, low self-discharge, long cycle life, and less environmental effect (Gao et al., 2025). The charging stations usually provide three modes: fast, average, and slow (Shahed and Rashid, 2024). Customers must pay additional costs to build the chargers if they require the fast mode, i.e., increased charging power. Picking an average or slow charging mode means the charge power is lowered, which is beneficial for battery life and minimizes the expense of charging (Wang et al., 2020a). There exist various methods of battery charging (Ramakrishnan et al., 2024). The current and voltage needed to charge a battery determine the charging method. Constant current (CC), constant voltage (CV), constant current-constant voltage (CC-CV), constant power-constant voltage (CP-CV), and are the basic modes of battery charging used in EV chargers (Jeon et al., 2021). Fig. 5(a-d) shows the concepts of the CC (Shi et al., 2017), CV (Trivedi et al., 2018), CC-CV (Chen et al., 2024),CP-CV (Tomaszewska et al., 2019) charging techniques, respectively.

The effect of V2G services and ultra-fast charging on battery deterioration has also been studied recently. Several researchers asserted that the dynamic charging technique, such as multi-stage constant current-constant voltage (MCC-CV), constant current-constant voltage with negative pulses (CC-CVNP), and multi-stage constant current-constant voltage with negative pulses (MCC-CVNP), can be used to increase driving range and battery lifespan (Huang et al., 2020). According to experimental results, dynamic fast-charging profiles can significantly lessen capacity loss and battery deterioration as compared to static fast-charging profiles (Abdel-Monem et al., 2017).

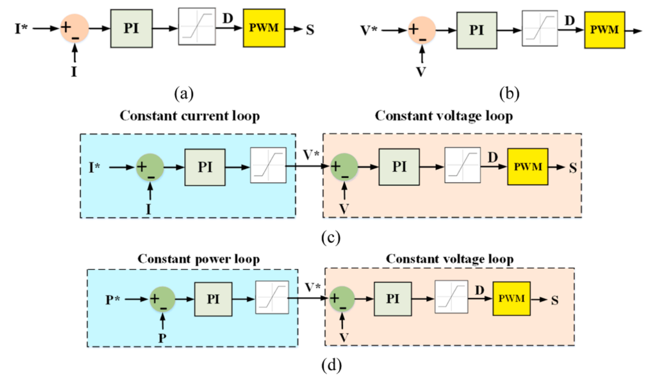

Fig. 5. Concept of charging techniques in EVs.

4. Bidirectional trends converter for EV charging and discharging

An isolated output-input converter operates as a bidirectional converter, allowing power to flow in both directions between the input and output (Tuluhong et al., 2025). In contrast, non-isolated bidirectional converters (NIBDCs) transfer power without magnetic isolation. These converters offer benefits such as a simpler design, reduced electromagnetic interference, and the absence of bulky transformers. These characteristics make NIBDCs especially suitable for applications where compact size and low weight are essential (Al-Obaidi et al., 2022). Isolated topologies, on the other hand, utilize a high-frequency transformer to convert DC into AC, which is then rectified back to DC, thereby providing galvanic isolation between the input and output. Compared to isolated converters, non-isolated topologies typically operate at lower voltage levels but are preferred in systems where electrical isolation is not a requirement. Nonetheless, transformer design and reduced leakage inductance are critical for these converters (Khan et al., 2024b). The subsequent subsections will analyze the configurations of these converters.

4.1. Classification of bidirectional DC-DC converters

In a NIBDC, direct electrical connectivity exists between the source and the load, with no galvanic isolation. Bidirectional power transfer can be facilitated by implementing an antiparallel diode across the switching device in cases where this functionality is not inherently integrated into the converter design. However, the absence of electrical isolation restricts the use of NIBDCs in high-power applications, where safety and isolation are paramount. As a result, these converters are predominantly utilized in low-power systems, where their benefits—such as higher efficiency, lower cost, compact form factor, and simplified control—outweigh the need for electrical separation (Alam et al., 2024). The eight distinct groupings are listed below bidirectional converter designed for dual functionality. Fig. 6(a) illustrates the developed unidirectional buck-boost converter. Traditional buck's one-way switches have been replaced by bidirectional power switching, while a boost converter facilitates the creation of two-way switches. A brief delay is implemented between processes to mitigate cross-conduction (Alrubaie et al., 2024). The original unidirectional Cuk converter technique from (Taghizadegan Kalantari et al., 2021) was utilized to eliminate input/output current ripples, facilitating the development of a bidirectional converter. The properties of the Cuk

Table 1
Evaluation of conventional methods for charging batteries in EVs.

Aspect	Function	Advantages	Limitations
CC (Shi et al., 2017)	The battery is charged with a constant current until it attains a specified voltage.	• Fast charging. • Simple implementation. • Effective for initial charging.	• Battery damage risk • Inefficient for the full charge • Requires monitoring
CV (Trivedi et al., 2018)	Charging a battery with a constant voltage leads to a decrease in current as the battery approaches a fully charged condition.	• Safe charging • Efficient for the full charge • Reduces polarization	• Slow charging • Complex control • Not suitable for initial charging
CC-CV (Chen et al., 2024)	The system integrates CC and CV methodologies. Initially, it uses the CC charging to reach a predetermined voltage, then switches to CV charging.	• Balanced charging • Extended battery life • Widely used	• Complexity • Longer charging time • Higher costs
CP-CV (Tomaszewska et al., 2019)	The battery charges at a constant power level during the initial phase of the charging process. As the battery nears full charge, the system shifts to constant voltage charging to reduce the likelihood of overvoltage situations.	• Reduced polarization • Faster charging • Improved efficiency	• Complex implementation. • Higher costs. • Limited adoption.

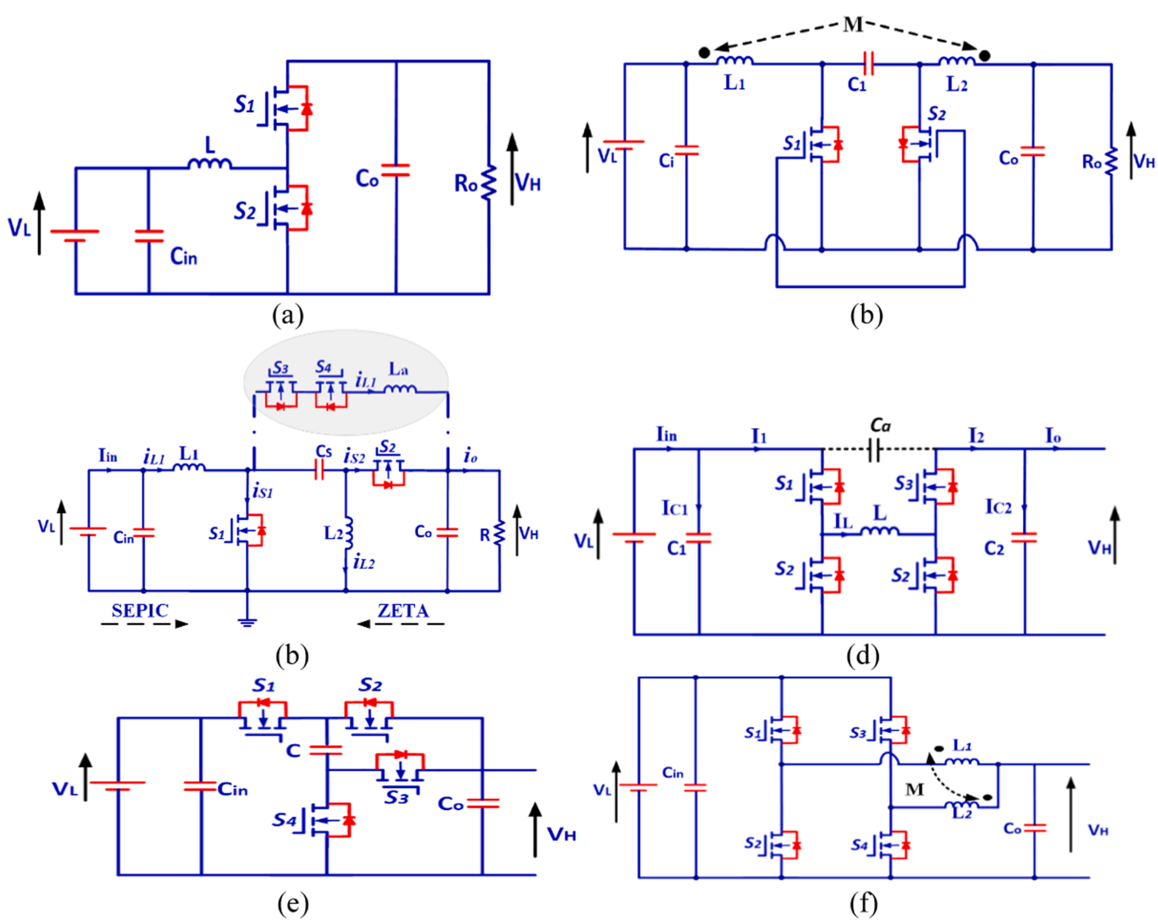

Fig. 6. Classification of non-isolated bidirectional DC-DC converter which (a) buck and boost,(b)cuk,(c) spice and zeta,(d)cascaded,(e) switched capacitors, and (f) interleaved (Alrubaie et al., 2024).

converter, such as continuous input and output current, can be modified. The original power switch and diode were replaced with two bidirectional switches, as shown in Fig. 6(b). Fig. 6(c) illustrates Zeta and Sepic DC-to-DC converters.

In contrast to Cuk converters, the output is not positive. This converter can function as a SEPIC or Zeta converter, depending on the power flow. A Sepic converter transfers power from VL to VH, while a Zeta converter transfers power from VH to VL. Sepic and Zeta converters exhibit both boost and buck operational modes. Eliminate existing waves. The auxiliary branch of this converter must establish a new direct power supply connection between its source and destination nodes. The characteristics of reduced ripple voltage, elevated output voltage, a favorable ripple factor range, and enhanced power density are superior to those of non-isolated systems (Shahin, 2015).

Fig. 6(d) illustrates the cascade DC-to-DC converter. A bidirectional technique employing a switched capacitor enhances the voltage conversion ratio of the converter as shown in Fig. 6(e). In the converter, Switched-Capacitor cells exhibit bidirectional behavior (Kim et al., 2007). This topology does not include an inductor. The absence of magnetic devices facilitates the ease of circuit integration. The converter can generate a constant input current without an inductor by connecting and operating two comparable cell strings in an antiphase. SC converters exhibit significant input current ripple, which can result in electromagnetic interference (EMI). The circuit design is deficient in EMI control. The charging trajectory of a capacitor can be modified through current and voltage control, thereby mitigating many of these challenges. The complexity and cost of converters have increased (Yuan et al., 2023). Interleaving mitigates switching frequency current ripples in a bidirectional DC-DC converter, as illustrated in Fig. 9(f), thereby decreasing the size of the EMI filter. Power inductors may be connected directly or in opposing orientations within an interleaved converter (Chung et al., 2003). The inverse coupling diminishes phase current ripple and enhances transient responsiveness (Salem et al., 2017). It is possible to consider 2, 4, 16, 25, or 36 steps. Microprocessors and multi-stage automotive electronics utilize Voltage Regulator Modules (VRMs). Interleaving can reduce filter size, enhance dynamic responsiveness, and improve thermal management (Wong et al., 2000).

4.2. Isolated bidirectional (IB) DC-DC converter

Substituting a buck-boost converter's inductor created the flyback converter. Adjusting the isolation transformer's turn ratio of this converter can boost the voltage (Paul et al., 2019). Because of its simple circuitry, this converter is straightforward to operate. The high voltage stress on switches causes a drawback to these converters. This converter needs snubbers and a focused transformer design strategy to limit leakage current. This limits its use to low-power applications that require converter. The bidirectional isolated Cuk converter features two inductors, one transformer, two switches, and two diodes, as illustrated in Fig. 7(a) and (b) (Tong et al., 2025). Also, the converter is isolated. The source and load currents pass continuously through this converter, and the output terminal is isolated from the system. Low cost, low operating frequency, minimal noise, and efficiency are all benefits of magnetic integration. In Fig. 7(c), bidirectional push-pull converters enable electricity to flow in both horizontal and vertical directions. During analysis, numerous topology adjustments were devised to enhance the current amplitude control technique of the leaky inductor and reduce conduction losses (Peng et al., 2004).

A unidirectional forward converter can also be used in reverse direction, as shown in Fig. 7(d). A clamped circuit can switch the converter's zero voltage. This converter needs an additional inductor to store energy in the transformer. The features of many converters have been studied in (Hong et al., 2025; Wang et al., 2024). The converter should store energy in the transformer to reduce circuit volume. Forward flyback, push-pull forward, and air gap leakage inductance should also be considered. These converters use isolated transformer topologies on the main side. However, current-fed or voltage-fed transformers create the secondary side of the transformer. Dual active bridge phase shift converters are widespread among academics due to their simple construction and ability to transfer power in both directions. Renewable energy systems utilize them due to their unique properties. A "dual active bridge converter" is a bidirectional converter with buck and boost functions, as shown in Fig. 7(e). This converter debuted in (Raghavendra et al., 2020). Its simple construction, control, converter port isolation,

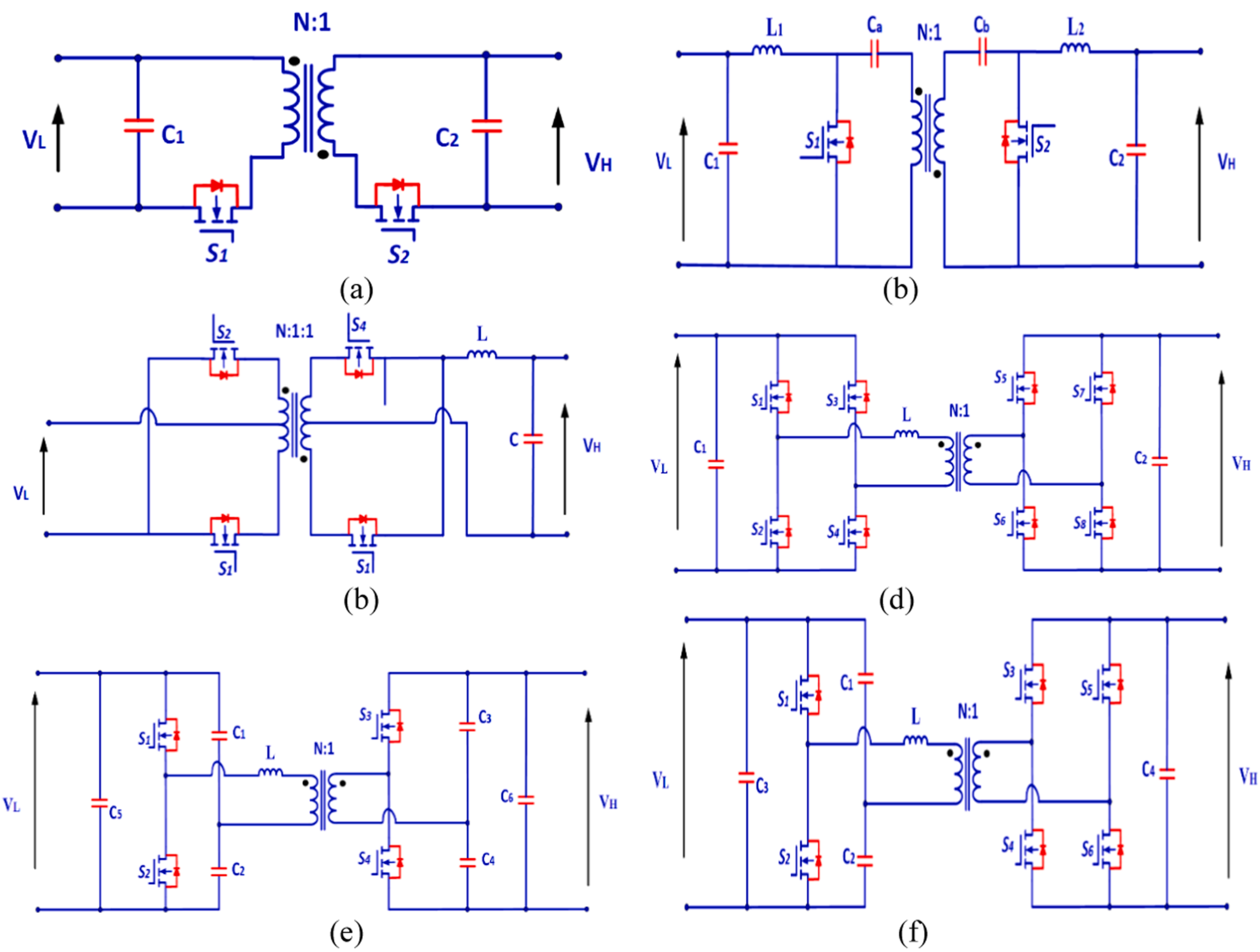

Fig. 7. Classification of isolated bidirectional DC-DC converter.

and bidirectional power transfer might benefit many applications. A dual half-bridge allows smooth switching and easy control. Its excellent power density makes it ideal for low-power applications, such as hybrid energy distribution systems. This converter's design makes use of voltage-fed half-bridge topologies on both sides of the transformer, as illustrated in Fig. 7(f).

5. Benefits of the V2G mechanism

EVs may export energy to the public grid during "peak" periods and recharge during "valley" periods to accomplish peak shaving and valley filling (Li et al., 2019a). Although distributed power resources and charging demands on the public grid are reduced when idle, EVs will require energy. EVs are mobile with V2G battery technology (Rahmani-Andebili, 2019). Traditional loads are less flexible and dispatchable than EVs. Most significantly, EVs deliver power instantly, more quickly than a standby. As a result, V2G technology enables EVs to function as emergency power sources during blackouts (Sovacool et al., 2018). Researchers worldwide are researching V2G technology in EVs and MGs (Chen and Zhang, 2024). Multiple charging and discharging approaches optimize EV-grid interaction. V2G technology uses EV batteries to lower peak demand, level grid loads, and boost renewable energy (He et al., 2024). Scaling up the technology makes the energy business more innovative, more efficient, and sustainable. This technology continually manages vehicle-grid power flow to ensure cost-effective operation with optimal returns and zero carbon emissions. Unidirectional G2V and bidirectional (G2V and V2G) charging are the main modes (Udendhran et al., 2025). A bidirectional buck-boost converter boosts V2G and bucks G2V for battery charging (Rwamurangwa et al., 2022). Unidirectional EV chargers predominate—No-reverse EV charging (Habib et al., 2018). EVs can enhance the power system spinning reserve in this mode. Managing electricity flow helps adjust grid voltage and frequency (Pavić et al., 2015). Unidirectional chargers are easy to use and cheap to maintain; hence, most residential and public charging outlets utilize them. At the cut-off level, G2V battery charging requires a negative current. After reaching the cut-off voltage, the charging current reduces (Saraswathi and Ramachandran, 2024). Charging stops at roughly 100 % SOC. In G2V mode, the off-board charger buck converts. It supplies a charging voltage below the DC link voltage.

Bidirectional charging boosts energy efficiency and reliability, but bidirectional EV charging presents regulatory challenges, high upfront costs, and electric vehicle incompatibility (Habib et al., 2015). Power electronic converters are needed for bidirectional operation. EV charging and discharging employ AC/DC reversal. The DC/DC stage efficiently manages current, charging, and discharging as a buck-boost converter. Assume the EV battery must power the grid or load. Increase the low battery voltage to the DC connection. V2G has a positive battery current (discharging current) and CV till the current cutoff. Thus, the voltage falls (Leijon, 2025). This SOC falls. When the battery voltage and current reach 0 % SOC, discharge is complete. The research forecasts that bidirectional V2G networks can cut peak grid demand by 20 % and utility expenses by 10–15 %. Research suggests that V2G-renewable energy cooperation might improve renewable energy utilization by 30 %, thereby reducing curtailment. V2G could turn EVs into sustainable energy producers (Kumar et al., 2025). The adoption of interoperable communication protocols and regulatory frameworks is essential. Protocols such as open charge point protocol (OCPP) 2.0.1 and ISO 15118 facilitate advanced V2G interactions, enabling bidirectional power flow and seamless integration with grid and market operations (Safari et al., 2025; Kester et al., 2019; Santos et al., 2024). Standards like International Electrotechnical Commission (IEC) 61850 and IEEE 2030.5 ensure real-time communication between EVs, aggregators, and utility systems, supporting functions such as dynamic voltage regulation and smart charging coordination (IEEE Standard for Smart Energy Profile Application Protocol, 2018; Oumaima et al., 2024). Fig. 8 illustrates the benefits and challenges of V2G.

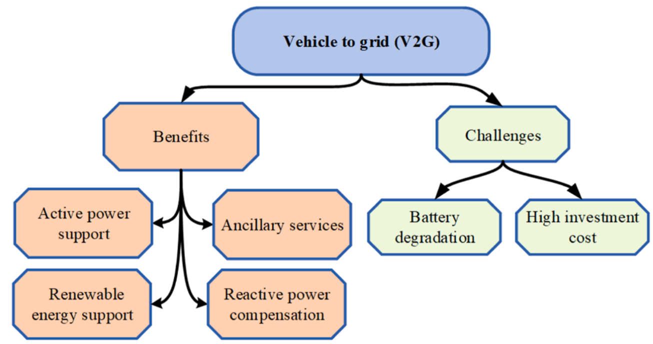

Fig. 8. The benefits and challenges of the V2G technique (Shariff et al., 2019).

Fig. 9 illustrates the interaction between EV owners, V2G aggregators, and the power grid, highlighting the exchange of benefits through contracts, grid services, and shared revenues.

5.1. Ancillary services

Power system services have been leveraged to capitalize on V2G over the past few years (de la Torre et al., 2023). Grid dependability, demand-supply balance, and power transfer from seller to buyer are all possible with ancillary services (Mastoi et al., 2022). Power grid control and spinning reserve are two categories of ancillary services. Frequency and voltage controls are provided by the power grid regulation to satisfy the demands of generation and load (Knezović et al., 2017). The ability of the EV to plan charging and discharging to improve power demand management is the main advantage of relying on V2G technology. When generation surpasses load demand during off-peak hours, spare energy may be utilized to charge the EV (Topel and Grundius, 2020).

By utilizing the right converter stages and controller algorithms, the EV can also transmit electricity to the grid, thereby meeting peak load demand and eliminating the need for expensive peak power plants. In electric systems that use load management techniques such as load shifting, flexible load, valley filling, peak clipping, power conservation, and load building, among others, the V2G approach can be the most effective (Alsharif et al., 2021).

5.2. Active power support

EVs require active power assistance in order to drain the batteries. Therefore, bidirectional V2G may be the only viable option (Mastoi et al., 2023). Typically, peak power is only required for a limited time during the day. Thus, it will be more economical to supply the peak load demand from distributed sources. By providing electricity to the power grid during peak load hours for peak load shaving, EVs can reduce the strain on power system components and increase profits for EV owners. Owners of EVs can charge their batteries at reduced energy rates during off-peak hours (Yang et al., 2024). Creating a demand on the grid during an off-peak hour is known as valley filling, whereas peak shaving is the process of lowering the peak grid load through load management.

To lower losses and improve the grid's load factor, EVs' load may be moved from peak to off-peak hours by controlling charging and discharging (Einaddin and Yazdankhah, 2020). With the peak load shaving method using V2G technology, the power equipment's capacity can be fully utilized, and unnecessary upgrade expenses can be avoided. In addition, time-shifting of EV charging to off-peak hours is a worthy strategy to prevent overloading and ageing of the power system equipment. V2G technology is utilized in (Ghafoori et al., 2023; Tepe et al., 2022; Elkholy et al., 2024), to analyze grid characteristics and peak load-shaving potential. The findings indicate that an effective energy management system can reduce power consumption by up to 6 %.

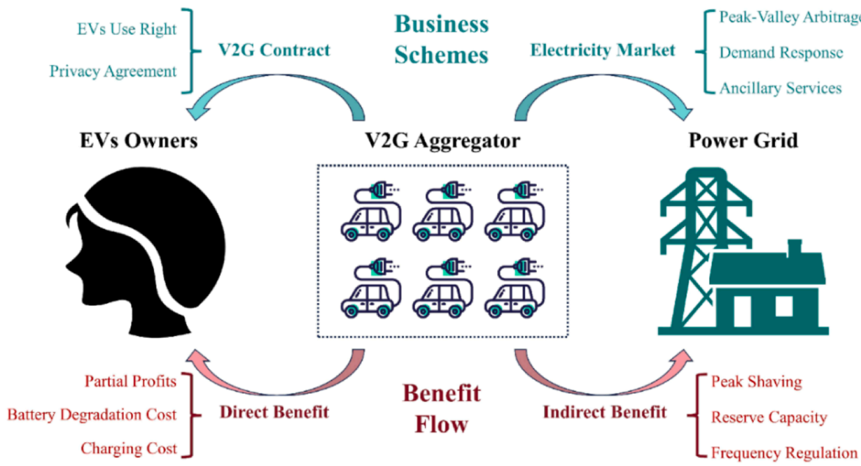

Fig. 9. V2G operational and benefits flow model (Wan et al., 2024).

Additionally, through capacity reserves resulting from onboard energy production, voltage and frequency stabilization, and peak shaving, onboard PV-based energy generation in battery electric vehicles (BEVs) broadens the application area of V2G technology for grid support.

5.3. Reactive power compensation

In the power system, reactive power compensation provides voltage control (Amamra and Marco, 2019). Additionally, power factor adjustment is offered via reactive power assistance, which lowers power losses in the power line and minimizes current flows from production. This service can also reduce power equipment loads, increasing the efficiency of the power system (Pirouzi et al., 2020). The DC-link capacitor of the EV bidirectional battery charger provides reactive power correction, ensuring that this service does not shorten the battery's lifespan. Several control algorithms are used to regulate the AC/DC converter's switching in order to accomplish reactive power compensation. Maintaining active and reactive power aims to lower grid voltage swings and energy purchase expenses. A two-level coordinated voltage control method for EV chargers (EVCs) is developed in (Wang et al., 2019a) to regulate low-voltage distribution networks. By detecting the crucial bus voltage and analyzing the control signals that interact between each EVC, a greater degree of voltage control is achieved. At the lowest level, each EVC's active and reactive power output is computed while accounting for charging loads and operational restrictions. The (Jabalameli et al., 2019) considers the EV to be both a source of active and reactive power. It proposes a control strategy that minimizes overall system costs, comprising loss, energy, and voltage imbalance costs, by optimally charging and discharging the EVs. In addition to providing a voltage control service, reactive power compensation based on day-ahead pricing signals is a cost-effective solution. EVs' active and reactive power is controlled to reduce transformers' energy loss and operating costs. By managing the reactive power, the proposed method may improve the voltage, power factor, and power quality indices (Madahi et al., 2021). For the reactive power compensation and voltage regulation involving EVs, a two-level hierarchical control technique based on model predictive control (MPC) is proposed in (Li et al., 2019a).

5.4. Support for renewable energy resources

Environmental factors significantly impact the availability of renewable energy sources. A fleet of EVs can be utilized as energy storage or backup to address the intermittent nature of renewable energy sources (Manousakis et al., 2023). In situations where renewable energy output is limited, the EV fleets act as backups, supplying the necessary electricity. In the meantime, they also serve as energy storage to take in surplus power from renewable energy resources (Sagaria et al., 2024). According to research, increasing grid-connected EV battery capacity enables the integration of more renewable energy into the power system. By modifying the schedule of customers' EV charging, an EV charging control strategy is outlined in (Kikusato et al., 2020) to minimize PV curtailment caused by a voltage rise in the low-voltage distribution network and regulate the amount of self-consumption of PV power.

EVs are designed to charge and discharge in a way that minimizes energy expenditures and supports the integration of renewable energy sources. Additionally, to reduce battery deterioration, the number of charging/discharging cycles is kept to a minimum. A framework for coordinating grid and residential energy management systems without interfering with EV use for driving is presented in (Kikusato et al., 2019). Using grid voltage constraint data from the grid energy management system and anticipated power, the home energy management system creates an EV charging and discharging schedule to reduce household running expenses and PV curtailment. To maximize the penetration of wind resources and minimize the cost of EV charging while accounting for battery degradation, a real-time scheduling algorithm for charging and discharging a fleet's EVs is presented in (Sharifi et al., 2020). It is taken into consideration to schedule wind farm systems and EV fleets in tandem with the day-ahead wholesale market. As a price-setting performer, the impact of coordinated wind farms and EV fleets on market outcomes and pricing is taken into account. Furthermore, the optimization problem's objective function takes into account the decrease of hazardous petrol emissions. In (Raoofat et al., 2018), the demand response of EVs is utilized for wind power curve flattening. A two-layer hierarchical controller is suggested where, in the higher layer, the ramp rate is estimated, and the request signal is transmitted to all the involved EVs. In the lower layer, a fuzzy controller is suggested by designing two fuzzy indices to quantify every EV's inclination to participate in the demand response program. These indices are deduced from the SOC and the remaining time before the EV departs from the parking lot.

The global V2G technology market is projected to grow at a compound annual growth rate (CAGR) of 26.6 %, rising from \$11.3 million in 2023 to approximately \$59.2 million by 2030, according to data from V2G-HUB, as of December 2023, 27 countries, 131 projects, and over 6800 bidirectional CPs are in operation globally (Market, 2023). In regional economic research at national or regional levels, researchers have utilized market surveys, financial models, and techno-economic models to evaluate the applicability and economic benefits of the V2G model in developed regions, including China (Zheng et al., 2021), Nordic countries (Sovacool et al., 2020), Denmark (Noel et al., 2018), Canada (Rahman et al., 2023), South Korea (Hong et al., 2012), and

Indonesia (Huda et al., 2020). These investigations validate V2G's capability to offer grid ancillary services and create economic advantages for electric vehicle owners and power companies. The ability of V2G technology to engage in peak-to-valley arbitrage is examined in (Shi and Guo, 2023), and it is determined that at the city level, V2G technology can shift 2.7–4.3 % of the charging load from peak to off-peak hours, resulting in considerable power cost savings.The energy management strategy of V2G technology in Shanghai's distributed PV housing was studied in (Chen et al., 2020). It was discovered that the transfer of power from photovoltaic generation and valley sources can improve the utilization efficiency of both systems while also producing significant financial benefits. Furthermore, the results indicate that China may save 2.02 % and 2.08 % on overall power system costs by 2030 if unidirectional and bidirectional V2G technologies are utilized. Furthermore, it might increase the proportion of wind and solar power generation in the energy mix by 1.33 % and 1.28 %, respectively, and reduce the power system's yearly carbon emissions by 2.27 % and 2.95 % (Yao et al., 2022). A cost-benefit analysis was performed in (Ahmadian et al., 2018), indicating that V2G technology could be a cost-effective choice in a power system with abundant wind resources. A different cost-benefit analysis conducted in Shanghai confirmed the effectiveness of V2G technology in facilitating peak shaving (Li et al., 2020). Additionally, in (Luo et al., 2020) demonstrated that integrating V2G technology resulted in an increase in solar PV installations at charging stations and a decrease in reliance on the grid. Moreover, the investigation into capacity expansion with V2G found that it could reduce planning expenses for further development of wind turbines or postpone the need for investment in energy storage, as well as in grid infrastructure (Mehrjerdi and Rakhshani, 2019).

6. Challenges of V2G

Despite its numerous advantages, V2G technology is still in its developmental stages. For it to achieve widespread adoption, a range of economic, technical, and social obstacles must be addressed.

6.1. Battery degradation

Despite the potential for contributions to the development of grid intelligence through the integration of V2G technology, battery lifespan remains a substantial technical impediment (Lehtola, 2025). Additional battery deterioration by frequent charge and discharge cycling for V2G users is one of the most significant barriers to V2G expansion (Harnischmacher et al., 2023). Grid demand, electricity pricing, and the user's needs must be considered. To manage this complicated situation, it is necessary to utilize intelligent control systems (Berk İslim and Çatay, 2022). To optimize charge and discharge cycles, researchers have been interested in developing sophisticated battery management systems (BMS) that utilize machine learning algorithms and predictive models to adjust charging depths and rates in real-time based on the battery's health (Wu et al., 2025). To prevent the misuse of EV batteries, a V2G control technique has been developed. The battery's state of health (SoH) has been continuously monitored, which has also successfully decreased the degradation. When operating on the grid, SoH monitoring enables V2G systems to limit the depth of discharge (DoD) actively. Research has demonstrated that the confinement of DoD within 20–30 % for each V2G session averts long-term degradation while preserving the potential to supply grid services. This balance ensures that V2G operations do not over-stress the battery. The balance between monetary and technical battery parameters is necessary to achieve maximum benefits for power utilities and EV owners (Acharige et al., 2023). In (Bhoir et al., 2021), several V2G services were simulated to examine their impact on battery degradation. Research indicates that the net load shaping, peak load shaving, and frequency regulation are the most degrading V2G services. The impact of primary frequency regulation service provision on battery ageing is described in (Calearo and Marinelli, 2020). The deterioration of lithium-ion batteries in BEVs is examined in (Sagaria et al., 2025). With the use of V2G technology, the compensation cost is determined when BEVs are utilized as the primary energy storage devices (Ortega-Vazquez, 2014).

6.2. High investment cost

The expensive cost of updating the power grid is another obstacle to V2G deployment. For V2G to be implemented, the infrastructure must be improved. A bidirectional battery charger would be required for EVs in the V2G system (Goncearuc et al., 2024). A bidirectional battery charger is subject to strict safety regulations and features an extremely complex controller. Frequent cycles of charging and discharging are necessary for V2G functioning; these energy conversion operations result in extra conversion losses. Significant energy losses to the electrical grid may occur due to various energy conversions associated with the extensive fleet of EV charging and discharging procedures (Adhikary et al., 2023). Bidirectional charging, commonly referred to as V2H technology, can serve as a backup power source in the event of a power outage or as an additional grid source for domestic charging purposes.

6.3. Vehicle to home (V2H)

V2H technology is fundamentally similar to V2G, with the key distinction being the direction of power delivery. In V2H, the EV supplies electricity directly to a connected home, rather than feeding it into the broader utility grid, enabling the operation of household electrical devices (Vadi et al., 2019). The vehicle powers the home, and the home powers the car when electricity is inexpensive or during a power failure. Therefore, home users can utilize their EVs as temporary storage by leveraging the extra energy to meet their requirements (Pillewar et al., 2022). A power meter at the grid main connection point is an additional device that has to be added to the V2H system. This meter is employed to track incoming and outgoing grid power. When the system detects that the house is drawing power from the grid, it alerts the bidirectional EV charger to drain it at the same capacity, thereby nullifying any grid consumption. Two-way electric vehicles can charge a house, export energy to the grid, and serve as a backup energy source during grid outages or disasters (Zafar and Slama, 2022). Fig. 10 illustrates the V2G, G2V, and V2H charging technologies in terms of power flow. Table 2 compares V2G, G2V, and V2H on different bases.

7. PV-powered EV charger

Single-source and hybrid energy systems are the two main categories of renewable energy systems that power EV chargers. Combining EVs

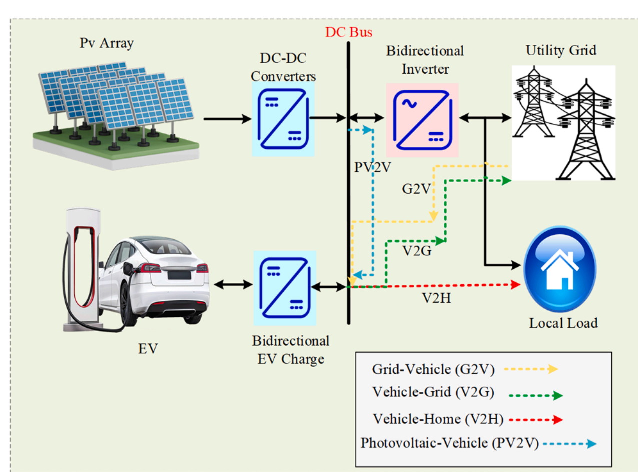

Fig. 10. EV charging technology (Venkatesan et al., 2024).

Table 2
Comparison between V2G, G2V, and V2H based on different aspects.

aspect	Vehicle to grid	Grid to vehicle	Vehicle to home
Power Flow	Bidirectional power flow from the grid to the EV for charging mode and from the EV to the grid in discharging mode	Unidirectional power flows from the grid to the EV in charging mode only	Bidirectional power flow from the grid to the EV in charging mode and from the EV to the home in discharging mode
Objectives	Charging EVs from the grid and vice versa helps stabilize the system and provides financial benefits to EV owners.	Charging EVs from the grid helps stabilize the system by controlling EV charging times.	Provide backup power to homes during outages or peak demand periods using stored energy in EV batteries.
Advantages	• Offer auxiliary services that enhance load levelling, active and reactive power support, power quality, and voltage profile. • Peak load shaving, frequency, and voltage control. • Reducing emissions and grid power losses. • Higher profit and improved load factors. • Make it possible for RES to integrate with the grid.	• Simple power control strategy • Reduced operational costs, power losses, emissions, overloading, and connectivity problems. • Supports renewable energy utilization by charging EVs during periods of high solar/wind generation, reducing reliance on fossil fuels and lowering emissions	• Provides energy independence by powering homes during outages or when the grid is unavailable • Reducing electricity bills by using stored energy in EV batteries to power homes during peak demand periods • Enhances grid stability by reducing the demand for grid electricity during peak times
limitations	• Fast battery degradation. • A complex control is required to ensure seamless integration with the grid and manage the bidirectional power flow. • High device stress, energy losses, capital costs, and complexity. • Smart meters and sensors are required.	• A power connection was necessary for certain services.	• Limited battery capacity may not be sufficient to power a home for extended periods. • High complexity and cost of implementation, like V2G. • Its impact on overall grid stability is limited compared to V2G.

and renewable energy resources with power networks brings about novel solutions to environmental and operational issues of contemporary energy systems (Rehman et al., 2023). Solar PV systems represent one of the most suitable renewable energy sources for charging EVs. They are efficient, their cost is decreasing, and they can be readily applied in urban and rural areas (Merrington et al., 2023). PV powered EVCS offer significant benefits compared to conventional grid-connected stations for a cleaner energy system (Sithambaram et al., 2025). For environmentally sensitive islanded areas, such as nature heritages, EVs and MGs can be considered simultaneously to achieve zero fossil fuel utilization. However, most islands do not have factory loads; therefore, the total load is higher in the evening than during the daytime (Chae et al., 2020). Additionally, EV charging loads are higher at night, depending on the consumer's lifestyle. These load patterns significantly reduce the peak contribution of PV power output, and a larger ESS may be necessary for MGs. However, due to their mobile nature, EVs differ significantly from energy storage systems. Even if there are enough EVs at the charging station, a V2G may not occur. Hence, it would shave peak power consumption or improve MG stability (Alrubaie et al., 2023).

Although PV-powered EVCS can improve MG stability, several factors must be considered. In this arrangement, the load voltage needs to be controlled due to variations in the PV voltage (Zhang et al., 2022). An EV system can absorb such variations. However, a DC-DC converter powered by MPPT is combined with the PV array to tackle this variation and ensure improved operation. This setup guarantees effective energy harvesting from the PV panels. MPPT mechanisms employ different algorithms to control the necessary DC voltage (Fachrizal and Munkhammar, 2020). However, PV system performance can be intermittent, weather dependent, and limited by the inability to generate energy during nighttime (Bhagat et al., 2023). A grid connection can act as a backup to mitigate these disadvantages by enabling the sale of any excess energy back to the grid, generating potential income streams, and enhancing overall energy reliability (Brenna et al., 2020).

Several studies comparing AC and DC architectures in solar-powered electric vehicle charging stations (EVCS) demonstrate that DC-coupled systems offer superior energy efficiency and system simplicity, particularly for bidirectional applications (Gerber et al., 2018; Cleenwerck et al., 2023) In (Yu et al., 2022), evaluated a novel hybrid AC/DC charging station with PV integration and found that the DC link reduced the number of conversion stages, resulting in 5–7 % higher energy efficiency compared to a pure AC-coupled setup.

Bidirectional AC-DC and DC-DC converters can enable active power sharing between the EV battery and the AC grid in both directions. An MG-based EV charging needs a strong, coordinated controller to ensure stable and reliable operation (Jang et al., 2021). Hence, a locally coordinated controller can easily switch between grid-connected operation and islanding mode. Additionally, a local controller can enhance the power quality of the EV charging MG system by eliminating all detrimental harmonic impacts on the utility distribution system introduced by the battery-charging process through appropriate active power factor correction. A hierarchical control architecture for V2G systems in EVs provides stability, efficiency, and economic optimization by dividing the control functions into three levels: primary for real-time response, secondary for medium-term horizon balancing, and tertiary for planning and optimization at long-term time horizons (Singh et al., 2021). The general approaches to hierarchical control in MG, along with the advantages of each level, are explained in the following section.

8. Hierarchical control technique

This technique comprises three control layers: primary, secondary, and tertiary. The primary control layer uses local source and load controllers to regulate the standard bus voltage. Meanwhile, the secondary control layer maintains stability by keeping the voltage and frequency within predetermined ranges. Finally, the tertiary control layer manages distribution and power flow within the system as part of the hierarchical control strategy (Shuai et al., 2018). By implementing a suitable hierarchical control architecture, the system can be more adaptable and scalable, allowing for the integration of additional distributed power units (Siviö et al., 2020). When a MG implements a hierarchical control system, it begins operations at the highest level of the system and progresses to the lowest level, automatically controlling the system's operation. The top and bottom tiers of this sophisticated control system function separately. However, the lower levels of the system cause disruptions that are immediately detected and compensated for by the control system, which transfers the impacts of the disturbance from the lower side to the higher side (Cárdenas et al., 2023).

8.1. Primary control for MG without an electrical vehicle

This is the bottom layer in the hierarchical control framework, which operates with the fastest response time to maintain real-time stability and performance (Liu et al., 2025). This control level modifies the frequency and amplitude of the voltage reference provided to the inner current and voltage control loops (Li et al., 2023). Additionally, the oscillations in the MG system caused by steady power-type loads are dampened by this layer. To provide effective power management, decentralized load-sharing control techniques can also be employed at this layer.

The primary control layer is primarily responsible for regulating bus voltage and ensuring proper power sharing among DERs in MGs. This layer directly manages the output power of converters using local measurements without requiring communication (Ahmed et al., 2021). To prevent overloading, power-sharing control is necessary to ensure equitable power sharing among units involved in voltage and frequency regulation (Anttila et al., 2022). The primary control provides the reference points for the voltage and current control loops of DERs (Mohammed et al., 2023). This principle can be integrated into voltage source inverters (VSIs) using the well-known P/Q droop method. The control strategies of AC MGs can be mainly divided into three types: P/Q control under grid-connected conditions, VF control, and droop control under the islanding mode of operation (Shahgholian, 2021). Fig. 11 shows the classification of primary control for MG.

Droop control's adaptability makes it the most popular dispersed control strategy. This method has been examined for islanding detection (Liu et al., 2022). Droop control's key benefit is power sharing without a communication link. This gives MG freedom and autonomy. Inverter-based generation in the MG is possible since it is not limited to DGs like synchronous machines (Fusero et al., 2019). Inverters can be connected in parallel using this control method (Pawar et al., 2021). Fig. 12 illustrates the circulation of active and reactive power in parallel VSIs. However, power sharing becomes inaccurate when the two inverters have different equivalent output impedances. Eq. 1 illustrates the active and reactive power transferred to a typical AC bus.

$$\begin{cases} p = \frac{EV}{Z}Cos(\theta-\delta) - \frac{V^2}{Z}Cos(\theta-\delta) \\ Q = \frac{EV}{Z}Sin(\theta-\delta) - \frac{V^2}{Z}Sin(\theta-\delta) \end{cases} \quad (1)$$

Where V and E are the amplitudes of the MG bus voltage and the inverter output voltage, δ indicating the phase angle between the MG bus voltage and the inverter output voltage. Z and θ are the amplitude and angle of the output impedance, respectively. Eq. 2 illustrates the V/f droop characteristics: as active power production increases, the load angle decreases, resulting in a lower frequency; conversely, as reactive power drawn increases, the terminal voltage declines in the MG's inverters. With a slightly lower frequency and terminal voltage, more reactive power and power can be extracted from the inverter. Its generating capability determines the droop characteristics of each inverter in an MG (Guerrero et al., 2011).

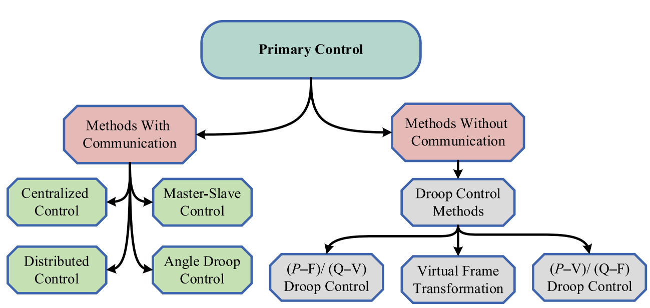

Fig. 11. Classification of primary control for an islanded MG.

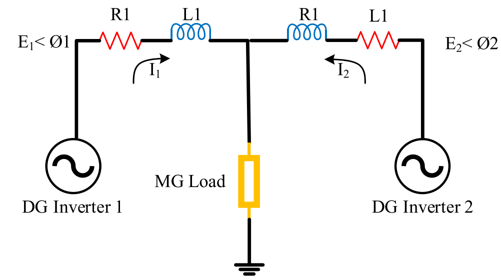

Fig. 12. Equivalent circuit of two parallel-connected inverters (Chen et al., 2018).

$$\omega = \omega^* - m(P - P^*) \quad (2)$$

$$V = V^* - n(Q - Q^*)$$

Where P^* and Q^* represent real and reactive power references, respectively.ω^* and V^* denote the grid-rated angular frequency and voltage amplitude. In contrast, ω and V are the references, while m and n indicate the slopes of the droop characteristics. The droop control strategy enables each distributed generator (DG) to allocate power demand following its droop characteristic function. Fig. 13 illustrates the droop characteristic.

Due to its inability to share harmonic signals, droop control is ineffective for nonlinear load units. To appropriately represent the harmonic current. The droop mechanism also affects power-sharing, which depends on unit output and line impedances. Therefore, virtual output impedance loops can fix this (Lin et al., 2019). Additional control variables include output impedance. Droop control is the most popular dispersed control method due to its versatility. Virtual impedance control combined with droop improves control performance by making the network more inductive (Han et al., 2016). The virtual impedance approach in primary control helps solve the power-sharing problem with parallel distributed generators (DGs). Eq. 3 shows the output voltage.

$$V_o^* = V_{ref} - Z_D(s).i_o \quad (3)$$

Where V_{ref} is the output voltage reference with no load, $Z_D(s)$ is the virtual output impedance, and (i_o) is the output current of the inverter (Guerrero et al., 2005). A virtual impedance loop is implemented to ensure the decoupling of P and Q and to make the system more damped without inducing additional losses. Fig. 14 illustrates the virtual impedance loop of the other control loops, including the inner current and voltage loops, as well as the droop control.

8.2. Primary control in microgrid with electric vehicles

Primary droop control offers several key benefits when used for microgrid EV charging. It enhances frequency stability by efficiently allowing EV chargers to respond to frequency fluctuations, which is critical in microgrids with significant renewable energy penetration (Veronica and Kumar, 2019; Gao, 2024).Droop control also improves voltage regulation, maintaining consistent voltage levels amidst intermittent renewable energy and dynamic EV loads, ensuring a stable power supply (Carrizosa et al., 2022). The droop control's autonomous power allocation feature facilitates efficient and flexible power distribution management between EVs and other distributed energy resources without a central controller. Droop control also stabilizes the microgrid's load by modulating EV charging levels according to the state of charge and grid conditions, thereby avoiding overloading and optimizing resource utilization (Shekhar and Alam, 2024).

Additionally, it reduces the adverse effect of EV fast charging on the primary grid by controlling the charging to minimize the stress on grid infrastructure, which is especially suitable for DC MGs (Saadati

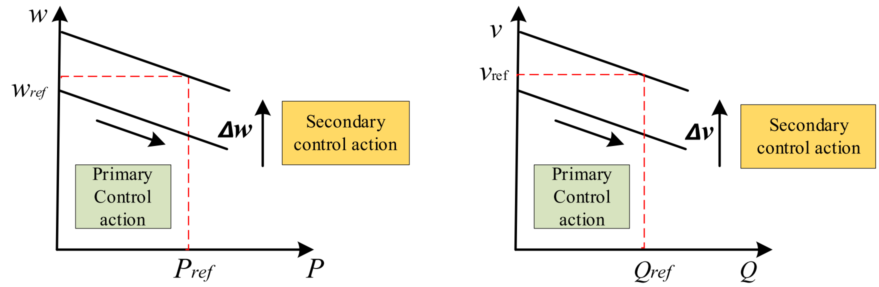

Fig. 13. P/Q droop functions (Jasim et al., 2023).

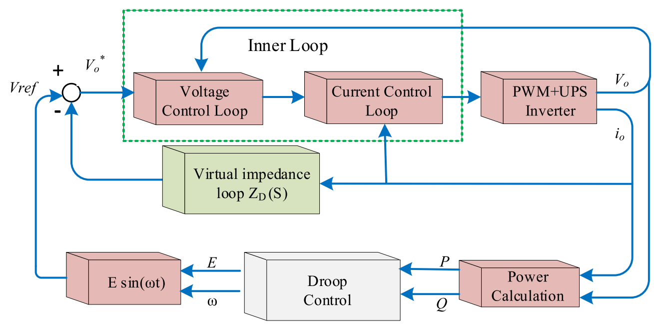

Fig. 14. Primary control loops.

Toularoud et al., 2024). Adaptive droop control methods enable EV chargers to respond more effectively to variations in grid conditions, allowing EVs to contribute to grid stability by providing ancillary services such as frequency regulation and voltage support (Liu et al., 2015). Doop control methods are robust and scalable and can be applied to MGs of different sizes and complexities. This ensures that the control system can handle increasing EVs and renewable energy sources without impacting performance (Shirkhani et al., 2023). The primary benefits of droop control in EV charging include improved frequency stability, voltage regulation, autonomous power sharing, load balancing, less grid effect, adaptive response, and scalability and robustness, which make it a valuable tool for the integration of EVs into MGs and improving the overall efficiency and reliability of the energy system.

The drawbacks of droop control for EV charging in low grid capacity areas include some technical issues. The significant issues of concern are the stable frequency and voltage levels owing to the intermittent behavior of EV charging loads and the grid's inability to absorb such fluctuations (Liu et al., 2015), the power quality issues in the form of voltage sags, swells, and harmonic distortions are amplified, causing possible grid instability and overloading (Aurangzeb et al., 2023). The random nature of EV charging instances and high power requirements may cause peak loads, compromising grid stability. Furthermore, the complexity of tuning the droop coefficients, the unavailability of communication infrastructure, and the requirement for high processing rates and response times are also significant challenges. Traditional droop control limitations on current sharing accuracy and dynamic load compliance are substantial challenges in effectively regulating EV charging (Yong et al., 2023).

In the context of large-scale EV integration, the primary control layer must be capable of adapting to rapid and unpredictable changes in power demand and injection due to stochastic EV charging and discharging behavior, especially under V2G operations. To preserve microgrid stability under these conditions, recent literature emphasizes the use of adaptive droop control strategies that dynamically adjust the droop coefficients based on real-time voltage, frequency, and current conditions. A coordinated sectional droop charging control method for an EV aggregator engaged in a microgrid frequency regulation is presented in (Zhu et al., 2018). Research on droop control techniques for energy scheduling in grid-connected systems, which attests to the viability of droop control for bidirectional power flow and reducing total harmonic distortion (THD) in EV charging stations, is suggested in (Ghosh et al., 2024). In (Qin et al., 2020), adaptive bidirectional droop control is developed for Freedom EVs, enabling them to charge or discharge with a specified power autonomously. This control, based on the state of charge, battery capacity, remaining time, and other parameters of each EV, stabilizes the MG.

8.3. Secondary control in microgrid without electric vehicles

Secondary control refers to the management of energy in an MG system or the supervisory control level in a hierarchical control system. The secondary level balances the tertiary and primary levels by managing the mismatch between set points and MG power measured in the primary level (Yamashita et al., 2020). This control is slower than the primary control, as it decreases communication bandwidth by utilizing sampled microgrid variables and performing complex calculations. This control ensures MG's dependability, economy, and security. This control layer is relevant when the MG enters island mode with scattered energy sources. This control level can have synchronization loops. It restores system frequency levels to reference values when the primary control fails. Secondary controllers typically compensate for frequency variation and voltage range. In multi-bus MGs, the secondary control maintains the voltage profile of all AC buses within working limits (Cheng et al., 2023). During synchronization, this control layer provides microgrid network connection conditions. This layer also ensures MG power quality and smooth operation (Singh et al., 2021). Unlike the primary control, the secondary control coordinates all regional generating units via large-area communication systems.

For this control level, distributed, centralized, and decentralized control systems have been utilized (Tayab et al., 2017).Centralized, decentralized, or distributed secondary control mechanisms can be used depending on the type of communication (Razmi and Lu, 2022). Small MGs employ centralized control, whereas large ones utilize distributed methods. Centralized control controllers use internal control loop principles. Centralized mechanisms, which are frequently employed for small MG that are initially manually controlled, were utilized to assess MG control (Khayat et al., 2020). This technique uses a microgrid central controller (MGCC). The MGCC receives data from DG units, compares it to control variables, and transmits control commands to units via high-bandwidth communication links (Hasan et al., 2023). Communication is essential to the smooth running of a centrally controlled system.

The central controller demands faster communication, which may not be possible in a large area (Yoldaş et al., 2017). Changing the pre-configured central master controller settings for an upgraded environment can be a challenging task. Because the master controller failure stops secondary control activity, the MGCC is less secure (Zhou et al., 2020). The secondary layer uses decentralized and distributed control to address these challenges. Each DG must use distributed techniques to acquire neighboring information to avoid a single point of failure (Babayomi et al., 2022). The decentralized control does not need a local controller to communicate with other regional or central controllers, but some local controllers can communicate with the neighboring control unit, reducing communication (Shirkhani et al., 2023). With low communication, complete decentralized control is also impossible because system units are highly interconnected and can render the system unstable or underperforming. A third technique, dispersed control, can trade off the two controls (Palizban and Kauhaniemi, 2015a). Fig. 15 shows secondary control designs. A distribution secondary control strategy is proposed for voltage restoration and power sharing during island operation. Unlike other secondary controller strategies, it is based on the feedback concept and can only be designed for every DG if every bus's voltage is accessible (Shafiee et al., 2013). In contrast, distributed control uses local controllers for each DG to distribute secondary control functions. Every DG only communicates with a subset of its neighbors across low-bandwidth channels (Bidram et al., 2013)

Secondary layer functions vary across different literature sources; however, the consensus among authors is the same: at this level, secondary voltage and frequency control do exist. Energy management (EM) operations vary, to which authors attribute the functions of secondary or tertiary hierarchical control levels; all EM systems operate on the same level or, in some applications, split tasks between these two levels. The selection of a suitable control method for microgrid control depends on the objectives and characteristics of the MG considered. Furthermore, the resources available are important parameters in selecting the control method, such as centralized, decentralized, and distributed (Alam et al., 2019).

8.4. Secondary control in microgrid without electric vehicles

Secondary control in EVCS is a key level of a hierarchical control system, higher than the localized activity of primary control, for managing the charging activity of a fleet of electric vehicles. Its primary task is to enhance charging for both user benefit and grid stability by aligning the charging schedule to reduce grid stress, optimize the use of renewable energy, and lower charging costs. This involves sophisticated algorithms considering real-time grid conditions, EV battery state-of-charge, electricity price, and user preference (Ray et al., 2023).

In the presence of stochastic power flows and large scale of EV participation, secondary control enables EVs with V2G capability to participate in ancillary services markets, providing crucial grid support services such as frequency regulation, voltage support, and demand response (Zheng et al., 2018). Successful deployment depends on the availability of a secure communications infrastructure that links a centralized or distributed controller to EV charging points and other grid equipment, allowing for the collection and processing of relevant data.

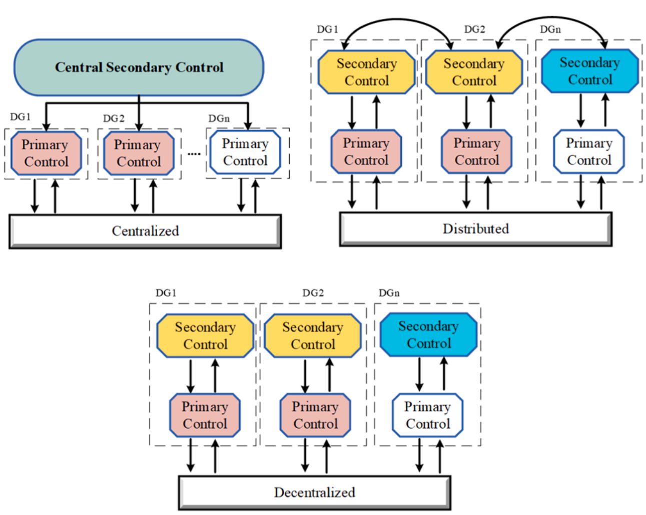

Fig. 15. Centralized, distributed, and decentralized architectures of secondary control.

Secondary control acts as a link between primary control and higher-level energy management, turning general commands into charging instructions that support smooth EV integration and a more stable, efficient power system. Secondary control of EV charging offers significant benefits in terms of efficiency, safety, and energy management, but at the expense of increased complexity, cost, and maintenance issues. Secondary control systems largely rely on a reliable communications infrastructure to operate effectively. When the communications infrastructure is weak or unstable, the performance of the control system may be compromised, thereby affecting the overall charging experience (Yang et al., 2018).

8.5. Tertiary control in microgrid without electrical vehicles

Tertiary control is the highest degree of intervention after secondary control, coordinates and manages several microgrids that communicate to improve the upper-level system power quality (Liu et al., 2020).Tertiary control is called supervisory control, which control the MG power exchange. The active and reactive grid powers are compared to the intended reference values by monitoring the P/Q ratio at the PCC (Palizban and Kauhaniemi, 2015b). The last control level has the slowest response and optimizes microgrid operation economically and technically. Centralized and decentralized tertiary control are possible.

Cost determines tertiary control technique selection. The tertiary control level replenishes the secondary control reserve and manages microgrid congestion in island mode. Power injection is coordinated by resource availability and demand. Tertiary control balances loads and ensures seamless transitions between grid-connected and islanding modes. Both islanded and connected operational modes require DG communication because of the different tasks performed by the tertiary control level. Communication helps DGs coordinate actions and enhance MG performance. Tertiary control can be more efficient and reliable with an advanced communication infrastructure and clever algorithms. Eq. 4 calculates the error between the reference and actual data to ensure quality power-sharing (Sahoo et al., 2017).

$$\omega^* = k_{pP}(P_G^* - P_G) + k_{1P}\int (P_G^* - P_G)dt \tag{4}$$

$$V^* = k_{pQ}(Q_G^* - Q_G) + k_{1Q}\int (Q_G^* - Q_G)dt$$

Where P_G^* and Q_G^* are the real and reactive power references for power transfer from VSC to the primary grid, ω* and V* are the corresponding frequency and voltage setpoints to be applied at the secondary control level to restore the frequency and amplitude of the output voltage of the VSC. kp and ki are the proportional and integral gains of the PI compensator. Subscripts P and Q are used as compensators for frequency and voltage restoration. *The principal stages of the three layers* of hierarchical control can be summarized in Fig. 16.

The main objectives of a three-layer hierarchical control system can be illustrated in Fig. 17.

8.6. Tertiary control in microgrid with electrical vehicles

Tertiary control optimizes energy distribution, often using an EMS. Energy generation and consumption are monitored, controlled, and optimized by the EMS (Liu et al., 2020). The EMS also forecasts renewable energy generation, load consumption, weather, and prices. The EMS controls electric vehicle charging to limit grid power intake while the MG is connected to the grid (Salvatti et al., 2020). This enables the EMS to optimize energy use and reduce electricity costs. Hierarchical EVCS control limits the data exchanged between operators. The system is more reliable in the event of communication or computation failures. At the tertiary control level, managing power exchange and economic coordination across microgrids becomes increasingly complex when

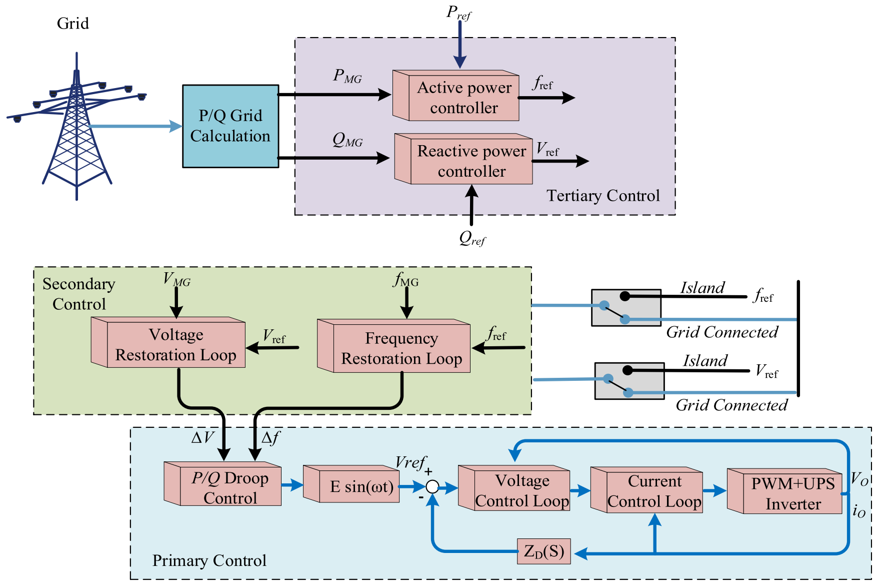

Fig. 16. Overall stages of the three layers of hierarchical control (Guerrero et al., 2011).

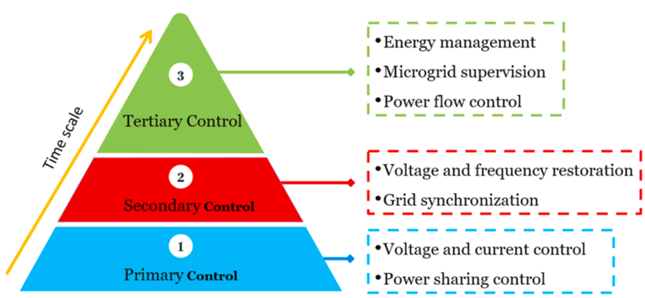

Fig. 17. Overall, the hierarchical control layers have objectives for EVCS (Mohammed Amine et al., 2023).

bidirectional EV energy flows and stochastic renewable inputs are present. Fig. 18 shows the hierarchical role in EVs.

Modern tertiary control architectures utilize MAS that enable decentralized, autonomous decisions while maintaining system-wide objectives, such as cost minimization, load balancing, and energy trading (Rashidi et al., 2021; Zhang and Wu, 2025). These agents can dynamically reconfigure their behavior based on real-time EV fleet availability, electricity price signals, and local MG conditions. To address uncertainty, recent works also incorporate distributed consensus algorithms and game-theoretic approaches, which help achieve stable and efficient outcomes despite variability and communication delays. These developments are particularly important for scaling EV participation while preserving overall microgrid stability. Fig. 19 shows typical electric vehicle charging station EMS designs (Vishnuram and Alagarsamy, 2024).

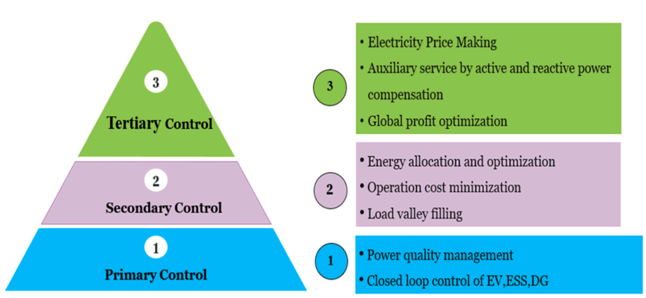

Fig. 18. Function of hierarchical control for MG with EVs (Wu et al., 2022).

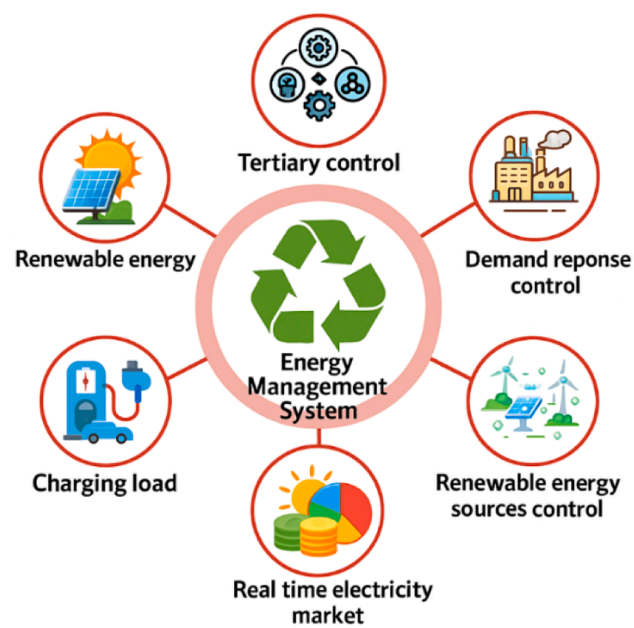

Fig. 19. Typical EMS design for EV charging stations (Vishnuram and Alagarsamy, 2024).

9. EMS design within different controls for EVCS

Other optimization techniques for EMS in EVCS are divided into traditional and AI-based methods. The first group includes proven techniques such as model predictive control, stochastic and robust programming, mixed-integer linear programming, and linear programming. AI EMS approaches consist of fuzzy logic and neural network techniques (Sora et al., 2024). Fig. 20 shows how a forecast-based scheduling system supports energy management in a MG with EVs. It uses predictions of solar energy, wind energy, electricity demand, and EV availability to make intelligent decisions about when to charge or discharge EVs. Based on this data, the system sends power dispatch signals to the microgrid and control commands to the EVs. This setup

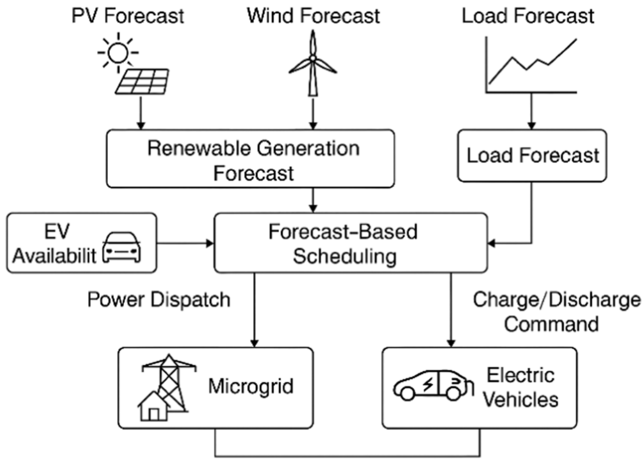

Fig. 20. Schematic of predictive and control for renewable-driven EV charging in MGs.

helps optimize renewable energy use, reduces waste, and maintains grid stability while meeting user needs.

9.1. Linear programming (LP) and mixed-integer linear programming (MILP)

LP and MILP have been widely adopted in the EV charging scheduling problem due to their effectiveness in handling complex constraints and optimizing charging schedules. MILP models are commonly used for developing networks of EV charging stations, coordinating charging operations, and optimizing EV charging and discharging because of their capacity to handle discrete variables and limitations (Moghaddam and Akbari, 2022). LP methods are also applied, especially for problems that can be formulated as linear optimization problems, to optimize power supply and manage energy demand efficiently (Li et al., 2024a). In (Chawal et al., 2024), an EV charging station system was optimized using the MILP model. It presents a two-stage framework that combines the system design challenge in the first stage with the EV charging station control problem in the second stage. In (Umetani et al., 2017), a linear programming technique implementing a heuristic algorithm for scheduling the charging and discharging of EVs was developed. The algorithm also addresses uncertainties in EV departure and load demands, thereby flattening the load profiles.

9.2. Model predictive control (MPC)

A robust model predictive control technique for islanded MGs was suggested in (He et al., 2021)and (Zhai et al., 2017) to cope with the dynamic behavior of loads and RES output. The framework incorporates a mixed deterministic integer programming model for energy management to minimize costs, along with an online energy scheduling strategy that assists the MG in adjusting accordingly to various unforeseen risks in energy management. This approach improves the reliability of the MG's operational management and minimizes the system's operational costs to some extent.

9.3. Stochastic and robust programming technique

A promising approach to maximize renewable energy utilization and minimize curtailment in islanded microgrids with limited storage involves stochastic scheduling of EV charging/discharging. A two-stage stochastic programming model that co-optimizes the sizing and operation of PV, battery energy storage system (BESS), and EV chargers under uncertainty is proposed in (Dongxiang and Chengbin, 2020). Their framework aligns EV demand with variable renewable output, reducing energy losses and improving self-consumption in off-grid applications. In (Dong et al., 2025), a stochastic optimization framework is proposed for a PV-BESS-EVCS system, which dynamically adjusts EV charging and discharging schedules based on PV and storage availability. These two methods significantly reduced curtailment and enhanced renewable utilization compared to deterministic control strategies. These models highlight how two-stage and rolling-horizon stochastic techniques, when applied to MGs with EV flexibility, can reduce curtailment and support resilient, renewable-rich islanded operation, even under limited storage capacity. A hybrid stochastic and robust optimization method was proposed in (Chang et al., 2020) to reduce the electricity cost and overcome some challenges of uncertainties in RES generation, load demand, and grid tariffs. The technology selects stochastic electricity price scenarios, and then the robust optimization strategy manages uncertainties in RES generation and loads for each price scenario.

9.4. Fuzzy logic technique

A simple and low-cost EMS for islanded DC MG based on a PI controller and a fuzzy logic algorithm was presented in (Nasab et al., 2019). This control strategy utilizes supercapacitors, allowing for high charging and discharging cycles, which reduces stress on the battery's energy storage and results in a longer battery lifetime. The EMS recovers the DC bus voltage in the power imbalance between supply and demand.

9.5. Neural network technique

A Lagrange programming neural network was employed to optimally schedule a hybrid MG while maximizing power generation and minimizing the cost function (Wang et al., 2019b). To offer a cost-effective solution, the loads are separated into four categories: thermal, price-sensitive, controlled, and critical. This approach uses RES power generation as input data for the control mechanism and a radial basis function neural network to forecast day-ahead load demand. From the simulations obtained, the method proved its ability to determine the optimal solutions for the ESS and power generation resources. Table 3 compares various optimization techniques for EMS, including classical and AI-based approaches.

To improve the effectiveness, stability, and integration of EVs with MGs, several control and energy management techniques have been investigated. The proposed EMS employs a dynamic programming approach, utilizing future projections of PV generation and demand to optimize both G2V and V2G. This method reduces grid dependence and enhances the efficiency of microgrids. However, it faces scalability challenges and requires high computational power, which may impact real-time processing (Salvatti et al., 2020). A droop-inspired nonlinear control strategy ensures a stable DC voltage. It provides ancillary services, such as frequency support, but lacks the secondary and tertiary control levels necessary for optimal power management and long-term stability (Carrizosa et al., 2022). A fuzzy logic controller effectively manages power flow, integrates solar PV and battery storage systems, and maintains bus voltage levels. However, it increases system complexity due to multiple power conversion stages and tuning requirements (Hadero and Khan, 2022). The fuzzy-sparrow search algorithm (SSA) optimizes power management and enhances energy resource utilization, but real-time data collection and computational efficiency present significant challenges (Mohan and Dash, 2023).

Using the Lyapunov stability criterion, the ANN with Integral Terminal Sliding Mode Control (ITSMC) ensures efficient MPPT, DC voltage regulation, and safe EV charging. However, it assumes a constant renewable power supply, which may not reflect real-world fluctuations and suffers from computational complexity (Mehdi et al., 2023). A novel energy management strategy reduces grid consumption and maximizes solar energy usage, but it is not generalized for large-scale MGs and struggles with accurate battery modeling (Bouhedir et al., 2025). An intelligent charging station employing fuzzy logic and a decentralized

Table 3
Comparisons of different optimization techniques for EMS based on various strategies.

Methodology	Advantage	Disadvantage	Main Applications
Linear Programming (LP) (Li et al., 2024a)	It provides optimal control actions, handles constraints and multi-objective optimization, and is suitable for dynamic and uncertain environments.	Increase battery degradation of EVs as a result of full discharge	LP is used for problems formulated as linear optimization problems, such as optimizing power supply and managing energy demand.
Mixed-Integer Linear Programming (MILP) (Chawal et al., 2024)	1. Enhance MG by lowering the cost of operation. 2. Capable of solving large optimization problems in a reasonable time	The model does not consider the cost that comes with battery degradation	MILP is used for problems that require discrete decision-making, such as scheduling charging operations, coordinating charging stations, and optimizing the operation of hybrid power sources.
Model Predictive Control (MPC) (He et al., 2021)	1. Reduced operation cost 2. Help stabilize the MG voltage	1. Increase the battery degradation of EVs as a result of full discharge	1. Real-time control of microgrids 2. Optimal scheduling of energy storage systems3. Dynamic load management in smart grids
Stochastic and robust programming technique (Chang et al., 2020)	1. Minimize the cost of MG 2. Enhance MG reliability due to the realization of expected energy losses and load expectation losses.	1. Complex formulation, hence resulting in high computational time 2. Increase the battery degradation of EV as a result of full discharge	Managing uncertain energy demand and optimizing charging schedules under uncertainty.
Fuzzy logic technique (FLC) (Hadero and Khan, 2022)	1. Improved battery life 2. Help energy exchange with the grid and minimize the fluctuations	1. Does not consider power losses and the voltage and frequency regulation of MG 2. Complex formulation, hence resulting in high computational time	Real-time control of EV charging, optimizing energy usage, and managing battery state of charge.
Neural network technique (Shahriar et al., 2020)	1. Optimize MG performance through the maximum utilization of RES and DER. 2. Improved battery life 3. Minimized import of power from MG	1. Complex formulation and computational time 2. The performance depends on a specified setpoint	Predicting energy demand, optimizing energy distribution, and adaptive control of EV systems.

EMS effectively stabilizes DC bus voltage and ensures reliable energy flow. However, system efficiency varies with EV availability, and fuzzy logic requires precise tuning (Abraham et al., 2023). The Improved Honey Badger Algorithm (IHBA)- based EMS optimizes G2V/V2G operations using PV forecasts, thereby reducing energy imbalances and improving load distribution. However, it requires high processing power and struggles with real-time implementation (Srihari et al., 2024).

A rule-based power management strategy efficiently handles EV charging under power limitations, reducing grid dependency while ensuring stable operation. However, system performance is affected by unpredictable EV arrivals, variations in SoC, and dynamic energy demands (Wang et al., 2020a). The Searching Peak and Valley Algorithm (SPVA) manages energy flow, reducing grid dependence and enhancing charging reliability. However, its effectiveness depends on real-time variations in SoC and computationally demanding control algorithms (Wang et al., 2020b). A Fuzzy Inference System (FIS) optimizes PV utilization, increases self-consumption, and reduces grid dependency; however, its high computational demand makes real-time implementation challenging (Mouelhi et al., 2024). The Dollmaker Optimization Algorithm (DOA) and Spatial Bayesian Neural Network (SBNN) enhance EV charging efficiency by predicting demand and optimizing power distribution in hybrid MGs, reducing computational time. However, metaheuristic optimization introduces complexity, requiring advanced forecasting for real-time performance (Eswar et al., 2025). Sliding Mode Control (SMC) and Fuzzy Logic Control (FLC) have been proposed for EV fast-charging stations for microgrid stability. SMC outperforms FLC by providing faster response and lower voltage ripple. However, SMC is highly sensitive to system parameters, requiring accurate modeling, and both methods demand significant processing power (Mohammed et al., 2022). Similarly, Particle Swarm Optimization (PSO)-tuned fuzzy logic controllers improve DC bus voltage regulation and energy distribution, but require extensive computational resources, making real-time applications challenging (El Mezdi et al., 2024).

A Flow Direction Algorithm (FDA)-tuned CNN effectively balances power between DC and AC MGs, optimizes EV charging/discharging, and mitigates grid disturbances. However, it requires sophisticated real-time data integration and processing, making practical implementation complex (Prasanna Lakshmi and Premalatha, 2025). An energy management and control system for DC MGs is proposed to enhance power flow management and ensure stable EV charging. However, its efficiency is limited under low solar and wind conditions, with battery storage not compensating for prolonged low-generation periods (Sayed et al., 2019). Despite advancements, several limitations persist. Many algorithms and control strategies face real-time implementation challenges due to computational complexity. Intermittency, battery storage limitations, and forecasting accuracy constrain renewable integration. Moreover, EV-based power management is influenced by vehicle availability, SOC, and scheduling complexities (Dev et al., 2025). Scalability remains a concern for large-scale microgrid applications, necessitating more advanced control and optimization techniques to address these challenges. These findings highlight the progress and ongoing challenges in EV charging, microgrid stability, and renewable energy integration, emphasizing the need for robust, efficient, and scalable solutions. Different control strategies for EVs have been proposed, as illustrated in Table 4.

10. Future directions for microgrid with EV integration

Although considerable progress has been made towards incorporating EVs into microgrids, current literature lacks cohesion regarding control hierarchical levels, stability modeling, compatibility, and standardization. A current trend of existing literature reveals a focus on specific topics, including converter control and energy management communications, without a unified structure that facilitates synchronization and stability with increased levels of EV integration (Dev et al., 2025; San et al., 2020; Li et al., 2024b, 2019b; Liu et al., 2023; Park and

Table 4
Comparisons between different control techniques for EV charging.

Ref.	Microgrid		RESs &Storage	V2G Capability	EMS	Method used	Remarks
	MG Operation	MG Type					
(Salvatti et al., 2020)	GC	AC	PV	√	√	Dynamic programming technique	**Pros:** • The proposed EMS reduced grid dependencies and improved the MG efficiency. • The model can be extended to various microgrid configurations and power generation capacities. • The EMS operates in real-time, ensuring dynamic and responsive management of energy resources **Cons:** • Dependence on forecast accuracy The EMS requires significant processing power for real-time optimization, particularly as the number of EVs increases.
(Wang et al., 2020a)	GC and IS	DC	PV and Battery	x	√	Real-time rule-based algorithm	**Pros:** • Reduced grid reliance • Reliable EV charging • Economic benefits from interaction with EV drivers **Cons:** • The number of connected EVs and their SOC levels affect the system's efficiency. The system must handle dynamic variations in EV arrivals and energy demands, making real-time optimization and control implementation complex.
(Carrizosa et al., 2022)	GC and IS	DC	PV	√	x	A droop-inspired nonlinear control strategy	**Pros:** • Provides ancillary services to the AC grid. • Effective in scenarios with varying numbers of connected EVs. • No need for extensive storage infrastructure. • Ensures DC grid voltage stability. **Cons:** • Long-term stability depends on SoC and ongoing power flow. • Secondary and tertiary control levels are not covered. Real implementation of nonlinear controllers can be complex and require "trial and error" methods.
(Hadero and Khan, 2022)	GC and IS	DC	PV and Battery	X	√	FLC	**Pros:** • Solar PV reduces reliance on the grid. • The FLC keeps bus voltage within an acceptable range regardless of load variations and intermittent power from renewable energy sources. **Cons:** • FLC requires proper tuning and design. • System efficiency depends on the number of connected EVs. Multiple power conversion stages lead to energy losses.
(Abraham et al., 2023)	GC and IS	DC	PV and Battery	√	√	FLC	**Pros:** • The system adapts rapidly to variations in power supply and demand. • The FLC maintains DC bus voltage regulation and prevents power fluctuations. • The system operates reliably under various microgrid conditions, ensuring seamless power flow. **Cons:** • Dependence on EV availability. Complex tuning of FLC
(Mohan and Dash, 2023)	IS	DC	PV, FC, and Battery	X	√	Fuzzy-SSA	**Pros:** • Effectively addresses fluctuations in an MG and enables EV charging using intelligent hybrid energy management control. • Fuzzy-SSA can optimize the power management of the DC microgrid, making better use of energy resources.

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Table 4 (*continued*)

Ref.	Microgrid		RESs &Storage	V2G Capability	EMS	Method used	Remarks
	MG Operation	MG Type					
							Cons: • Fuzzy-SSA requires proper tuning and design. • Computational Efficiency Challenges in real-time implementation
(Mehdi et al., 2023)	GC and IS	Hybrid	PV, WT, SC, FC and Battery	√	X	ITSMC	**Pros:** • This approach ensures stable DC bus voltage regulation with minimal steady-state error, even under varying load and generation conditions. • The use of an ANN for MPPT optimizes PV energy utilization, enhancing system reliability. **Cons:** The ITSMC requires significant computational resources, making real-time implementation challenging for lower-end microcontrollers.
(Bouhedir et al., 2025)	GC	AC	PV, Battery	x	√	A novel energy management strategy	**Pros:** • Maximizes PV energy utilization, reducing dependency on the primary grid. • Uses a rule-based approach that eliminates the need for complex forecasting. • Dynamically adjusts charging and discharging based on real-time conditions. **Cons:** • Excess solar energy may go unused or be inefficiently injected into the grid without a vehicle plugged in. In low irradiance conditions, energy supply may not be sufficient, requiring grid reliance or additional storage.
(Srihari et al., 2024)	GC	AC	PV and Battery	√	√	IHBA	**Pros:** • Stable load profile • Reduced grid reliance • Efficient energy management **Cons:** • Dependence on forecast accuracy. • Energy management efficiency is affected by the number of connected EVs and their SOC levels. Complex implementation.
(Wang et al., 2020b)	GC	DC	PV and Battery	√	√	SPVA	**Pros:** • Reducing grid dependency • Enhancing charging reliability • The proposed system sets different power limits for peak and valley periods, ensuring the stability of the public grid. • Effectively manage energy flow. **Cons:** • The system's efficiency fluctuates based on the number of connected EVs and their state of charge (SOC). • The real-time EMS relies on complex control algorithms, which increase computational requirements and make implementation more challenging. The system's success relies on user compliance with optimal charging/discharging schedules. User behavior variation can affect the ability to achieve peak shaving and valley filling.
(Mouelhi et al., 2024)	GC	DC	PV and Battery	x	√	FIS	**Pros:** • Efficient power management prioritizes PV production for EV charging, stationary storage, and the power grid. • Reduced energy costs and better synchronization between energy generation and demand. **Cons:** • Implementing the FIS method requires detailed modeling and precise input parameters, which can be complex and resource-intensive. The effectiveness of the control and management strategies relies heavily on accurate and timely data regarding EV

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Table 4 (*continued*)

Ref.	Microgrid		RESs &Storage	V2G Capability	EMS	Method used	Remarks
	MG Operation	MG Type					
							characteristics, PV production, and user behavior. Inaccurate or delayed data can impact the performance of the system.
(Eswar et al., 2025)	GC and IS	DC	PV, WT, SC, and Battery	x	x	DOA and SBNN	**Pros:** • The method enhances the reliability of EV charging stations by effectively managing MG fluctuations and predicting EV load demand. • The proposed method has a lower processing time, making it more efficient for real-time applications. **Cons:** • Computational complex and expensive, especially in highly nonlinear and dynamic MG environments. The system's efficiency depends on balancing supply and demand in real-time, particularly during grid isolation scenarios, which may require advanced forecasting and real-time control strategies.
(Mohammed et al., 2022)	GC	DC	PV	√	√	SMC and FLC	**Pros:** • Fast and Efficient Charging. • This control eliminates single points of failure, making the system more reliable. • Effective in addressing voltage sag and power losses by using an EV battery. **Cons:** • Advanced controllers like SMC and FLC require complex computation for tuning and implementation. The system needs robust computational resources for real-time execution.
(El Mezdi et al., 2024)	GC and IS	Hybrid	PV, WT, and Battery	x	√	FLC and PSO	**Pros:** • Improves renewable energy use, • Reducing reliance on the grid • Dynamically balances energy flow between different sources and loads, optimizing performance and ensuring stability under varying conditions. **Cons:** Using PSO to optimize fuzzy logic control parameters increases the computational burden, which may require high processing power for real-time operation.
(Prasanna Lakshmi and Premalatha, 2025)	GC	hybrid	PV, WT, and Battery	√	√	FDA and CNN	**Pros:** • The proposed method effectively balances power between DC and AC microgrid components, loads, and EV charging and discharging. • Enhances grid stability and reliability while mitigating disturbances. • FDA with CNN enables real-time, intelligent decision-making based on historical data. **Cons:** • Training CNN with the FDA requires significant computational resources, which may limit its real-time deployment in low-power embedded systems. The model relies on high-quality historical data for accurate forecasting. Inaccurate or missing data can impact the system's prediction capabilities.
(Sayed et al., 2019)	IS	DC	PV, WT, and Battery	x	√	Master slaves	**Pros:** • The proposed control strategies provide excellent performance under different operating conditions. • The system is designed to withstand disturbances and recover quickly, maintaining a stable DC-link voltage despite fluctuations in renewable energy generation. • BESSs increase the reliability of the system **Cons:** • If the solar irradiance and wind speeds are too low, energy production may not meet demand because it works only in islanded mode. Battery storage helps, but it has limited

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Table 4 (*continued*)

Ref.	Microgrid		RESs &Storage	V2G Capability	EMS	Method used	Remarks
	MG Operation	MG Type					
							capacity and may not be sufficient during extended periods of low generation. • The EMS requires advanced control algorithms and precise monitoring to ensure optimal operation. The system's reliability heavily relies on the battery storage unit, which may degrade over time, leading to increased maintenance costs.

Moon, 2022; Sajid et al., 2025; Altin et al., 2023; Ahmad et al., 2024; Garg et al., 2019; Mekkaoui et al., 2024). Table 5 presents the main research gaps and respective future works obtained by this survey to shed some further insight on key areas where current techniques fall short and more complex solutions, including multi-input multi-output (MIMO) analysis for stability modeling and digital twin-assisted control, along with secure market-driven EV aggregation techniques, are further needed to advance the ongoing trend.

Table 5
Research gaps and future direction for EV integration in microgrids.

Research area	Limitations	Identified research gaps	Future research directions
Hierarchical control coordination	Conventional droop and secondary control lack coordination with fast EV dynamics; limited SoC-awareness.	Lack of multi-layer coordination between EVs and MH control loops under varying SOC and grid modes.	Develop multi-timescale control with predictive EV models and distributed optimization, ensuring real-time coordination among EV charging and storage systems.
Stability of converter-dominated EV integrated microgrids	Most studies use small signal or signal inverter models.	In a sufficient MIMO stability framework for multiple grid-forming and EV chargers interacting through ordinary buses.	Formulate generalized stability or μ-analysis criteria; validate experimentally on multi-inverter-multi-charger microgrids.
Communication and Cybersecurity	Standards communication protocols focus on interoperability, not resilience.	Sparse studies on cyber-attacks targeting V2G communication and control.	Design intrusion detection, encryption, and resilient control architectures integrating cybersecurity with hierarchical control.
Aggregator-based Scheduling and Market Integration	Aggregators are mainly modeled for economic dispatch, ignoring mobility uncertainty.	Lack of stochastic scheduling that includes driver behavior and grid constraints.	Employ reinforcement learning for adaptive market participation while maintaining grid stability and EV battery health.
AI and Digital Twins	Existing AI control is mostly trained offline on small datasets.	Lack of real-time learning with safety and explainability guarantees.	Integrate digital twins with physics-informed AI for adaptive EV-microgrid control and predictive maintenance.
Standardization and Policy Framework	Current grid codes and standards do not define V2X operational envelopes.	Missing test protocols for EV-based ancillary services and cybersecurity compliance.	Collaborate with standardization bodies to define metrics and testing frameworks for EV-integrated MGs.

10.1. Hierarchical control coordination

Conventional droop control and secondary control schemes are not fully synchronized with the dynamics of EVs and changes of state of charge (SoC) and operation modes of the power grid. Future works should involve designing control methods that coordinate at a range of timescales using predictive models of EVs and optimization techniques for autonomous control of a number of EVs; storage; and DG (Sora et al., 2024).

10.2. Stability of converter-dominated EV integrated microgrids

A validation of power electronic converter interfaces so dominating requires intensive MIMO modeling techniques to accurately represent the interaction existing between various grid-forming converters and EV charging systems. Further research should introduce generic stability theory methodologies, like μ analysis or structured singular value techniques (Dev et al., 2025; San et al., 2020)

10.3. Communication and cybersecurity

Today's interoperability communications (OCPP and ISO 15118) target functionality instead of resiliency. Because MGs with the EV paradigm involve intensive information communication, the system becomes prone to latency attacks, spoofing, and denial of service. Therefore, future works should target the design of cyber-resilient communications with built-in hierarchical control layers that incorporate intrusion detection systems and control redundancy (Arena et al., 2024; Ahmad et al., 2024)

10.4. Aggregator-based scheduling and market integration

Today's state-of-the-art aggregator modeling fails to account for the stochastic behavior of drivers, charging costs, and grid limits. Further studies should investigate market-oriented and stochastic modeling frameworks incorporating runtime optimization techniques with AI-assisted forecasting and peer-to-peer energy trading for fair and affordable EV access to broader ancillary services markets (Sajid et al., 2025).

10.5. AI and digital twins

A promising innovation that can help unlock a new breed of microgrids with a seamless integration of EVs could be the integration of AI and digital twin technology. Indeed, the current hierarchical control strategy may not always be adequate for efficiently managing the uncertainties involved with microgrids that integrate many EVs. AI control systems that incorporate reinforcement learning algorithms or a hybrid physics-informed machine-learning technique may help unlock autonomous or predictive control of the system concerning voltage and energy costs. This strategy could help the microgrid to predict the loads and optimize the charging of the EV batteries.

Digital Twins (DTs) can compensate for AI by replicating physical microgrid infrastructures as digital entities that synchronize with actual operations at all times. This way, Digital Twins can simulate operations to analyze system dynamics and perform predictive maintenance of EV chargers, converters, and energy storage. Integrated AI and Digital Twins can help achieve continuous optimization and fault analysis at different control levels to assure autonomous self-learning for MGs enabled with EV technology. AI can benefit from future research focused on hybrid modeling of Digital Twins that integrate AI with physics-based modeling for microgrids (Liu et al., 2023; Park and Moon, 2022; Sajid et al., 2025; Li et al., 2019b; Altin et al., 2023; Ahmad et al., 2024).

10.6. Standardization and policy framework

Although there has been a dramatic advancement in EV-MG technology integration, the lack of a standardization and regulation framework has been a key hurdle for broader implementation. Today's standardization initiatives, like ISO 15118, IEC 61850, and IEEE 2030.5, are almost exclusively focused on communication compatibility and conformance to a standard at a global scale and lack consideration for the entire range of second-generation requirements for seamless power transaction validation and cybersecurity assurance. This further holds back standard organization for energy trading at a global level.

Future policies must establish common testing procedures and operation ranges for vehicle-to-grid (V2G) and vehicle-to-everything (V2X) services to facilitate safe and interoperable functioning. Relevant authorities should also set policies for peer-to-peer trading of energy, cyber-security requirements addressing the hardware as well as the software layers for charging points. Cooperation between energy companies and other stakeholders is vital for fostering global commonality to guarantee safe and normalized integration of EVers into intelligent microgrids to form a key elemental base of future renewable energy infrastructures. This can only be made achievable by developing common global standards that address future smart microgrids for sustainable energy solutions.

11. Conclusion

The increasing trend of integrating EVs into the present power system facilitates a paradigm shift in MGs management. This is due to the ability of EVs to transmit power in reverse, which enables MGs to switch from passive to active systems. This study has provided a detailed insight into developing hierarchical control techniques ranging from primary to tertiary levels for integrating EVs into the MG system. At the operational level, DC-coupled and hybrid AC-DC charging system architectures enabled by state-of-the-art bi-directional DC-DC and AC-DC converters appeared as important facilitating factors for efficient energy transfer. Studies on converter architectures indicated that the utilization of wide bandgap semiconductors (SiC/GaN materials) and optimized switching patterns can improve the efficiency of energy conversion and compactness of the entire system. Also, the provision of ancillary services of voltage and frequency regulation, reactive power compensation, and peak demand management by means of V2G and V2H services was found to enhance the reliability of the power system. On the other hand, the research also focused on the need for intelligent energy management systems that incorporate Model Predictive Control (MPC), Mixed-Integer Linear Programming (MILP), Stochastic Optimization, and Artificial Intelligence-based techniques like Fuzzy Logic, Neural Networks, and Multi-Agent Systems (MAS). This would help achieve predictive scheduling and control of uncertainties caused by renewable energy sources and the stochastic behavior of EVs. Despite the progress made, some open issues for further study remain. A stable MIMO analysis needs to be conducted for converter-control mitigation to guarantee stability with a high level of EV integration.-delay, cybersecurity problems of communication latency, compatibility issues and correspondence for diverse applications of an intelligent charging system with a focus on degradation of energy storage systems.

Further research efforts should target the design of standard communication frameworks and hardware-in-loop testbeds to validate smart control algorithms. Under the direction of intelligent control and safe information transfer, which supports microgrids with electric vehicles, a key building block for future sustainable power infrastructures will be provided that offers efficiency, flexibility, and carbon-neutral transport solutions for next-generation smart power supply systems.

CRediT authorship contribution statement

Mohamed Salem: Writing – original draft, Supervision, Investigation, Formal analysis, Data curation. **Ali Jawad Alrubaie:** Writing – original draft, Investigation, Formal analysis, Conceptualization. **Khalid Yahya:** Writing – original draft, Validation, Supervision, Project administration, Investigation, Formal analysis. **Mahmood swadi:** Writing – review & editing, Writing – original draft, Resources, Formal analysis, Data curation. **Saleh Al Dawsari:** Resources, Investigation, Funding acquisition. **Mohamad Kamarol:** Supervision, Resources, Methodology, Formal analysis.

Declaration of Competing Interest

On behalf of all authors, the corresponding authors declare that there are no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript. This declaration is provided in accordance with the journal's policy on disclosure and transparency.

Data availability

No data was used for the research described in the article.

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