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Review article

A survey on enhancing grid flexibility through bidirectional interactive electric vehicle operations

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ABSTRACT

Smart grids (SG) constitute a revolutionary concept within the energy sector, enabling the establishment of a bidirectional communication infrastructure. This infrastructure significantly improves control, efficiency, and overall service quality in power systems. The study provides an in-depth survey on the classification of EVs, including both plug-in and non-plug-in EVs, and the integration process of V2G, including bidirectional power flow analysis. Moreover, various control strategies for EV integration are explored, ranging from centralized and decentralized to hierarchical control structures. Further, the research thoroughly examines the potential benefits of EV integration and addresses associated challenges, such as battery degradation, infrastructure requirements, cybersecurity and communication issues, grid congestion, and consumer behavior. The study goes beyond theoretical exploration and offers a comprehensive simulation analysis. This analysis leverages the storage capabilities of EVs to provide grid support services. A real-time dynamic dispatch strategy is formulated to integrate EVs into the automatic generation control of multi-energy systems. The findings demonstrate that EVs can effectively mitigate forecasting errors in a power network heavily reliant on wind energy sources. Consequently, the storage capabilities of EVs contribute to enhancing grid flexibility in managing the intermittency of renewable energy resources.

1. Introduction

1.1. Background

Due to recent technological advancements, the Smart grid (SG) has emerged as an attractive alternative to the conventional power grid. The Electric Power Research Institute (EPRI) (Sollecito, 2009) defines an SG as "a power system that (a) consists of multiple automatic T&D systems that operate in an integrated, secure, and efficient manner, (b) is capable of managing emergencies through self-healing responses and is responsive to the needs of utility and energy markets, and (c) serves millions of consumers and includes a robust communication infrastructure that enables real-time operations. The main objective of this novel platform is to attain an uninterrupted power supply, promote energy sustainability, protect the environment, prevent major system breakdowns, and optimize the operational expenditure of power generation and distribution (Bush et al., 2013). Recently, there has been a dramatic increase in distributed generation due to the expansion of renewable energy, notably solar and wind energy. These weather-dependent resources require energy storage systems (ESS) to accommodate peak power demands. Connecting distributed generation and ESS to the power grid makes the power system structure more complex, costly, and difficult to control (Yang et al., 2023).

Consequently, the EVs are largely adopted with the SG due to their convenient charging, low tariffs, low maintenance expenses, and improved performance (Sami et al., 2019). Moreover, EVs have a

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significant role in mitigating air pollution, contributing to a cleaner environment, reducing carbon dioxide emissions and noise pollution, injecting power, and absorbing energy in prosumer mode (Sanguesa et al., 2021; Ullah et al., 2023). Different nations have implemented policies to reduce their dependence on fossil fuels and successfully integrated EVs into their future power sectors. EVs operate in two modes for SG applications, including consumers and prosumers, as shown in Fig. 1. In the consumer mode, G2V, an EV battery is charged by drawing power from the grid. In the prosumer mode, also called V2G, an EV contributes to the grid at periods determined by the market operator or in response to the grid loading conditions, which may be either lightly or heavily loaded (Basit et al., 2020).

1.2. Literature review

During the past decade, research efforts related to the production, installation, and marketing of EVs have advanced significantly. Some research examines broad topics such as the historical development of EVs, provides classifications based on design and engine characteristics, and evaluates the impact of these vehicles on the electrical infrastructure. For instance, (Asghar et al., 2021) provides an up-to-date and in-depth review of EVs, including the EV sales and future projections, the cost and performance progress of battery packs and power electronics, the charging infrastructure requirements, and the lifetime costs and emissions. Likewise, (Vadi et al., 2019) details EVs, plug-in hybrid electric vehicles (PHEVs), battery packs for energy storage systems, and V2G interaction (Sami et al., 2019). discusses incentives for consumers to use EVs, the advantages of connecting EVs to the grid, and the connection between SG and EVs. In addition, (Asghar et al., 2021) analyzes various economic and social benefits of deploying EVs and their integration into the current grid system (Shaukat et al., 2018). examined the environmental effects of V2G technology and several types of energy storage systems used in EVs of SGs (Zeng et al., 2015). designed a model to evaluate the economic benefits and drawbacks of deploying V2G technologies to provide grid performance-based regulation services (Tookanlou et al., 2020). performed a cost-benefit analysis of all V2G and G2V operation entities, such as EVs, EV charging stations, and power providers. Similarly, (Asghar et al., 2022) examined a wide range of challenges, including developing the required infrastructure, power quality concerns, frequency control issues, battery deterioration, the impacts of distribution equipment, and voltage and current distortions. The authors in (Z. Ullah, K. Ullah, and G. Gruosso) have extensively reviewed the EV model in the AGC integration of large-scale wind-integrated power systems. Different control techniques are explored and compared to deduce the conclusion of reducing dependency on conventional power systems. The most efficient technique in reducing the supply-demand error was the combination of EVs and wind power reserves.

The authors in Falahati et al. (2016) conducted a thorough system response analysis, mainly focusing on inertial and primary control levels. They utilized a finely tuned adaptive mechanism to ensure maximum system reliability, especially under challenging conditions. This approach demonstrates the potential of effectively utilizing EV capabilities for grid regulation, which could significantly increase the proportion of renewable energy in modern power systems. In Giordano et al. (2020), another study examined the impact of growing EV numbers on grids, specifically emphasizing concentrating on lower energy prices and providing flexible grid capacity. These strategies aim to integrate EVs efficiently while avoiding transformer overloads (Diaz-Londono et al., 2022a; Diaz-Londono et al., 2022b). discussed the influence of evolving energy practices on power grid regulations and highlighted the role of aggregators in connecting flexible loads such as EVs to the power grid. Through a financial perspective and methodology, they assessed benefits for end-users and aggregators, identifying scenarios where aggregation is advantageous and uncovering potential conflicts of interest. Numerical results showcased varied consumer benefits and situations where intermediaries may not be beneficial.

The main challenges facing the adoption of EVs as a means for providing flexible services to distribution grids are attributed to economic and institutional factors. In this context, this paper extensively examines the fundamental operations of V2G and G2V to uncover potential benefits and associated challenges. Furthermore, a detailed simulation analysis utilizes real-time data from EV batteries to provide auxiliary services to the grid in multi-energy systems. The suggested methodology is rooted in the economic optimization of the grid, capitalizing on the utmost capacity of EVs to reduce the grid's reliance on traditional energy sources.

1.3. Structure of the paper

The manuscript is structured as follows: Section 2 systematically categorizes electric vehicles (EVs) into Plug-in Electric Vehicles (PEVs) and Non-Plug-in Electric Vehicles (N-PEVs). Section 3 centres on Vehicle-to-Grid (V2G) interaction and encompasses three primary facets: vehicle-to-vehicle (V2V) and vehicle-to-home (V2H), with a primary emphasis on V2G. The power flow of the V2G system is examined, and the differences between unidirectional and bidirectional V2G technologies are differentiated. This section also delves into power control strategies within the V2G system, exploring centralized, decentralized, and hierarchical control structures. Section 4 examines the potential advantages of V2G systems, encompassing active power support, reactive power support, and facilitation of renewable energy integration.

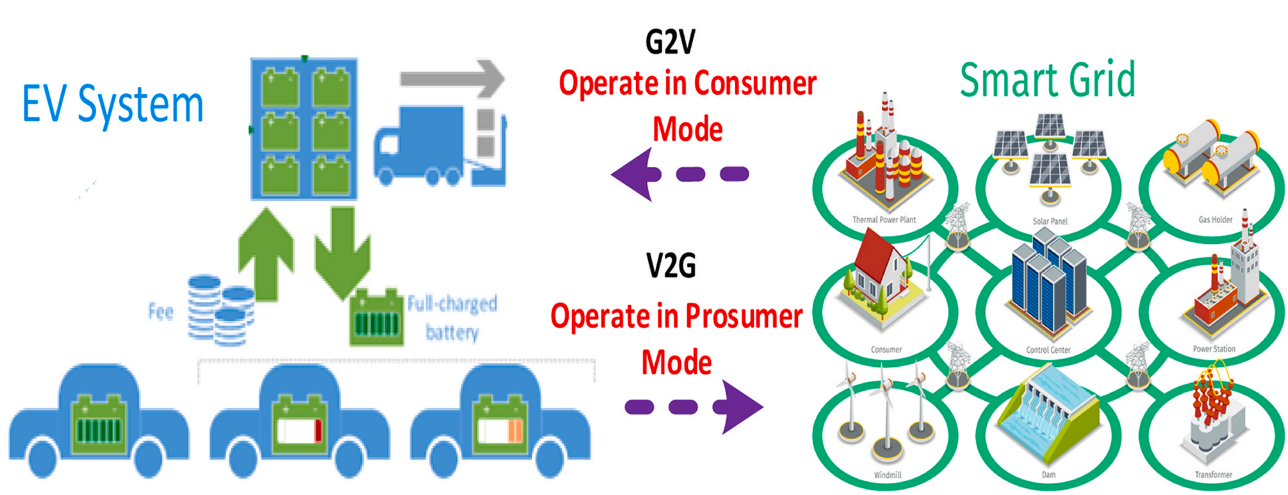

Fig. 1. EVs and SG Interaction.

Nevertheless, it also addresses the prevailing challenges confronted by V2G systems. Section 5 provides an in-depth simulation analysis, wherein a real-time dynamic dispatch strategy is formulated for the AGC unit to incorporate the storage capacities of EVs for power grid balancing services. The findings of the paper are presented in Section 6.

2. Electric vehicles classification

EVs can be divided into two main groups: Plug-in Electric Vehicles (PEVs) and Non-Plug-in Electric Vehicles (N-PEVs). Hybrid electric vehicles (HEVs), a type of N-PEV, combine an internal combustion engine (ICE) with one or multiple electric motors that derive power from stored batteries. PEVs are further classified into two distinct subcategories: Plug-in HEVs (PHEVs) and Battery EVs (BEVs). In contrast to BEVs, which only rely on batteries to power their electric propulsion system, PHEVs combine the advantages of both a rechargeable battery pack and an ICE to provide a wider mobility range. Table 1 provides a detailed comparison of different types of EVs.

2.1. Plug-in electric vehicles

2.1.1. Battery electric vehicle

BEVs rely solely on electric power for propulsion and do not contain an ICE or utilize liquid fuel (Asghar et al., 2021; Damiano et al., 2014). BEVs commonly incorporate large battery packs that provide the automobile with an adequate driving distance of roughly 160–250 kilometers, with certain models exhibiting the potential to cover up to 500 kilometers on a single charge (Sanguesa et al., 2021). Electric motors create much more torque (turning power) than ICE at a given RPM. This shows that the rapid acceleration of BEVs is visually distinct from conventional vehicles. Fig. 2 depicts the detailed structure of Nisan Leaf BEVs.

Table 1
Comparison between BEVs, PHEVs, and HEVs (Madras, 2019).

Descriptions	BEVs	PHEVs	HEVs
Energy source	Battery	Battery, Gasoline	Battery, Gasoline
Propulsion system	Motor	Motor and engine	Motor and engine
Fuel facilities	Charging Station	Charging station, Gas station	Gas station
Cost	Higher	Moderate	Moderate
Road tax	Low to zero	Low	Moderate
Regenerative braking	Yes	Yes	Yes
Charging point required	Yes	Yes	No
V2G service	Yes	Yes	No
Advantages	Lowest operating costs Engine generates no noise Zero CO2 emissions Minimal auto parts Highest MPG Optimal energy efficiency	Lower maintenance cost Lower fuel cost Lower CO2 emissions Higher fuel economy compared to HEVs Multiple refuelling facilities	Cheaper compared to BEVs and PHEVs Low CO2 emissions Higher mileage capacity Multiple refuelling facilities
Disadvantages	Higher purchase cost Limited battery range Charging takes longer Temperature sensitivity of the battery Fewer charging options	Relatively expensive High technical complexity Fuel dependency Unpredictability of resale value Fewer charging options	Engine noise Lower fuel economy compared to BEVs and PHEVs High technical complexity Fuel dependency High maintenance cost

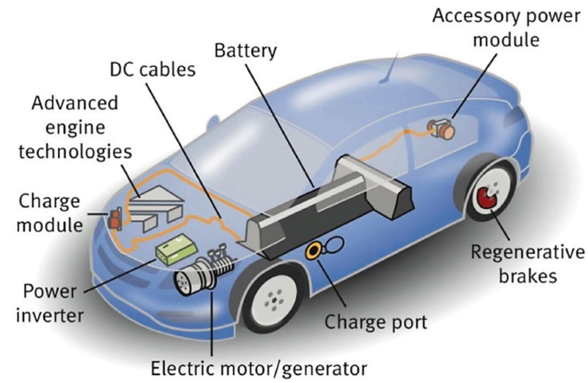

Fig. 2. Nisan leaf anatomy ($author1$ et al., 21]</id><collab>DELFI</collab><>https://www.newkidscar.com/electric-car/nissan-leaf-anatomy-bev-anatomy/).

2.1.2. Plug-in hybrid electric vehicle

PHEVs represent a promising technology for sustainable transportation systems, and currently, their adoption is a notable increase. According to the research, 10.5 million EVs were delivered in 2022, including 2.9 million PHEVs (Bibra et al., 2022). In 2023, total EV sales were predicted to reach 14.3 million, with PHEV sales accounting for 3.3 million. These vehicles combine the advantages of both electric and ICE. A plug-in external electric source powers the electric motor. Due to their ability to store large amounts of electrical energy from the grid, PHEVs significantly reduce fuel usage under normal driving conditions (Vadi et al., 2019). Depending on the battery's SOC, the PHEV may switch between two different modes of operation. When the battery SOC reaches 100%, the PHEV switches to charge-depletion (CD) mode, where the battery starts discharging from 100% (Galus et al., 2019).

Upon reaching the SOC boundaries within the Critical Discharge (CD) range, the PHEV automatically transitions into charge-sustaining (CS) mode. The PHEV harnesses power from the internal combustion engine and regenerative braking systems in this operational state. Refer to Fig. 3 for an illustrative representation delineating the intricate architecture of PHEVs.

2.1.3. Non-plug-in electric vehicles (N-PEVs)

NPEVs or HEVs use an ICE and an electric motor for propulsion (Sanguesa et al., 2021). Unlike PHEVs, HEV batteries cannot be plugged into a conventional electrical socket. On the other hand, the energy produced by the vehicle's ICE is used to recharge the battery, which drives the electric motor. In modern HEVs, the regenerative braking system is also used to charge the batteries, which is an efficient method for extending the driving range of HEVs by reducing fuel consumption. Globally, the growth of HEV is accelerating due to the rising consumer consciousness of environmental preservation. The worldwide market for HEVs reached 7.6 million units in 2022, with approximately 2 million HEVs sold in the European Union alone (ACEA, 2022). According to

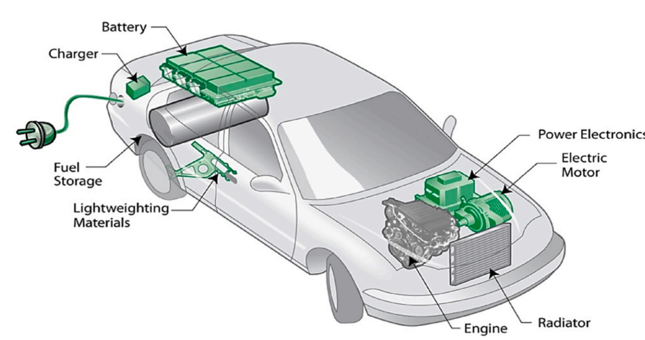

Fig. 3. Detailed structure of PHEVs (Kuiper, 2009).

estimates, the HEV market will reach 40.4 million units by 2028, with a growth rate of 30.4% forecast between 2023 and 2028. Fig. 4 depicts the detailed structure of HEVs.

3. Vehicle-to-grid (V2G) interaction in the SG systems

Vehicle-to-vehicle (V2V), vehicle-to-home (V2H), and vehicle-to-grid (V2G) are three examples of emerging EV technology, as shown in Fig. 5 (Li et al., 2023). "V2V" refers to a smart technology that uses specialized short-range communications to allow vehicles to share information. Vehicles equipped with V2V communication may learn about the location and speed of other V2V-enabled vehicles in their immediate vicinity. V2H refers to bartering services between the EV charging port and the EV batteries. In these situations, EV batteries may provide backup power for renewable energy systems and household appliances. V2G is a novel approach that connects EVs and PHEVs to the grid through energy-storage technologies that permit bidirectional power transmission between the electrical power facilities and the EV battery (Inci et al., 2022). The vehicle can receive energy from the grid to charge its battery. Conversely, when the grid needs energy during peak consumption, the vehicle can transfer power back to the grid, supplying much-needed power. Consequently, EVs may provide grid services in a V2G network, including but not limited to peak power reduction, load balancing, voltage and frequency control, current harmonic filtering, and better usage of available power plant capacity (Asghar et al., 2022). In addition, EVs might improve the technical capabilities of the grid in areas including performance, security, stability, and generation dispatch through V2G technology. Table 2 summarizes several V2G prototype initiatives with diverse objectives and capabilities.

3.1. *V2G power flow*

Power flow regulation relies on efficient communication, which is a crucial component of the V2G system (Shariff et al., 2022). The power operator depends on the communication infrastructure to maximize profitability, minimize greenhouse gas emissions, and improve grid power quality. The local aggregator enables V2G power flow by facilitating communication between the grid and consumers or prosumers. The intelligent meter transmits exhaustive data on power transactions directly to the data centers. Electrical power is directed from the G2V for battery charging, and it can reverse its direction to facilitate peak shaving or implement the "spinning reserve" concept. The power flow can function in either unidirectional or bidirectional modes.

3.1.1. *Unidirectional V2G*

The term "unidirectional V2G" describes a kind of V2G technology in which electricity only flows in one way. These methods are appealing because of the existing infrastructure, but adding a controller significantly raises the cost. The unidirectional method is helpful for power grid operations, including power grid regulation (Mastoi et al., 2023). The implementation of unidirectional V2G technology is examined within the context of trade policies between power utilities and EV owners. To incentivize the adoption of EVs, the commercial policies of energy providers must ensure reliable access to charging infrastructure for EV owners (Sami et al., 2019). During periods of high demand, the power company may experience overloading. Additionally, implementing unidirectional V2G systems has the potential to achieve both profit minimization and maximization for utility companies and consumers/prosumers. The V2G unidirectional mode of operation is limited in its ability to provide certain essential services, including peak load capping, spinning reserve, frequency regulation, and voltage regulation.

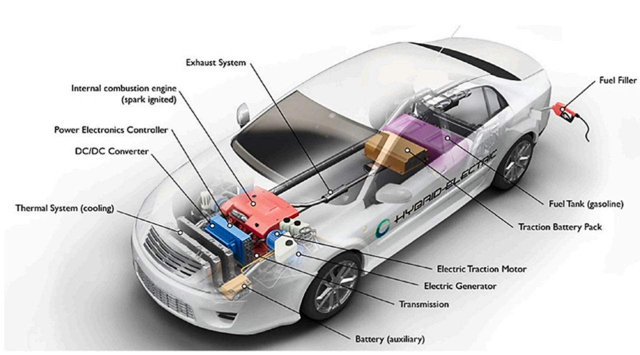

Fig. 4. Detailed structure of HEVs (U. S. D. o. Energy, 2023).

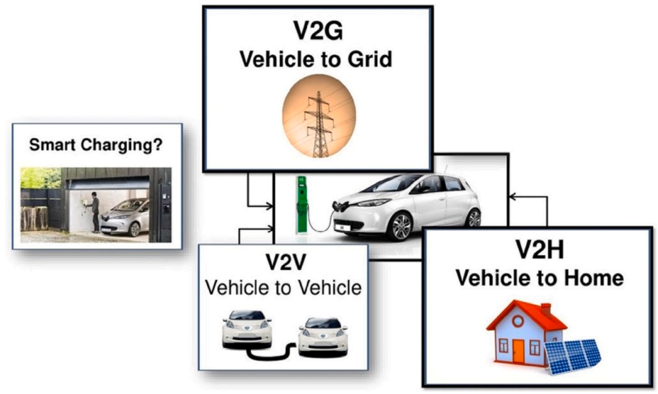

Fig. 5. EVs emerging technology (Zhou et al., 2020).

3.1.2. *BidirectionalV2G*

The term "bidirectional power flow" describes a technique in which EVs and the power grid may exchange energy in both ways (Asghar et al., 2022; Mastoi et al., 2023). Compared to unidirectional V2G, it provides many advantages, including incorporating an AC/DC converter and a DC/DC converter to facilitate the two-way transfer of energy (Heydari-doostabad and O'Donnell, 2021). In the charging mode, energy from the grid is rectified by converting AC to DC, and in the discharging mode, DC is converted to AC and injected into the grid. In contrast, choppers are used to regulate the transfer of energy in both directions. The DC/DC converter, whether functioning as a buck converter, boost converter, or buck-boost converter, is designed to respond during loading and discharge modes. Bidirectional V2G technology offers greater adaptability and potential for improving power system operations. Table 3 provides a detailed summary of the advantages and disadvantages of bidirectional V2G systems.

3.2. *Power control strategy*

As the integration of EVs into the power grid increases, charging and discharging them will become increasingly complex (Aghajan-Eshkevari et al., 2022). This will significantly impact the power system's stability and cause problems for its control, administration, and operation. Optimal power control is essential for the smooth integration of EVs into V2G systems. This strategy must effectively prioritize customer interests and provide essential grid support services. User preferences, including charging times, battery SOC limitations, and travel demands, should be considered. The system must also use advanced techniques for predicting and responding to grid conditions and power costs to maximize grid interactions. In the literature, three different approaches are used to control the charging and discharging of EVs on the power grid. These include centralized, decentralized, or hierarchical control (Yu et al., 2022). Each of these systems has advantages and disadvantages that are influenced by their distinct coordinating methods. Fig. 6 denotes the power transfer between SG and EVs. Table 4 presents a detailed summary of the centralized, decentralized, and hierarchical control structures.

Table 2
An overview of some of the world's V2G pilot projects (Dawn et al., 2023).

Country	Project	Charge Points	Type of Chargers	Timeframe	Services
Australia	Realising Electric Vehicle to Grid Services	51	DC	2020–2022	FR, RE
Belgium	Elia V2G	40	DC	2018–2019	FR
Belgium	V2G Zelzate	22	DC	2020–2023	FR, RE, TS
Canada	Peak Drive	21	DC	2019–2025	DS, TS
China	Smart microgrid EMS	5	DC & AC	2019-ongoing	EB, FR, TS
Denmark	Bidirektionales Lademanagement - BDL	50	DC	2021–2022	AR, FR, TS
Denmark	Parker	50	DC	2016–2018	AR, DS, FR
Italy	E-mobility Lab	13	DC & AC	2021-ongoing	FR, RE, TS
Japan	M-tech Labo	5	DC	2010–2013	EB, TS
Japan	Leaf to home	4000	DC	2012-ongoing	EB, TS
Netherlands	Direct Solar DC V2G Hub	14	DC & AC	2020–2023	DS, EB, FR, DS
Netherlands	Smart Solar Charging	22	AC	2015-ongoing	DS, TS
Netherlands	Utrecht V2G charge hubs	80	AC	2018-ongoing	AR
Portugal	V2G Azores	10	DC	2020–2021	AR, FR, TS
Switzerland	SunnYparc	250	DC & AC	2022–2025	DS, TS, RE
Switzerland	V2X Suisse	40	DC	2021–2023	AR, DS, FR, RE
United Kingdom	OVO Energy V2G	320	DC	2018–2021	AR
United Kingdom	Electric Nation Vehicle to Grid	100	DC	2020–2022	DS, RE, TS
United States	INVENT – UCSD	50	DC & AC	2017–2020	FR, DS, TS
United States	US Air Force	13	DC	2012-ongoing	EB, FR, RE, TS
United States	SmartMAUI, Hawaii	80	DC	2012–2015	TS

Abbreviations: AC: Alternating current; AR: Arbitrage; EB: Emergency backup.

Table 3
Comparing unidirectional and bidirectional V2G systems (Dawn et al., 2023; Shariff et al., 2022).

V2G System	Grid services	Advantages	Disadvantages
Unidirectional	Peak load capping Spinning reserve Frequency regulation Voltage regulation	Need less equipment Easier to control Extend EV battery life with minimum cycling Minimize emissions	One-way battery charging limits flexibility Market constraints Depends on the availability of vehicles Possibility of grid failure during peak hours
Bidirectional	Spinning reserve Adaptable to fluctuating demand Reduce peak power reduction Support reactive power Regulate the power factor Voltage/ frequency control	Reduces power loss Minimizing operational expenses Reduce pollution Preventing grid overload Increase operational savings Maximize renewable energy integration	Problems with battery degeneration High start-up cost More hardware is required Both the charge and discharging phases experience greater energy losses Greater technical concerns

3.2.1. Centralized control structure

In a centralized control system, grid operators or aggregators directly oversee EV charging and discharging operations. First, an aggregator or grid operator collects and analyzes the necessary data and each EV's charging needs (Aghajan-Eshkevari et al., 2022). After that, the rates for charging and discharging EVs are determined, considering the current state of the network as well as the particular objectives. This control system can significantly regulate and offer the grid a wide range of services. For instance, (Li et al., 2021) introduces a method to efficiently handle V2G behavior across multiple time scales to tackle the optimization problem using a centralized control structure. The proposed solution effectively tackles the issue of peak shaving in the grid and provides a fast grid power balance adjustment service. The optimization algorithm also considers the charging needs and schedules to enhance control performance and fulfil user preferences. A centralized system is proposed to manage the charging and discharging of EV batteries efficiently (Nguyen et al., 2015). This system integrates certainty equivalent adaptive control with a consumer engagement program. The proposed method tackles the sporadic nature of RERs to enable the incorporation of a wide range of RERs into smart grids. The optimization algorithm considers consumers' charging demands and schedules to enhance performance and ensure client satisfaction. Though central control has many benefits, it is not without limitations, such as the necessity for all EVs to maintain a specified minimum level of charge regularly. Further, this specific framework lacks adaptability, resulting in increased expenses. This is because there is a need to include supplementary generators, such as backup generators and supporting facilities, to handle exceptional situations, such as high-demand periods and power drops. Another disadvantage of the centralized method is the higher delay in communication and more computational complexity when managing a large number of EVs and the extensive sharing of confidential information and decision-making data (Shang et al., 2021). Moreover, centralized solutions are not scalable and cannot adjust to new conditions, such as when EV users randomly join and leave the system.

3.2.2. Decentralized control schemes

Decentralized control allows individual EV owners to make choices about the charging and discharging their vehicle's batteries based on their specific requirements and goals (Aghajan-Eshkevari et al., 2022). In this control structure, grid operators or aggregators have only indirect control over the charging and discharging of EVs through pricing strategies such as offering incentives to shift EV charging demand from peak to off-peak hours. Therefore, developing a real-time power pricing mechanism is essential for effectively deploying V2G's decentralized control. In Ma et al. (2011), the author proposed cost-effective charging schedules demonstrating that suitable pricing mechanisms can encourage EV owners to shift their charging burden from peak to off-peak hours. According to another study, implementing a pricing system for EV charging, with a 50% price increase during peak hours and a 50% price decrease during valley hours, reduces the overall power cost of Beijing power networks by 0.302 billion CNY. Moreover, by extending the charging period of EVs and uniformly distributing the charging burden over an extended duration, it is feasible to mitigate the fluctuating grid load and reduce its impact effectively (Xu et al., 2020). Compared to the centralized approach, decentralized approaches offer several advantages, including reducing the communication load between EVs and the system controller (Chen et al., 2019). This approach reduces the need for extensive computation by dividing the burden among multiple agents, each responsible for completing its task. Since

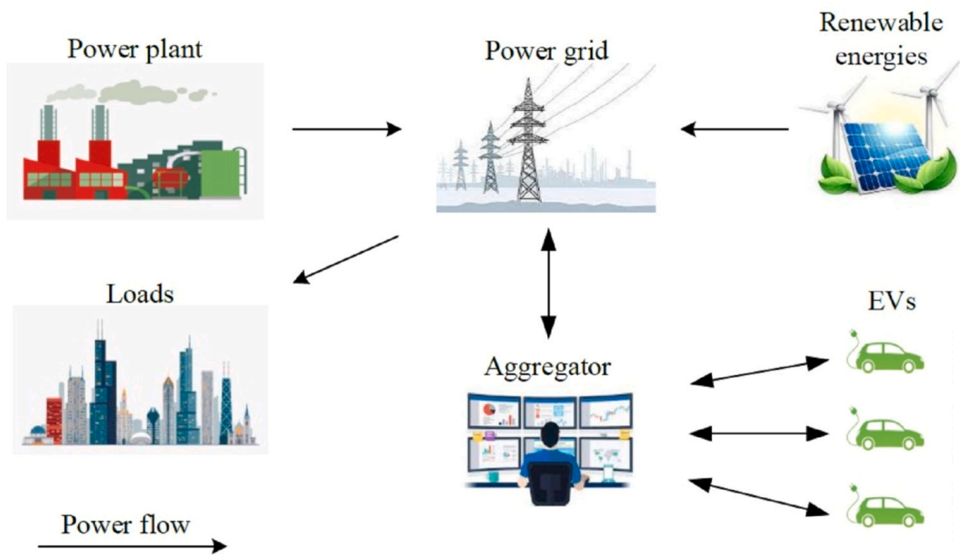

Fig. 6. Power transfer between Smart Grid and EV (Aghajan-Eshkevari et al., 2022).

Table 4
Evaluation of Control Paradigms: Centralized, Decentralized, and Hierarchical Control Systems (Hamouda et al., 2021).

Descriptions	Centralized	Decentralized	Hierarchical
Optimizing for Peak Performance	Global	Local	Control Structure Dependance
Communication load	High	Low	Low
Computational cost	High	Moderate	Low
Computational burden	High	Low	Almost low
Adaptability	Low	High	High
Level of shared information	Detailed	Limited	Depend on the control structure
Reliability	Low	High	High
Charging/discharging control	Direct	Indirect	Can be direct or indirect
Collecting data from large EV fleets	Difficult	Easy	Depend on the control structure
Concerns with the power grid's security	Low	High	High

the decentralized control technique only sends a minimal amount of data to a centralized operator, it ensures the privacy and security of its customers (Liu et al., 2017). In addition, this strategy reduces the cost of computing, optimizes power dispatch, and lowers the price of electricity by participating in the demand response (DR) market. Despite requiring fewer computer resources than centralized approaches, decentralized control techniques struggle to find optimal global solutions due to a lack of global knowledge (Hu et al., 2016). In the decentralized optimization design, each EV user would charge or discharge power according to their convenience, which might potentially breach power security and reverse power-flow constraints.

3.2.3. *Hierarchical control schemes*

The hierarchical control structure combines aspects of both centralized and decentralized structures, as shown in Fig. 7. A hierarchical control structure normally has two top and bottom layers (Aghajan-Eshkevari et al., 2022). At the top layer, all EV aggregator schedules are controlled by a central controller, while at the bottom layer, individual aggregators are in charge of monitoring and controlling a fleet of EVs and coordinating their charging and discharging. The aggregator can directly or indirectly regulate EV charging and discharging (Nimalsiri et al., 2019). In direct control, the aggregator sets the charging schedule for each EV in the fleet, whereas, in indirect control, it sends signals to the EVs to arrange their charging schedules.

In contrast to centralized controls, hierarchical controls distribute

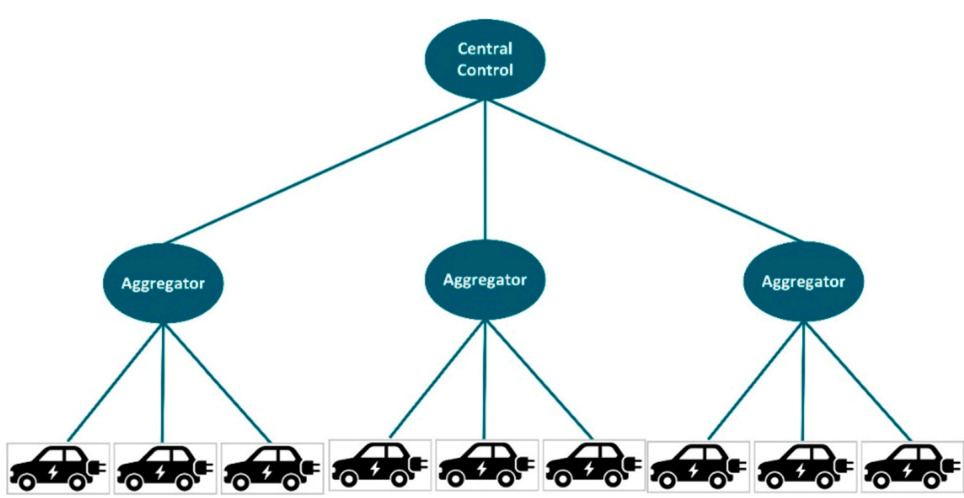

Fig. 7. Hierarchical control structure (Hu et al., 2015).

control and computation burdens to several direct or indirect aggregators over a tree-like communication structure. Hence, this control structure reduces the computational cost and requirement for a communication system compared to centralized and decentralized control. Recently, hierarchical control systems have been investigated to fulfil EV users' energy needs while facilitating grid services. In (Hu et al., 2015), a two-tiered hierarchical control system for EV integration into the distribution system that balances the demands of the EV owner while also providing grid services is presented. Using a three-tiered EV charging strategy that optimizes system load profile and charging costs, Xu et al. (2015) proposes a hierarchical structure to support coordinated EV charging across multiple timeframes. For the efficient charging of hundreds of EVs, a two-tiered hierarchical control system is presented, with the first layer addressing the optimal power allocation of EVs and the second describing the optimal operation of the distribution grid (Bharati and Paudyal, 2016). A coordinated and vehicle-layer control structure is proposed to integrate EVs into grid services (Wu et al., 2019). The vehicle layer controller determines charging power and energy availability based on vehicle attributes, charging equipment power rating, battery energy state, and upcoming trip information. Based on the required grid services, the coordination layer's centralized coordinator determines the optimal power distribution for a future look-ahead period. A two-layer optimum charging approach is presented to reduce load fluctuation in regional grids, and the computational complexity due to large-scale EV adoption is reviewed.

4. Benefits and current challenges of V2G systems

The V2G system has the potential to offer various services, each with distinct advantages. The deployment of a V2G system can potentially provide benefits, including power grid failure recovery, reactive power support, load distribution, and harmonics filters (Asghar et al., 2022). Additional tasks, including regulating voltage and frequency, become possible with the help of these services. Using EV batteries as a backup source for renewable energy resources (RERs) like solar and wind power might reduce demand on the grid and the costs involved with extending the infrastructure (Fathabadi, 2015; Ullah et al., 2020). Furthermore, V2G technology promises to mitigate the detrimental environmental effects while maximizing the economic benefits associated with EVs. However, the growing adoption of EVs poses potential disruptions to power distribution systems, leading to overload conditions in transformers, cables, and feeders. An additional generator becomes imperative to address this overload to alleviate voltage and current distortions. Additionally, the recurring concern among owners revolves around the expenses associated with battery degradation resulting from repetitive charging and discharging cycles. This section will delve into a comprehensive examination of both the advantages and challenges stemming from the interaction of EVs within the SG.

4.1. Benefits associated with V2G systems

V2G technology has the potential to provide numerous benefits, including savings for grid utilities, society, and EV owners. Below is a comprehensive list of the significant benefits that V2G technology offers.

4.1.1. Active power support

The V2G system included a bidirectional converter to provide active power. This converter facilitates the bi-directional energy flow within the system, allowing for battery charging, discharging, and grid power injection. The primary objective of this service is to mitigate excessive demands on the power system, ensuring a consistent and stable power supply (Asghar et al., 2022). Typically, daytime experiences lower electricity demand, whereas peak load periods present an opportunity for cost-effective power sourcing from EVs (Shariff et al., 2021). This methodology alleviates power system stress, offering a dual advantage of optimizing power utilization and enabling EV owners to capitalize on elevated energy rates.

The active power support provided by V2G technology is pivotal due to its multifaceted benefits. Notably, it minimizes overall power losses by operating the power system at a reduced capacity, which contrasts with traditional power system designs optimized for peak demand scenarios (Tan et al., 2016). During off-peak hours, electrical equipment often operates below its maximum capacity. Consequently, implementing the V2G system allows for deploying a peak load reduction strategy, maximizing equipment power utilization, and preventing costly upgrades. In utilizing V2G technology for peak power support, careful consideration must be given to various factors, including SOC, Depth of Discharge (DOD), and the feasibility of integrating the EV with the power grid.

4.1.2. Reactive power support

Reactive power support is used to regulate voltage in the power grid. The objectives of the distribution system, which include preserving voltage, reducing surges, and mitigating fluctuations, depend significantly on the availability of reactive power supply (Asghar et al., 2022). In addition, reactive power support is essential for maintaining power factors, ensuring optimal power flow, and mitigating line losses. The V2G technology facilitates the provision of reactive power support by EVs integrated with the power grid. In a bidirectional charger, reactive power is stored in a DC-link capacitor.

Unlike peak power shaving, reactive power regulation does not adversely affect the battery's life expectancy (Tan et al., 2016). This is attributed to the capability of the DC link capacitor to furnish complete reactive power, eliminating the necessity for the EV battery to participate in the transfer of reactive power. The nature of reactive power, whether capacitive or inductive, is contingent on the direction of its flow between EVs and the grid. When the flow is from EVs to the grid, the reactive power is capacitive and becomes inductive in the opposite direction (Zhang et al., 2023). In scenarios involving standard EV chargers without regulated reactive power, the reactive power from the EVs is conveyed to the grid in the third and fourth quadrants.

4.1.3. Renewable energy support

Electric power generation facilities and the transportation sector are preeminent contributors to carbon dioxide emissions, presenting a formidable challenge to human welfare and environmental equilibrium (Asghar et al., 2022). RES can contribute to environmental sustainability by decreasing reliance on fossil fuels. However, since RES is unpredictable and intermittent, it is more challenging to plan the daily operation of the electric grid (Mahrouch and Ouassaid, 2022). To address these issues, the V2G system employs a fleet of EVs as a backup or storage option for energy. Consequently, the implementation of V2G systems enables the integration of greater renewable energy capacity into the power system. Research shows that more EVs connected to the grid improve the power system's ability to incorporate renewable energy sources. EVs act as energy backups, providing extra power when renewable energy production is insufficient, and as energy storage, absorbing any excess electricity generated by renewable sources. Nissan and the Danish Technical University collaborated to demonstrate the potential advantages of the V2G system by deploying a fleet of Nissan LEAF EVs with bidirectional charging capabilities. By discharging energy from batteries back into the grid during peak demand, the V2G technology facilitated the integration of renewable energy sources Nuvve, 2021). The Dutch government initiated a similar program to examine V2G systems' technical and economic potential for grid balancing and renewable energy integration.

4.2. Current challenges and long-term implications of the V2G systems

4.2.1. Current challenges

While V2G systems have several advantages, greater EV adoption might disrupt power grid operations by overloading transformers, cables, and feeders (Asghar et al., 2022). Fast charging of many EVs in localized areas may significantly strain these power systems' equipment, leading to overheating, higher losses, and probable malfunctions. This disturbs the charging process, increases possible risks, and may result in power outages in impacted areas. Large investments in power system modifications and reinforcements are necessary to overcome these difficulties and meet the increased capacity demands caused by broad EV adoption. The following are some of the challenges that V2G technology presents.

a. Battery degradation

Temperature, DOD, charging rates, and the total number of cycles all contribute to the gradual deterioration of a battery over time. Although battery costs continuously drop, they account for about 40% of an EV's purchase price. The loss of energy capacity, defined by the State of Health (SOH), is an additional expense that must be deducted from the revenue generated by the provision of grid services (Thingvad et al., 2021). Depending on the source of the deterioration, the degradation of batteries can be categorized as either calendar aging or cycle aging. Calendar aging includes all aging mechanisms that degrade a battery cell regardless of charge-discharge cycles. The primary cause of calendar aging in batteries is the development of a passivation layer on the negative electrodes.

In contrast, cycling aging is observed during the charging or discharging of a battery. The degradation rate depends on the battery's operating temperature, number of cycles, and charge/discharge. In V2G technology, EV batteries are frequently charged and discharged to provide grid power or recharge the vehicle, thereby accelerating battery degradation (Guo et al., 2019). Frequently, charging and discharging raise temperatures and alter the chemical composition of the solid electrolyte interface (SEI) (Asghar et al., 2022). The SEI layer hinders battery performance by impeding reactions between the electrode and electrolyte. Further, the SEI layer assimilates certain active ions, elevating the battery's internal resistance and a consequential reduction in capacity over its operational lifespan. The investigation's findings unveiled that, after 300 cycles at 1 C, 2 C, and 3 C discharge, the corresponding capacity losses were recorded at 9.5%, 13.2%, and 16.9% of the initial capacity, respectively (Ning et al., 2003). Moreover, it was observed that the cell cycle showed a significant surge in internal resistance (27.7%) compared to new cells when subjected to a high discharge rate of 3 C.

b. Capital and upgrading costs of infrastructure

Compared to regular smart charging stations, the cost of V2G charging infrastructure is higher. Most expenses are attributed to the specialized inverter essential for transforming the DC power from the battery into the grid's AC power. To guarantee effective power conversion and grid reliability, the inverter used in V2G systems must satisfy certain technical specifications (Tan et al., 2016). Given the extra features and technical criteria required to manage bidirectional power flow, voltage control, frequency synchronization, and power quality management, these inverters are more complicated and expensive. The most recent V2G trials have concluded that the average expense of V2G hardware and setup in the United Kingdom is currently around £3700 higher than that of a normal smart EV charger (Banks, 2022). Grid-level power balancing is another important barrier for V2G systems since charging multiple EVs consumes significant energy (Asghar et al., 2022). While large quantities of energy cannot be stored, the network's ability to manage power demand and supply is critical to V2G reliability. In addition, fast charging stations impact the grid distribution network owing to their high energy needs, which are more than double the average household capacity. As per the analysis, the electrical infrastructure in the United States can support 73 percent of EV charging demands. Nevertheless, facilitating the charging requirements for additional vehicles would necessitate an annual energy consumption exceeding 910 billion kWh, equivalent to approximately 24% of the total energy output. Consequently, huge investments in electrical distribution infrastructure, transformers, and grid capacity expansions are required to accommodate the growing power consumption of EVs, particularly in densely populated regions.

c. Cybersecurity and the Communication Infrastructure

V2G communication differs from conventional systems due to its dependence on real-time factors such as vehicle control, speed, location, and charging and discharging protocols. Moreover, V2G communication networks typically operate within limited ranges, requiring real-time communication capabilities on a small scale (Giordano et al., 2023). During the configuration of a communication system, ensuring the security, timeliness, and efficacy of the transmitter and receiver authentication processes is essential. EVs and their interactions with a V2G operator must be protected by keeping all communicated data confidential. An intruder may attempt to obtain confidential information about EVs, such as their charging and discharging locations and payment methods (Conti et al., 2022). If the rival of a V2G operator discovers confidential details on the system's operations, such as the energy price supplied to EV consumers, the V2G operator's business could suffer. In addition, cyber assaults can affect a broad range of systems, including remote access, telemetry, monitoring, customer and operator data aboard or on mobile devices, and safety-critical aspects like driver steering and braking control (Jay Johnson et al., 2022). Electric vehicle supply equipment (EVSE) is an important interface between the vehicle and energy industries, especially the power grid. It relies on electronic systems for vehicle recharge and communication, making it vulnerable to potential breaches of cybersecurity and assaults. Attackers may alter connected EVs' charging and discharging behaviors, leading to discrepancies between supply and demand. This could lead to grid instability, localized power failures, and disturbances in the constant supply of electricity, affecting companies, households, and utility services.

d. Social Barriers

The involvement of a significant number of EVs is essential for the successful implementation of V2G systems. Nevertheless, the widespread acceptance of V2G technology has been impeded by social barriers, posing a significant obstacle to its adoption (Tan et al., 2016; Haddadian et al., 2015). The average EV driver is unfamiliar with batteries, the power systems, and the advantages of V2G, which can easily lead to misunderstandings regarding smart charging and V2G, thereby increasing consumer mistrust (Peeters, 2021). For instance, battery degradation effects are frequently overstated, preventing EV users from promoting V2G technology in its entirety. In addition, many EV owners reserve energy in their vehicle's battery for unplanned long-distance travel or unforeseen circumstances. Individuals are reluctant to deplete their batteries due to the scarcity of charging infrastructure and the anxiety related to a limited driving range. Some users have reported issues with the grid's congestion and the time it takes to complete transactions (Asghar et al., 2022). The lack of charging stations, especially those that support V2G, might discourage people from participating in V2G. With V2G, a third party manages the algorithm that charges and discharges an EV with the driver's approval (Peeters, 2021). Some individuals hesitate to grant this access if the algorithm makes an error and restricts their vehicle usage. Moreover, EV owners worry that the compensation offered will not offset the price of battery degradation or other expenses incurred by EVs when participating in V2G. Some EV models lack bidirectional charging capabilities, which also hinders the widespread adoption of V2G technology. Some variants of Tesla (Model 3, Model Y), BYD (Atto 3, Han EV), KIA (EV6), and Nissan cannot support bidirectional charging for V2G technology (Svarc, 2023).

e. Grid Congestion Issues
   Integrating EVs) introduces several challenges for power system operators. These challenges encompass the presence of waveform distortions (harmonics, interharmonics, and supraharmonics) during EV charging, posing difficulties in aggregating and propagating these distortions in low and medium-voltage networks (Slangen et al., 2020). While EV chargers were unaffected by shallow voltage dips, this study revealed that in the Swedish network with underground cables, even minor dips could significantly impact EV charging, influencing battery life and performance (Sudha Letha and Bollen, 2021). Additionally, asymmetric dips with phase angle jumps were identified as causing overvoltage and oscillations during EV discharging, particularly noticeable when fewer EVs are charging. The impact of flicker is more prominent in weaker grids but is primarily influenced by lamp topology, especially in lamps equipped with active power factor correction. Concerning PV-EV hosting capacity, it was observed that the impact of EV charging during the day is less than at night and depends on the relative coincidence factor between PV and EV (Seljeseth et al., 2013). The likelihood of undervoltage is low during the day and high at night, escalating with charging power and penetration levels. Hosting capacity, assessed in terms of curtailment, suggests a gradual increase in penetration within social and economic limits (Kundu and Hiskens, 2014). Moreover, the study found that Probabilistic Dynamic Line Rating (DLR), considering overload probability, offers the potential for increased hosting capacity regarding the number of EVs, allowing a continuous trade-off between risks and neglect. Temperature emerged as a significant factor affecting EV hosting capacity, with a temperature coefficient causing a 30% decrease during colder months due to rapid battery discharge (Hajeforosh and Bollen, 2021). Given the aforementioned challenges, it is recommended to incorporate surplus load, associated risks, and temperature factors into grid planning and mitigation strategies.
f. Consumer Behavior

The bidirectional charging process is pivotal in incorporating EV users as integral actors in the V2G system (Noel et al., 2019). A seamless implementation of V2G technology necessitates proactive engagement with EV users, addressing concerns such as potential loss of control during charging (Yilmaz et al., 2021) and apprehensions about possible reduced battery life due to V2G operations (Krueger and Cruden, 2020). Strategically fostering widespread acceptance among EV users involves comprehensively considering their charging requirements. These requirements, delineated by the EV user, encompass crucial facets of usage, with a prime example being the determination of the minimum range. This parameter, defined as the indispensable distance an EV must consistently cover, even in unforeseen scenarios like emergencies (Baumgartner et al., 2022), holds paramount importance for both EV users and aggregators in the V2G system. The minimum range not only stands as a critical criterion from the perspective of EV users but also assumes strategic significance for aggregators. It serves as a foundational element that outlines the flexibility potential contributed by EV users to the grid. Recognition and integration of the minimum range as an essential criterion ensure a harmonious equilibrium between EV users' requirements and aggregators' operational dynamics, thereby enhancing the overall efficacy and acceptance of V2G technology.

4.2.2. Long-term implication

Along with the aforementioned challenges, EV grid integration also has long-term implications for utility companies and grid operators in terms of operational planning and investment, which are given as:

a. **Operational planning:** Electric utility and grid users should include electric vehicles in their operational planning processes (Z. Ullah, K. Ullah, and G. Gruosso). This includes estimating EV adoption rates, predicting EV charging patterns, and assessing the impact of EV integration on grid stability and reliability. The plan will also include optimizing EV charging and release times to complement in-service programs while reducing costs and impacts.
b. **Infrastructure investment:** Grid operators must invest in infrastructure development to meet the growing demand for electricity payments. This includes expanding charging stations, improving transmission lines to handle heavier loads, and using smart technology to manage EV charging and discharging (Ullah et al., 2023) efficiently. Utilities must also invest in renewable energy and energy storage to offset the gap between electric vehicles. Regulatory authority: Utilities and grid operators should work with regulators to establish appropriate regulatory frameworks for EV integration. This includes developing EV charging models, using tariff models to encourage off-peak charging, defining grid interconnection rules and dividing the service line into EVs.
c. **Customer engagement:** Electric utilities need to engage with customers to encourage electric vehicle adoption and encourage positive charging behaviour (Li et al., 2023). This could include providing incentives for off-peak charging, providing EV charging infrastructure and educating customers on the benefits of EV integration for a stable and resilient grid.

5. Simulations result for V2G systems: a case study

This research presents a case study in which an AGC is developed for a power system network incorporating substantial wind energy integration. The motivation behind this development lies in addressing the issue of power unpredictability stemming from the challenges associated with wind energy forecasting. The integration of large-scale wind energy necessitates an augmented provision of operating reserves from conventional generation units, escalating the power system's operational costs. In light of these challenges, exploring and implementing alternative methods for procuring operating reserves, particularly from non-conventional energy sources such as wind power systems and electric vehicles, is imperative. Fig. 8 depicts a network model comprising various power-generating units and an EV aggregator model.

The generating system includes thermal and gas technologies, a Type IV wind turbine model, and an EV aggregator. The network has been designed to support the power grid for primary and secondary control in grid balancing services. The thermal generation system (TPGS) and the EV aggregator model will provide the required AGC and load frequency control support services. However, the gas turbine and wind power plant will solely contribute to primary control services. The model's objective is to realize the contribution of EV power in grid ancillary services. Furthermore, to enhance the inertial response of the grid, the network has been connected to the external grid, yielding a 6261 MW/Hz response within a 15-second timeframe. As shown in Fig. 8, the EV Model has been designed to furnish positive and negative regulation reserves when there is a power deficit and excess, respectively. Before activating the regulation reserves, the EV aggregator considers different constraints, such as the charging/discharging constant and the gain constant for frequency. The expected response delay is in the 0–3 seconds range. In this study, an EV fleet of 17000 with an average capacity of 7.5KW is assumed, which provides us with a cumulative capacity of 127.5 MW.

Fig. 9 shows the calculation of the regulation capacities for charging ($P^i_{EV,t} < 0$) or discharging power ($P^i_{EV,t} > 0$) from the maximum limits within a defined interval. In positive regulation, load is reduced, while in negative regulation, charging power increases. The following equations are used to calculate the positive and negative regulation capacities of an individual EV.

$$\cdot P^i_{PRP} = P^i_{\Delta t} - P^i_{(EV,t)} \quad (1)$$

$$P^i_{NPR} = \left(P^i_{EV,t} - P^i_{\Delta t}\right) \quad (2)$$

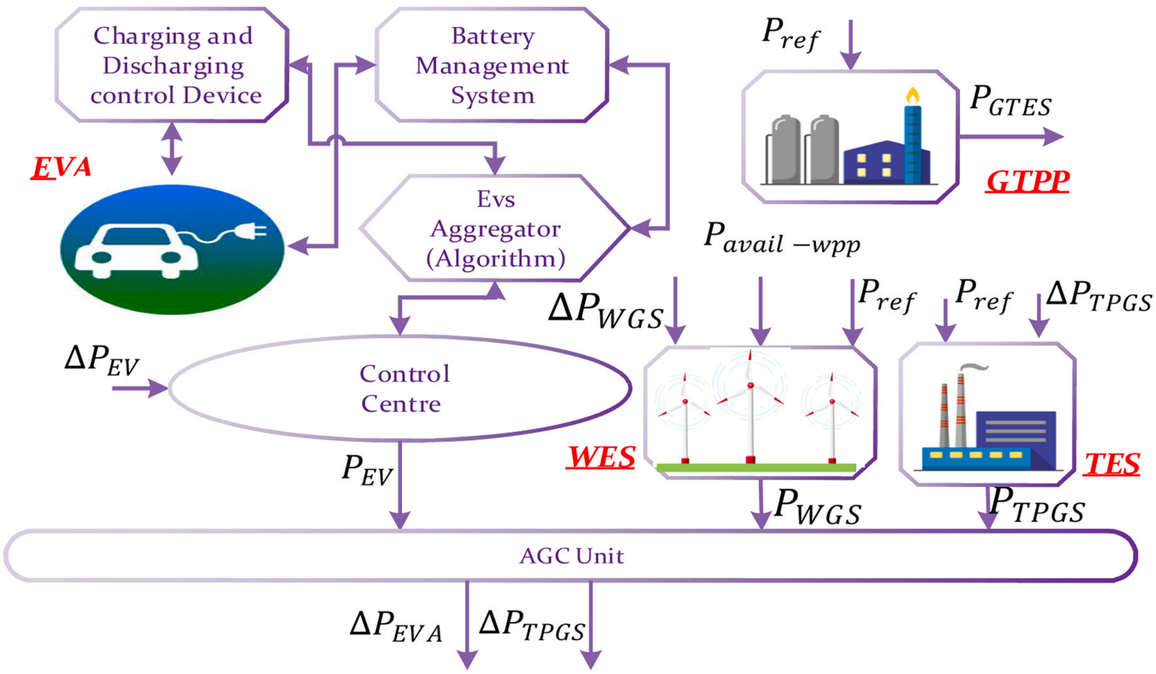

Fig. 8. Proposed Power System Grid with EV Model.

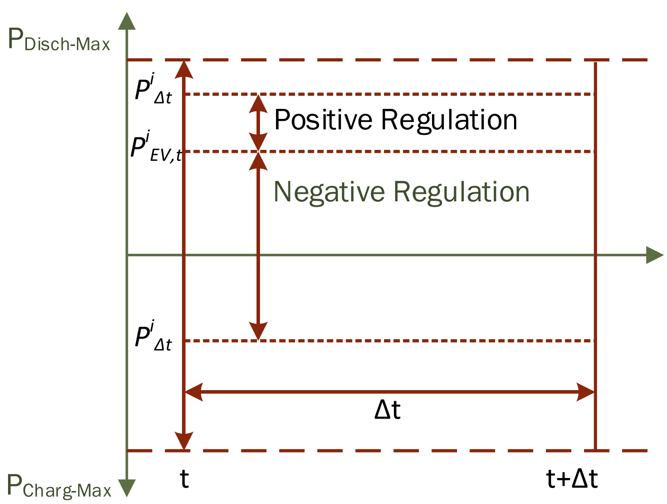

Fig. 9. EV's Positive and Negative Regulation Capacities.

PRR represents the positive regulation reserves, and NRR represents the negative regulation reserves. However, while calculating the positive regulation capacity, the ($SoC_{i\ need}$) must as per the user requirement 1. e ($SoC_t^i \geq SoC_{i,need}$) and the depth of discharge will be 60% to avoid degradation of the battery ($SoC^i_{\min,\ t+\Delta t} \geq 40\ \%$). In case of negative regulation, the constraint is the maximum charging power ($SoC^i_{\min,\ t+\Delta t} \leq 100\ \%$). Amidst the complexity of the simulation analysis, comprehensive efforts have been made to outline the operational capabilities and additional regulatory resources of the diverse range of generating units and EVs. These details are given in Table 5.

Fig. 10 (a) shows the real-time generation profiles of contributing power plant units, encompassing thermal Power generation systems (TPGS), gas turbine generation systems (GTGS), and wind generation systems (WGS) over a continuous 12-hour period. It is crucial to acknowledge that the actual input data for the wind power plants display significant disparities compared to the initially projected reference values (forecasted values) used in calculating the load-generation equilibrium. These variations reflect the inherent unpredictability due to the nature of WGS. The distinction between real and forecasted values and fluctuating load requirements results in an ongoing power imbalance between demand and generation. Resolving this issue necessitates prompt and efficient measures to reinstate equilibrium and ensure the power system's stability. Fig. 10 (b) highlights the disparity between load demand and cumulative generation from various generating units. Fig. 10 (c) presents the frequency response of the power system, characterized by continuous fluctuations due to dynamic generation and load behavior. Therefore, secondary reserves are utilized on a minute scale to restore the system frequency to its designated level and release the FCRs. Activation of secondary reserves can be achieved either through the AGC system or by manual intervention. The proposed AGC system employs an optimized and resilient approach by integrating EVs and TPGS to activate reserves. This integration facilitates advanced active power regulation services within renewable energy-intensive power systems. This intelligent power system effectively resolves grid balancing challenges and reduces the reliance on conventional sources for regulation purposes, thereby reducing environmental impacts, costs, and operational strain.

The case study delves into EVs' dynamic power control capabilities and a TPGS considering power equilibrium management. As indicated in Table 5, the EVs contribute a total regulatory power of ±75 MW using AGC system while ensuring the fulfillment of their primary response. Therefore, in this particular scenario, any deviation in the system frequency results in the generation of Area control error (P_{ACE}), a situation adeptly addressed by the AGC system by activating secondary reserves sourced from the TPGS and EVs. The combined primary response is derived from the generating units of the TPGS, GTGS, and WESs. Simultaneously, the secondary regulation relies exclusively on the coordinated contribution of the TPGS and EVs. The AGC dispatch strategy,

Table 5
Capacities and the Installed Reserves.

Generating units and EVs				
Network Model	TPGS	GTGS	WGS	EVA
Capacity in MW	1780	223	2790	127.5
Installed Reserves	±100	0	−500	±75.5

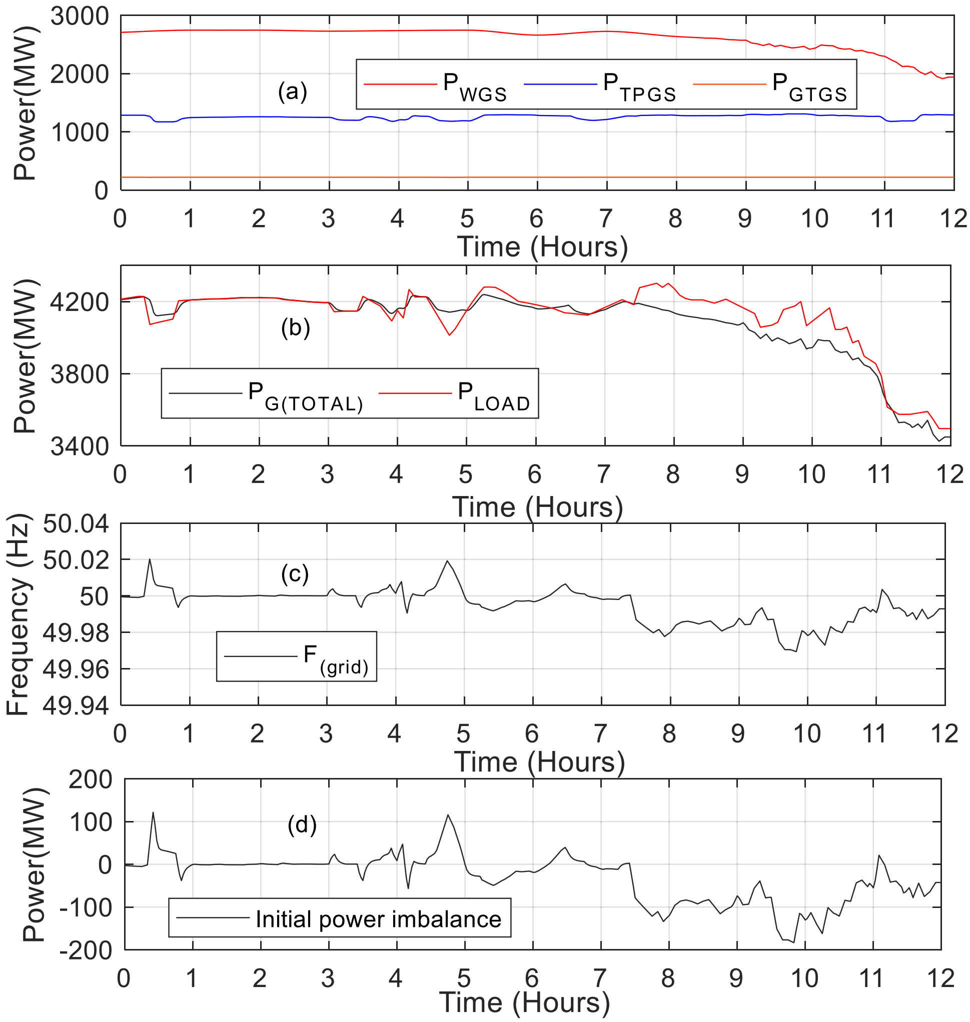

Fig. 10. (a) Real-Time Power Generation (b) Supply-Demand Dynamics (c) Network Frequency (d) Error Caused by Forecast Discrepancies.

exemplified in Fig. 11, encompasses a meticulous cost optimization process, ensuring the maximization of operational effectiveness and efficient allocation of resources. Various parameters are initially measured, and calculations are performed for each dispatch interval to quantify the positive regulation capacities (PRC) in instances where positive regulation ($\Delta P_s > 0$) is required; the AGC system mandates the utilization of available reserves by the EVA before any TPGS response. This preference is rooted in the reduced incremental cost of power generation obtained through electric vehicles. During a negative regulation process, the augmentation of battery charging power occurs under two conditions: firstly, when the TPGS operates at its lower limit ($P_{TPGS,min}$), usually established at 20% of its capacity, and secondly, when the secondary dispatch from the AGC descends to its lower limit ($\Delta P_{TPGS,min}$), denoted as −100 MW.

5.1. Results and discussion

Fig. 10d visually illustrates the initial imbalance between supply and demand, a challenge adeptly managed by the AGC system by dispatching reserve power from TPGS and EVs. Fig. 12 (a) shows the cumulative secondary dispatch (ΔP_{Sec})from participating generating units during the secondary response, following the P_{ACE} signal. The observed delayed response in this instance can be ascribed to inherent delays within the AGC system and the generating units. Fig. 12 (b) highlights the specific contributions of the TPGS (ΔP_{TPGS}) and EVs (ΔP_{EV}), to the secondary dispatch. The TPGS only engages when all available reserve power from the EVs has been utilized during the up-regulation process. Conversely, during down-regulation, priority is given to dispatch regulatory power from the TPGS over the EVs to minimize incremental costs. Fig. 12 (c) depicts the resulting frequency deviations within the system grid, as a result of the AGC response. Fig. 12 (d) contrasts real-time power imbalances pre and post AGC response, demonstrating a notable decrease in power imbalances for generation surpluses and deficits.

6. Conclusions and future directions

Emphasizing its dynamic role in the power system, the SG offers self-healing capabilities and serves a large consumer base as a sophisticated power system with integrated transmission and distribution systems. This study has focused on the increasing integration of EVs, highlighting the benefits of convenient charging, cost-effective tariffs, and environmental sustainability. The two operational modes of EVs, namely G2V and V2G, have been discussed in detail, especially in market and loading conditions. The exploration covers EV classification, V2G interactions, power flow regulation, and control structures. Additionally, the paper delves into the potential benefits and challenges associated with V2G systems. A notable contribution of this research is the comprehensive simulation analysis, where EV storage capabilities were harnessed to provide grid support services. Formulating a real-time dynamic dispatch approach facilitated the integration of EV capacities with the thermal energy system within the automatic generation control system. The findings demonstrate the efficiency of EVs in alleviating forecasting

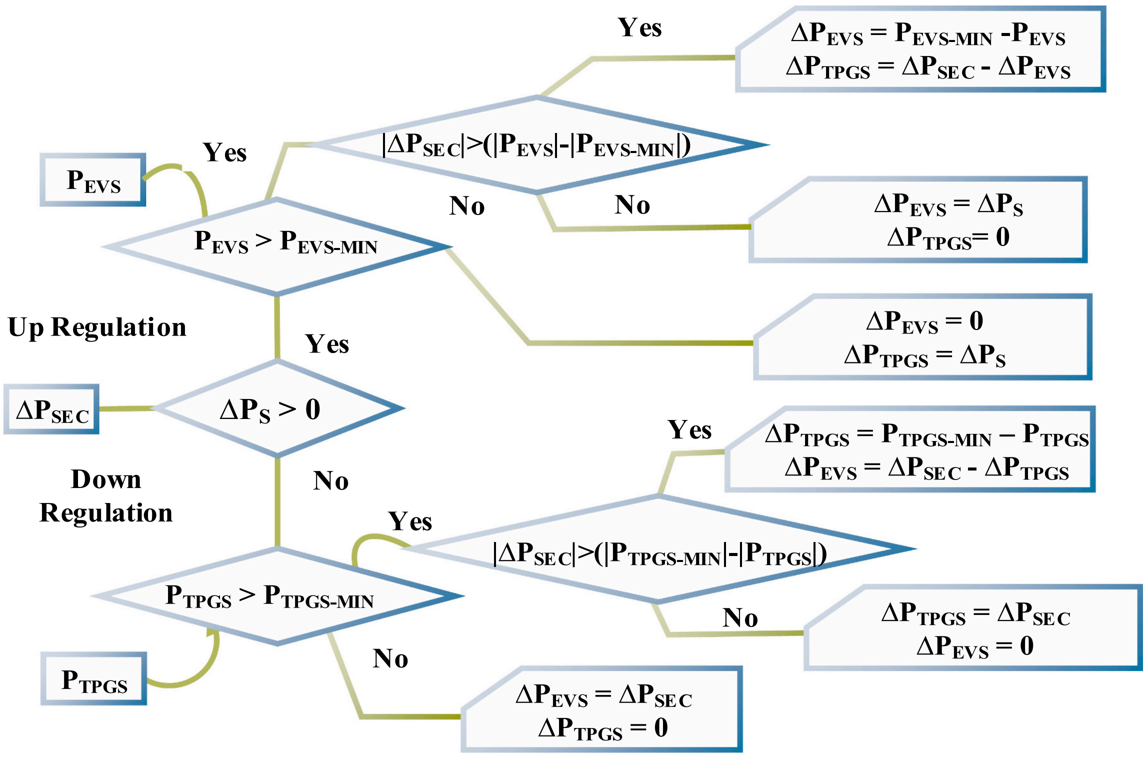

Fig. 11. Dispatch Strategy Integrating EV and TGS reserves.

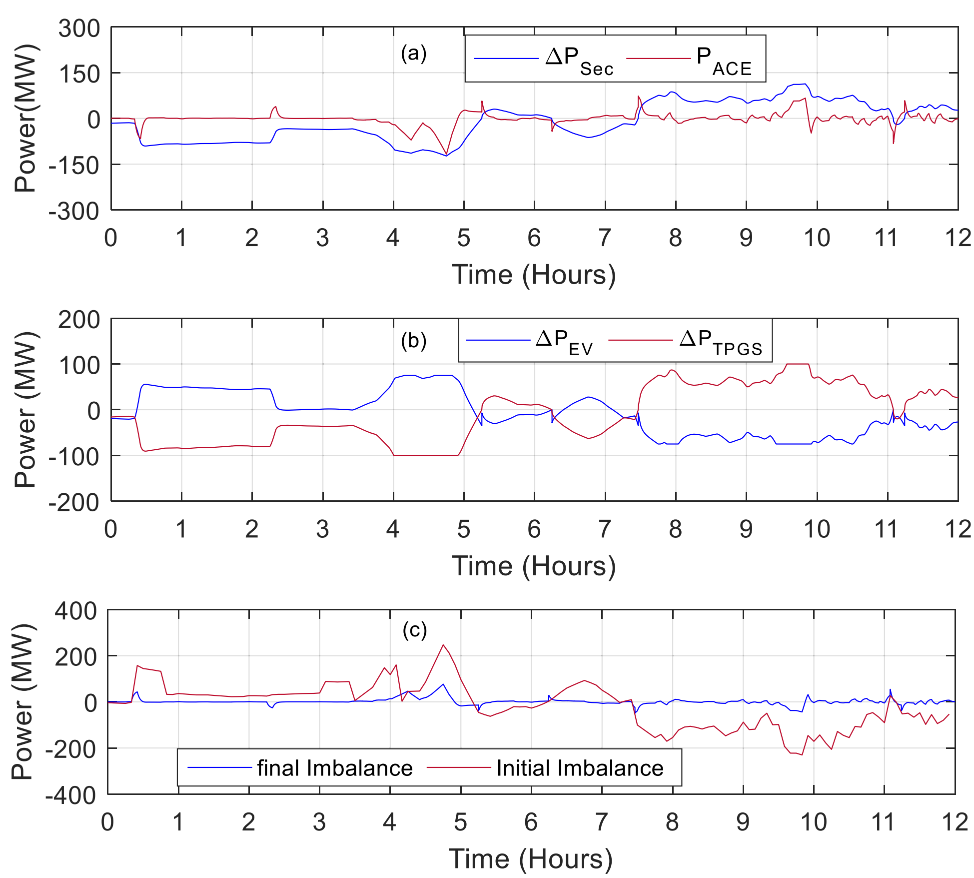

Fig. 12. (a) Area error and response, (b) TPGS and EV response, (c) Frequency error after AGC response, (d) Error comparison.

errors within a substantial renewable energy-based power network.

In the present study, an in-depth survey has been conducted focusing on the bidirectional approach of EV systems. However, the simulation model only addresses a multi-energy system's unidirectional aspect. There is potential for further exploration in the future, extending the simulation to encompass an AI-based bidirectional approach. This enhancement promises a more accurate prediction of grid parameters, ultimately elevating grid reliability and stability to new heights.

CRediT authorship contribution statement

Syed Fahad Murtaza Naqvi: Writing – review & editing, Software, Investigation. **Muhammad Minam Aziz:** Writing – review & editing, Software, Methodology, Formal analysis. **Muhammad Talha Ejaz:** Writing – original draft, Methodology, Investigation, Data curation. **Rafiq Asghar:** Writing – original draft, Validation, Software, Project administration, Data curation, Conceptualization. **Kaleem Ullah:** Writing – original draft, Visualization, Supervision, Software, Project administration, Formal analysis, Conceptualization. **Assia Mahrouch:** Writing – original draft, Validation, Resources, Formal analysis, Conceptualization. **Iqrar Hussain:** Writing – review & editing, Visualization, Resources, Conceptualization. **Zahid Ullah:** Writing – original draft, Software, Resources, Methodology, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

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

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