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Vehicle-to-Grid (V2G) Systems in Smart Grids: A Review and Case Study on AI-Based Energy Management and Grid Stability

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Abstract

Electric vehicles (EVs) are considered as one the most important part and parcel of future smart energy systems due to the smart electrification of transportation, and Vehicle-to-Grid (V2G) technology that leads to a viable way in improving grid flexibility, control peak loads and integrate renewable energy sources. The focus majorly on bidirectional power- electronic topologies, communication frameworks, control techniques, and AI-enabled optimization for uncertainty management and predictive operation helps to evaluate the current level of V2G research. The research addresses key deployment obstacles, such as worries about battery deterioration, immature infrastructure, unclear business models, cybersecurity vulnerabilities, and new power- quality issues including harmonics and supraharmonics, through a thorough synthesis of previous studies. A concentrated case study of India's electric bus (E-bus) transition highlights depot-level medium-voltage V2G (MV2G) as a currently underutilized system-level asset and demonstrates how fragmented planning and unidirectional grid readiness increase operational stress. Studies indicate that intelligent energy management, battery-health-aware operation, secure authentication frameworks, standardized communication protocols, and supportive regulatory procedures must all be coordinated for V2G implementation to be successful. The research indicates that in order to achieve scalable, economically viable, cyber-secure, and power-quality-resilient smart grid ecosystems, V2G must be positioned as a proactive design component rather than a post-deployment supplement.

Keywords: Vehicle-to-Grid (V2G); Bidirectional Power Electronics; AI-Enabled Optimization; Battery Health Management; Medium-Voltage Vehicle-to-Grid (MV2G); Supraharmonics; Power Quality.

How to Cite This Article

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Introduction

Vehicle to Grid(V2G) technology enable Electric vehicles (EVs) to support grid stability. This can be achieved when they are charged during off-peak hours and discharge when there is high demand of power. This technology will transform idle vehicles into productive energy assets that will play an important role in supporting grid stability and promoting the integration of renewable resources to grid support. Vehicle to Grid technology is considered to be a significant innovation in the field of Electric Vehicle technology. This technology will change the role of Electric Vehicle technology from being passive consumers to being productive prosumers. Vehicle to Grid technology will enable the bi directional flow of electricity between vehicle batteries and the grid. This means that Vehicle to Grid technology will enable electricity to be both consumed and produced. This technology will enable vehicle batteries to be charged, then enabling them to be used when there is high demand [1]. V2G is a component of the wider Vehicle-to-Everything (V2X) framework, which helps in applications like Vehicle-to-Home (V2H), Vehicle-to-Building (V2B), and Vehicle-to-Vehicle (V2V), so enhancing the utility of EV batteries for local and community energy solutions will be helpful for grid support. Successful coordination relies on standardized communication protocols such as ISO 15118 for the vehicle-charger interface and OCPP 2.0.1 to manage bidirectional energy flow mechanism. These systems enable cyber resilience, intelligent energy transactions for ensuring compatibility, and secure, automated, and the successful incorporation of EVs into modern smart grids [2 The idea of EVs functions as distributed energy resource and is enhanced by V2G technology, which acts as a small-scale energy storage network to improve grid reliability and supports in the addition of renewable energy sources. The vehicles which are at rest for 96% of the time will be used as large size battery to store energy. V2G enables bi directional energy flow, allow load to shift and during non-peak hours it will reduce the peak time. So, due to this the supply of energy will increase when demand is high. while it also contributes to stabilize frequency. By using the capability of V2G we can manage fluctuations in renewable energy generation methods to prevent grid overloading issues. To optimize load management and energy transactions V2G use digital platforms. Other from technical benefits, V2G will support EV owners to initiate de-carbonization initiative so that they will becomes both producer and consumer [3]. Some studies shows that global electricity demand from EVs could surge up to eleven times by 2030, uncoordinated charging poses a huge problem to urban power networks, which can lead to transformer overloads and voltage instability. If we necessarily adopt charging facilities with good management and systematically integrate it with V2G. Then it will also help to maintain grid stability. Demand Response programs encourage charging during off-peak hours. which helps to reduce pressure on infrastructure. while V2G enables EVs remain stationary for over 90% of the day and can act as mobile storage units that can absorb excess renewable energy and release it in times of high demand. By managing both reactive and active power in a bidirectional flow, V2G can contributes to reduce peak load, ensures frequency control, and can help to achieve voltage stability. Wireless Power Transfer (WPT) technologies enhance the scalability of urban environments. To make them ideal for smart cities and micro grids we can provide them contactless charging on roads or parking areas. However, a widespread implementation requires effective communication, real-time information updates, and flexible control systems to tackle the challenges presented by urban infrastructure and coordination [4]. Although it holds great potential, the extensive adoption of V2G technology faces a variety of economic, technical and regulatory challenges. The repeating cycles of charging and discharging of batteries will accelerate their degradation, while bidirectional converters may introduce harmonics, voltage inconsistencies and decreased efficiency. When there is large number of EVs integration there is a sudden rise in power requirement disrupting the power grid. The rise in expenses linked to infrastructures and operation, particularly for bi directional chargers limit the market readiness. Due to the lack of policies, different standards and insufficient allowance for users further reduce adoption. In case of public transport, such as electric bus depots, V2G may offer grid support during peak load but it also places pressure on local grid [5]. The purpose of this study is to understand the views of experts in the field of V2G, exploring different questions about the potentials and challenges of bidirectional charging and V2G for different stakeholders [3]. This research seeks knowledge about V2G architecture, examining the roles, potentials, and challenges for stakeholders involved in a V2G architecture, including consumers, V2G systems, power markets, and V2G communication operators [3].

Review Methodology

Search Strategy

A structured literature review was executed to make sure there is comprehensive coverage of V2G technologies, AI based optimization methods and associated power quality issues. Relevant publications were recovered from setup academic databases which includes IEEE Xplore, ScienceDirect, SpringerLink and Google Scholar. The search was performed using mixture of keywords like “V2G”, “Bidirectional Charging”, “AI in smart grid”, “electric bus integration”, “supraharmonics” in EV systems and “grid optimization methods”. The time range of review mainly focused on studies published between 2015-2025 also including a few earlier works.

Inclusion and Exclusion Criteria

To make sure importance and quality, the following inclusion criteria was applied:

- Refereed journal articles and conference papers.
- Studies that focus on V2G systems, smart grids, AI optimization and power quality.
- Recent Publications.

- Papers that provide experimental, simulation or case study based insights.

Exclusion criteria included:

- Non-refereed sources such as blogs and informal reports.
- Studies that are not directly connected to V2G or Ev grid integration.
- Redundant or duplicate publications

Quality Assessment

The selected papers were assessed based on:

- Publication source and reliability.
- Number of citations and research impact.
- Precision.
- Alignment with the review objectives.

Greater importance was given to studies that presented valid models, real world implementations.

Data Extraction and Synthesis

Significant information from chosen studies was methodically extracted and categorized into key areas:

- Basics and structure of V2G system.
- AI based improvement methods for energy management.
- Power quality problems including supraharmonics.

V2G Technology and its Importance in Contemporary Energy Systems

The Vehicle-to-Grid (V2G) technology introduces the concept of utilizing Electric Vehicles (EVs) as a form of distributed energy storage. Under the V2G model, the Grid-to-vehicle (G2V) concept illustrates charging of electric vehicles by plugging them into the grid due low demand periods and subsequently discharging the stored energy back to the grid during peak demand, referred to as V2G [6]. The flexibility potential of EVs can be realized by implementing smart charging and user incentives, as stated by the International Renewable Energy Agency (IREA). This idea will be essential for the successful integration of EVs and renewable energy [7]. Vehicle-to-grid(V2G), Vehicle-to-home (V2H) and Vehicle-to-vehicle (V2V) are three new grid-integrated technologies designed to take advantage of the battery storage capabilities found in EVs. The V2G technology heavily depends on continuous communication system, management protocols along with control to aid the transfer of electrical power between the power grid and electric vehicle [8]. The V2G systems have the capability of solving critical issues and offering multiple benefits and are therefore becoming increasingly important energy frameworks. Due to heavy reliance on conventional energy sources, the earth is facing issues such as air pollution, climate change, decreasing fossil fuel supplies and rising energy costs moreover, the transportation industry is responsible for almost 23 percent of the total greenhouse gas emissions. These escalating issues underscore the critical need to reduce these emissions. EVs utilizing V2G technology will support variable renewable energy sources and help achieve lower carbon intensity and improved energy efficiency [9]. It is advised to charge the electric vehicles during low demand hours and return energy back to the grid during peak demand. The V2G model is designed in such a way, wherein EVs serve as energy storage units and acquire energy during peak demand periods at a reduced cost and sell electrical energy in times of high demand at a premium. The figure 1 below shows the results from a survey on the demand fluctuations of a substation over a 24-hour period conducted at the Odhpura 132 kV substation in the Hathras district of Uttar Pradesh, India. The table clearly demonstrates that at 5 a.m., the substation experiences its lowest demand of 18.86 MW, while the highest demand of 48.99 MW occurs at 1 p.m. [10].

Table 1. *Fluctuations in Demand [10]*

Time	Demand(approx.)	Normalized Demand (%)
12 Midnight	24	48%
4 A.M	21	42%
5 A.M	19	38%
8 A.M	21	42%
12 Noon	48	96%
1 P.M	50	100%
4 P.M	39	78%
8 P.M	32	64%

$$f_{pev} = \frac{1}{\sqrt{2\pi\varphi^2}} e^{-\frac{(P_{pev}-\mu)^2}{2\varphi^2}}$$

This Table 1 shows a mathematical expression of a probability density function where fpev indicates the power available for V2G applications, μ represents the mean and φ denotes the standard deviation of a normal probability density function. The formula represents the deployment arrangement to measure and forecast the distribution of accessible EV power for V2G applications [11]. Electric vehicles featuring V2G technology will help stabilize power grids especially during peak demand periods, by balancing energy loads and assisting with voltage and frequency regulation [12]. This technology has a significant impact in improving the power quality in modern microgrids and smart grids especially tackling problems like imbalances, voltage surges, harmonics and flickering that results from distributed energy resources (DERs) [8].

Methods of Power Flow in V2G

Unidirectional Power Flow (G2V) and Bidirectional Power Flow (V2G) are the two main processes that monitor the flow of energy in EVs and the power grid [13].

Unidirectional Power Flow (G2V):
Unidirectional power flow describes the process of charging of an EV which involves the transfer of electrical energy in a single direction that is from the utility grid to the battery of the EV [14]. The Plug-in Electric Vehicles (PEVs) extract power from the grid in a unidirectional manner for charging. Their integration into the electrical system poses challenges because of their unpredictable power consumption patterns. PEVs pull power from the grid in a unidirectional manner for charging. This heightened demand, along with the irregular and intermittent characteristics of renewable energy sources, complicates the optimal power flow (OPF) problem.

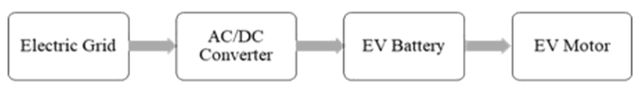

Fig. 1. *Unidirectional Power Flow*

Fig.1 shows a flowchart of an electric grid power flow through an AC/DC converter that charges the EV battery which further drives the motor.

Limitations in Terms of Grid Support:

- G2V systems do not permit the electric vehicle to send power back to the grid (Vehicle-to-Grid, or V2G) [15]
- G2V by itself is not a viable and economical energy storage solution to address the issues created by the fluctuating characteristics of renewable energy sources [15]
- One-way power flow restricts electric vehicles from engaging in dynamic demand management, which includes returning power to the grid when demand is high or when other grid needs arise [15]

This highlights that unidirectional systems are insufficient for the broader grid integration goals that bidirectional systems aim to achieve [15]

Bidirectional Power Flow (V2G)
Bidirectional power flow describes the ability of a battery charger to enable the transfer of power in both directions between an electric vehicle (EV) and the electricity grid [14].

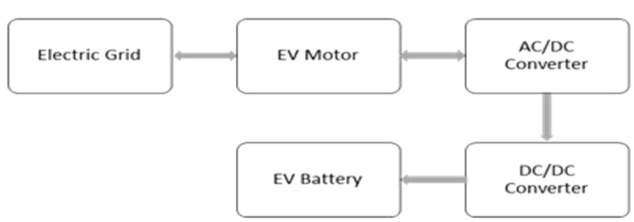

Fig. 2. *Bidirectional Power Flow [14]*

In Fig. 2 an AC/DC converter is used for exchanging power bidirectionally between the EV motor and the electric grid. This power then is stepped down through a DC/DC converter to charge or discharge the battery of an EV.

Usage and Objective

- Peak Shaving: In times of high electricity demand (peak load), PEVs can return their stored excess energy from their batteries back to the power grid through V2G, helping to alleviate the peak load on the system [16].

- Load Balancing/Valley Filling: While the primary focus of V2G is discharging energy during peak periods, in order to create a more balanced overall load profile, the energy utilized for peak shaving needs to be replenished during off-peak or valley times via G2V charging [16].
- Emission Reduction: According to the results shown by the simulation results, a visible reduction in the annual emissions and the total emissions of pollutants have been witnessed when PEVs are utilized for peak shaving and valley filling [16]. EVs not only draw energy to recharge their batteries but also have the capability of sending it back in the power grid. This feature is enabled by the implementation of bidirectional DC-DC converters [17].

Role of AC/DC and DC/DC Converters:

Bi-directional AC/DC and DC/DC converters are fitted in EV chargers in order to facilitate bidirectional power flow [18].

1. AC/DC Converters: These converters serve the purpose of rectification, converting alternating current (AC) from the electrical grid into direct current (DC) to charge the EV battery. In reverse, they convert the DC current from the EV battery back into AC before feeding it into the power grid during the discharging process [18].
2. DC/DC Converters: These types of converters, including Buck, Boost, and Buck- Boost converters, act as "choppers" to regulate the bidirectional power flow. They operate during both the charging (loading) and discharging phases of the EV battery [18].

Energy Flow Mechanism

The described system facilitates energy flow between the conventional AC grid, an Electric Vehicle (EV), and an AC load (representing a household or other local consumption), with the integration of a Photo Voltaic (PV) system. In Grid-to-Vehicle (G2V) mode, the EV battery is charged. Power can come from the AC grid or be supplemented by the PV system. This power first passes through a Voltage Source Converter (VSC), which converts AC to DC. Then, a Dual Active Full Bridge (DAFB) converter steps down the voltage to match the EV battery's rating. In Vehicle-to-Grid (V2G) mode, the EV battery discharges to supply the AC load and/or reduce demand on the AC grid. The PV system can also contribute power in this mode. Power from the EV battery is stepped up by the DAFB converter and then converted from DC to AC by the VSC before being supplied to the load or grid. The PV system is connected at the DC link for power injection. Photovoltaic System Integration in G2V: When the photovoltaic (PV) power is not available, the AC grid exclusively provides electricity to both the AC load and the electric vehicle (EV) battery. To alleviate the load on the AC grid from the EV, a PV system is incorporated. When there is available PV power, it works in conjunction with the AC grid to deliver electricity to both the AC load and the EV, thereby decreasing the amount of energy drawn from the grid. If there is no EV connected for charging, the produced PV power can be directed entirely to the AC load via the voltage source converter (VSC), which converts DC to AC, further alleviating the strain on the AC grid [19].

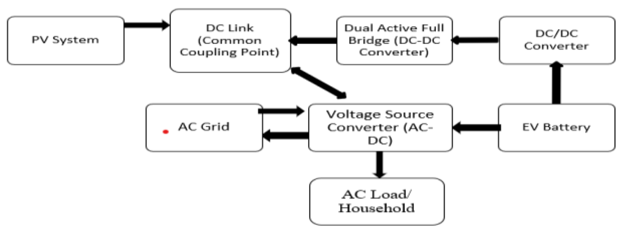

Fig. 3. *Energy Flow Mechanism*

Fig. 3 depicts how a PV system and EV battery feed power using the DC-DC converters into common DC link which is then distributed bidirectionally to AC grids and household loads using a voltage source converter.

Benefits of Bidirectional Charging

The benefits of bidirectional charging can be classified into categories like grid support, economic benefits, vehicle functionality along with enhanced system performance. These advantages cater the electrical grid, EVs and consumers [20], [21], [22].

Grid Support and Stability:

- Increased Grid Stability and Flexibility: Bidirectional charging improves the stability and efficiency of EVs that allows them to deliver secondary services to the power grid [20], [21], [22].
- Management of Peak Demand: EVs can help manage the electrical load which can result in reducing bills by billions of dollars every year. The balancing of electrical load is achieved by reducing peaks and increasing the output during low demand periods. These methods contribute significantly in diminishing the peak demand that assists utilities in delaying costly investments along with transmission and distribution upgrades [20], [21], [22].
- Regulation of Frequency and Voltage: According to IEEE1547 standard, the bidirectional On-Board Chargers (OBCs) can adjust fluctuations in the grid frequency or voltage with the required levels of active and reactive power. These chargers assist in frequency

and voltage regulation by aligning supply with demand for both active and reactive power [20], [21], [22].

- Integration of Renewable Energy: In to order to reduce the dependance on non-renewable energy storage solutions and facilitating a more reliable energy ecosystem, the batteries of EVs have capability of storing a large amount of renewable energy that is generated from variable sources such as wind and solar. The marginal expenses of charging can be reduced by the coordination of EV charging by the integration of EV charging [20], [21], [22].
- Mitigation of Grid Congestion and Harmonics: Bidirectional OBCs aid in reducing the current harmonics in the grid by treating battery chargers as variable impedance and employing appropriate filtering techniques. EVs will help in the reduction of grid congestion either by absorbing or delivering power at the time of peak demand [20], [21], [22].

Case Study: India's E-bus Implementation and V2G Potential

Current State: Infrastructure Without Planning

India is committed to electric mobility, as seen by its strong e-bus ambitions, an ambitious goal for a single city and a portion of a larger country. By 2030, India intends to deploy 50,000 electric buses. The flagship PM E-Drive initiative, which has set aside Rs. 10,900 crore, its largest funding portion specifically for e-buses over a two-year period ending in March 2026, is one of the main forces behind this shift. The goal of this program is to install 14,028 e-buses in nine significant cities. Delhi, Bengaluru, and Mumbai are the main cities to achieve these goals. E-buses are being bought and delivered more quickly than the grid can be modified to accommodate them [23]. E- buses require substantially more energy and have more concentrated charging schedules than private electric vehicles, putting a strain on existing local infrastructure. Even though depot charging, which is frequently done overnight, usually benefits from lower grid base loads, charging big fleets at once can still significantly increase system peaks. Direct charging of heavy-duty vehicles from local distribution networks may result in a number of hardware and power quality problems, including transformer overloads, harmonic distortion, and voltage drops and changes. Overloading causes excessive heating, which shortens the life of switchgear and transmission lines and causes insulation in transformers to break down [24]. Urban power systems, which are frequently not built in conjunction with transportation electrification programs, have substantial electrical load consequences due to the quick expansion of electric bus fleets. While the charging demand of individual electric buses is relatively low, grid impact assessments in the Indian context indicate that aggregate fleet charging can significantly strain local distribution networks, with fleets of 100 buses requiring roughly 2-3 MW, 500 buses requiring 10-15 MW, and large deployments of about 5,000 buses exceeding 100 MW of demand. There will always be risk of infrastructure bottlenecks and operational delays even in the presence of policies on peak load mitigation in the presence of uncoordinated planning between transport authorities and power suppliers [23].

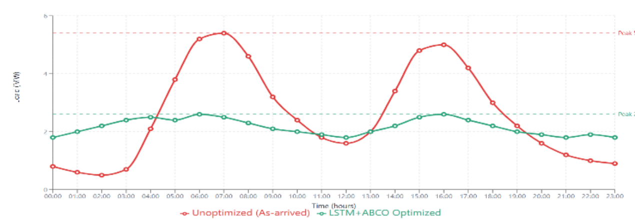

***Fig .4.** The figure shows a 24-hour depot charging load curve under unoptimized and AI-optimized conditions.*

Fig.4 The figure compares uncontrolled charging behaviour with LSTM and ABCO optimized scheduling for a BMTC depot. It shows visible peak flattening and load redistribution that is achieved through the intelligent coordination of both the scheduling methods [50],[51]. The shift to electric buses in the transportation industry is slowed due to inefficient cooperation among government industries, transportation companies, traffic authorities and power utilities. The lack of a central nodal authority reduces the synchronization between e-bus fleet growth and the grid in spite of this the transportation companies keep on purchasing e-buses which leads to insufficient or delayed charging infrastructure and more strain on the grid. Additionally, it is highly challenging to convince operators to switch from diesel to electric, predict the charging loads and control the impacts on the grid. All the problems combined as the result of the absence of an integrated demand forecasting tool, fragmented governance, delayed infrastructure design and lack of monitoring of data that hampers the effective integration of E-bus systems [25], [26]. The experience at the 11kV BMTC Depot 7 distribution feeder in Bengaluru's Majestic neighbourhood is an example of the gap between the grid and fleet electrification. The distribution feeder was initially installed to facilitate power to the residential and small business loads. However, there have been accounts of voltage fluctuations and power quality problems faced by locals. The episodes of voltage reductions and various power quality issues have been witnessed in the evening when many e-buses are charged collectively. Nearby businesses have been impacted by these disruptions and have been forced to temporarily turn off delicate electrical equipment in order to prevent damage. These effects show that the feeder's intended design capacity is being exceeded by charging loads, and the distribution network is functioning near its temperature and voltage stability limits. This case demonstrates how e-bus depots are currently viewed as passive, high-intensity electrical loads rather than as controllable energy assets from a systems perspective. Transformer stress is accelerated and peak demand is made worse by the lack of bidirectional energy flow devices, real-time load monitoring, or synchronized charging schedules. Due to the lack of grid management frameworks and enabling infrastructure, vehicle-to-grid (V2G) functionality whereby buses could provide local voltage regulation or peak shaving has not been investigated, as mentioned in the case. Therefore, the above episode shows how the national electrification goals will result in localized grid instability due to disconnected design and ignorance of MV2G methods. These experiences at the depot level showcase the danger of increased stress on the grid resulting from the rapid electrification of public transport [23].

The Missing Link: V2G as an Untapped Solution

V2G offers vital services like peak management, voltage support and frequency regulation by improving the grid stability. Due to the V2G technology, especially at the medium-voltage or depot level (MV2G), the EVs can function as distributed energy storage units that can provide power back into the grid. V2G introduces a cost-effective way to improve load management, reduce stress on grids and delay the expensive infrastructure upgrades by using current vehicle batteries rather than depending on grid reinforcements. By enabling local energy buffering at fleet depots, MV2G enables EV fleets to function as collective batteries with substantial aggregate capacity, turning depots into prosumers with the ability to engage in time-based energy arbitrage [27]. The sophisticate metaheuristic algorithms like Artificial Bee Colony Optimization (ABCO) effectively address high-dimensional optimization problems. Vehicle depots serve as the perfect nodes for V2G and V2X integration since they combine centralized control and predictability conditions that are perfect for ABCO algorithms. Depots are also ideal for putting in place standardized communication protocols that enable smooth V2G, V2B, and wider V2X integration, optimizing fleet dependability and grid support. The algorithm makes efficient use of long idle times, especially overnight parking to balance revenue production against battery degradation. It also provides useful opportunities for off-peak charging, peak-period discharging and grid assistance without sacrificing vehicle availability. A centralized energy management system at depots will improve the efficiency by lowering operational variability, enhance consistency and time efficiency. These can be achieved by coordinating energy flows with real-time grid conditions and pricing signals [28]. The V2G model is still mostly at a conceptual level. Even though it being a promising concept with its acknowledged potential for peak demand management and carbon reduction, the V2G technology lacks large-scale implementation. This is because the current implementations are failing to reflect the assumptions of a fully integrated smart grids and the majority of electricity utilities still run primarily unidirectional grid systems that are not built to support two-way power flows. The V2G systems face technical gaps like experienced smart meter, uniform technical and legal frameworks for reciprocal energy transactions. To overcome these gaps, a significant investment is required to shift from a utility centric, business models to distributed storage architecture and smart grid platforms. These platforms support infrastructure-to-vehicle (I2V) and vehicle to infrastructure (V2I) communication. The current grid infrastructure is still one-way and requires a structural shift to fully bidirectional systems. V2G deployment relies on next-generation battery management systems along with improved processing power and predictive intelligence features. As a result, even while V2G is recognized majorly as a problem solver, its full-fledged integration in the grid is still a theoretical concept [29]. Artificial intelligence (AI) and enhanced predictive controls enable accurate forecasting, safe bidirectional communication and intelligent decision-making.

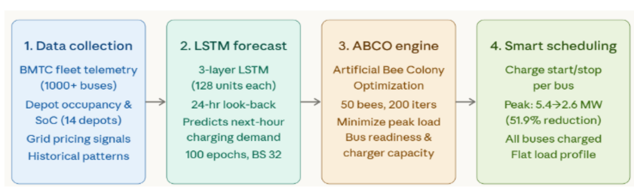

Fig. 5. *The figures the system architecture of BMTC electric bus depot based on LSTM and ABCO smart charging methods.*

The architecture explains data acquisition, optimization using ABCO and load forecasting with the help of LSTM. It helps to coordinate charging decisions to minimize peak demand [50],[51]. A functional and future ready V2G ecosystem is built on these tools. A complex integration of transport and grid data that covers real-time route characteristics including vehicle attributes, environmental factors and V2G potential, combined are necessary for the precise forecasting of energy requirements. According to the protocols like ISO 15118, Model Predictive Control in addition to machine learning, repetitive optimization of historical data, current operational states and future estimates are enabled. These intelligent IT protocols support in achieving forecasting accuracy as high as 0.5 percent and enable dependable peak-load shifting through the above mentioned. By managing extra factors like different renewable generation, erratic user behavior and changing electricity prices problems where standard deterministic models fail, AI further improves this framework. AI driven optimization enhances grid durability through very active peak shaving and frequency regulation using advanced models like LSTM networks, it also increases cost effectiveness and computational speed and protects important assets through predictive battery health management. The straightforward bidirectional charging concept of the V2G technology is changed into a dependable, intelligent and a highly responsive smart grid enabler accounting to the new advancements in AI including Explainable AI and safe AI architectures [30] [31].

Lessons of V2G Implementation: Insights from Literature and Case Analysis

Early V2G integration with Integrated Rural Energy Planning (IREP) makes it possible to construct intelligent, micro-scale energy systems. These systems balance sustainable supply with the local demand. Micro grids are used by planners that utilize EVs as bidirectional storage assets for peak shaving and load management. Renewable sources like solar and wind meet the majority of demand. The early adoption of V2G will improve grid stability, turn rural users into active energy prosumers, supporting energy access, economic resilience and environmental stability despite hurdles like high charger costs and battery degradation. The successful adoption is achieved by appropriate technological topologies that are backed by smart meters, aggregators and reliable communication infrastructure [32]. Electric fleets switch from passive charging to at active load management with the help of bidirectional V2G operation thereby increasing the EV's economic and grid worth. The EV fleets offer secondary services like frequency management, peak shaving and also serving as a flexible energy resource. EVs also operate as static loads to only fulfil the transportation demands and not provide any grid support. The best results come from combining these services; techno-economic assessments demonstrate that, in contrast to single-service operations, integrated frequency containment and peak shaving can produce positive long-term returns. Because regulated charging and discharges retain more stable and lower levels of charge than passive charging, active management also enhances technical performance by lowering battery deterioration. Bidirectional charges, clever compensation schemes that take battery wear into account, and sophisticated battery management systems that strike a balance between grid services and vehicle availability are all need to realize these advantages [33]. Growing the size of electric vehicles is crucial for enabling cutting-edge grid-support services like peak shaving and ancillary service supply, but it also increases operational, computational, and security threats. Particularly as traditional servers struggle with sequential data processing and increasing network latency, large, disorganized fleets can put a strain on grid resources, cause communication bottlenecks, and expose larger attack surfaces susceptible to data forgery, impersonation, and cyber invasions. On the other hand, when scale is properly managed, fleets become potent grid assets that can offer surplus power, frequency confinement, and substantial economic value through aggregated energy trading. Large fleets can function as synchronized systems that improve grid resilience and reliability rather than as sources of instability thanks to secure, scalable coordination architectures that use parallel processing through cloud–fog hierarchies and lightweight security measures like mutual authentication and Physical Unclonable Functions [33], [34]. While early V2G integration allows EVs to operate as mobile storage units that balance supply and demand through services like spinning reserve and peak shaving, reactive solutions to grid instability, such as deploying auxiliary synchronous generators during peak demand, are expensive and inefficient and frequently result in wasted off-peak renewable energy. Grid stability is greatly improved by using an anticipatory control technique, specifically a direct adaptive PID- PSS on the V2G side. This results in better damping, quicker settling times, and less oscillations during disturbances like load changes or solar PV shading. By avoiding voltage spikes and problems with power quality, this strategic design enables V2G systems to react to frequency variations seamlessly. Additionally, by lowering losses, enhancing voltage management, facilitating high renewable penetration, and permitting coordinated charging through aggregators, V2G readiness turns EVs into long-term distributed energy assets that fulfil user demand and guarantee grid dependability [35]. Although V2G-enabled systems are technically possible in a variety of operational contexts, such as battery degradation management, secure communication frameworks, renewable-integrated micro grids, and grid-support services, their efficacy heavily depends on coordinated system design. All of the cases show that the benefits of V2G come from the alignment of control techniques, battery-aware operation, cybersecurity protections, and institutional preparation rather than just bidirectional power transmission.

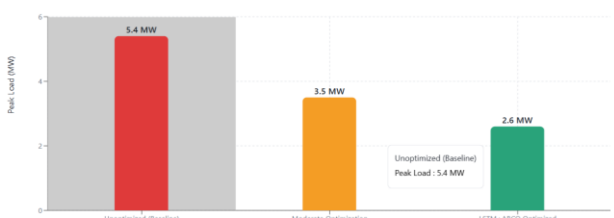

Fig. 6. *Bar graph representing peak load received through AI-based optimization.*

This bar chart illustrates the reduction in peak load from baseline (5.4MW) to optimized operation (2.6MW). It highlights a significant reduction that is approximately 51.9%, demonstrating the effectiveness of V2G enabled smart charging [50],[51]. These results imply that the lack of such coordination turns V2G from a system-level solution into a disjointed pilot concept when compared to extensive public transport electrification initiatives. Therefore, rather than being implemented as a retrofitted or isolated technology add-on, the case evidence supports the idea that V2G must be integrated as an essential planning component inside electric bus rollout strategies.

Problems and Their Mitigation Techniques

Technical Challenges

EV batteries wear out due to continuous charging and discharging with time. Due to this people doubt about the life of batteries, degrading EV impression. Battery efficiency diminishes due to charging to fast or in extreme hot or cold temperature in V2G scenarios where cycling occurs frequently. Lack of standardized charging infrastructure and communication protocols makes it difficult to integrate. Performance and cost effectiveness is decreased due to differences in charging speeds and energy conversion inefficiencies. Enhanced battery management, advanced systems and charging strategies ensures the sustainable progress of V2G technology [10].

Proposed Solutions

1. The challenges of V2G can be dealt with advanced approach that includes advanced battery management, digital standardization, enhanced charging approaches, and developed infrastructure. The degradation of batteries can be minimized through AI-driven maintenances by using super capacitors to manage the quick energy bursts and safeguard lithium-ion batteries. For real time coordination between EVs and the grid the issue of improper infrastructure can be minimized by applying advanced Information and Communication Technologies and Advanced Metering Infrastructure. Improper charging and pressure on the grid can be reduced with AI-based load balancing, evolving prices and demand-response programs shifting charging to less busy hours. Lastly by developing infrastructure such as advancing substations, transformers, and distribution networks while integrating renewable energy sources allowing EVs to act as mobile energy storage units, enhancing grid flexibility, efficiency, and long-term sustainability [36].

2. Due to V2G operations there is battery degradation and system losses which can be reduced by advanced lifecycle management, secure communications and high-performance power electronics. By Combining lithium-ion batteries with ultra capacitors in Hybrid Energy Storage Systems helps in reducing battery stress by directing high frequency current while thermal management systems and optimized HVAC controls helps in stabilizing operating temperatures and increase battery life. According to robust communication protocols such as IEEE 802.11p, IEEE 1609, and DSRC address standardization challenges, can be enhanced by secure authentication methods that includes physical unclonable functions and block chain based smart contracts to guarantee privacy, transparency and protection against cyber threats. Due to difference in speed of charging and improper conversion which are addressed using high efficiency multilevel converters, intelligent PWM based bidirectional power control that avoids misalignment, is reliable, is efficient and is secure V2G integration [8].

Critical Comparison

The first solution approaches AI driven grid coordination, block chain enabled energy trading and developed infrastructure improving scalability, renewable integration and grid flexibility. The second solution is more technology focused, which shows direct reduction of battery degradation through hybrid energy storage systems, advanced thermal management, high efficiency electronics and standardized secure communication protocols defined by IEEE making it more practical and economical. The second solution is more suitable for instant practical execution, whereas the first solution gives better benefits in long term, large scale smart grid merging.

Regulatory & Policy Challenges

The adoption of V2G technology faces many problems due to the absence of any standardized regulations, tariff structures and sufficient government backing. The system suffers from inconsistencies and unreliability due to unclear policies of energy pricing, compensation frameworks and data protection. The EU Electricity Market Directive 2019/44 current regulations are not fully prepared for large adoption of EVs. Due to the lack of government allowance and insufficient funding for research in smart charging infrastructure and improper battery management, there occurs difficulties for establishing reliable and scalable V2G environment [37] [38].

Proposed Solutions

1. The problems in adopting V2G and V2V technologies can be reduced by combining standardization, effective policy frameworks, substantial governmental support and focused research developments. By creating a shared compatibility layer by aligning charging connectors and communication protocols according to global standards like IEC and ISO/IEC which allows smooth V2G interaction, to ensure safety and effectiveness, it is backed by specialized certification organizations. Block chain enabled smart contracts for clear compensation can be achieved by making pricing constant and safeguarding data, along with strict protocols to data privacy laws and the use of decentralized identifiers to safeguard user information. The growth of infrastructure and practical implementation can be increased by enhancing government supports through funding, tax benefits and extensive pilot initiatives promotes. At last it is necessary to build better infrastructure of battery management system for real time monitoring for research purposes which can help for ensuring future quality services [39].

2. The growth of V2G and smart charging technologies can be increased by effective regulations, economic, technical and research-based approaches. Clear protocols make sure smart charging is working properly, EVs and energy system are communicating with each other without any issues. Economic performance may increase through Time of Use and changing tariff policies which supports value stacking and it is backed up by government allowances and subsidies for extensive charging infrastructure. Technical standardization with the help of unified IS, facilitates dependable V2G communication, whereas reliable data protection, cybersecurity protocols and the integration of smart charging into demand side response starts by increasing system reliability. At last, to minimized battery degradation, real world performance and shifting transportation power to electric power with grid stability goals there is ongoing support for research and disciplinary collaboration [7].

Critical comparison

The first approach highlights global standard alignment with the help of organizations like IEC and ISO/IEC which focuses on, block chain-based data protection and reliable government backed pilot programs to build trust and infrastructure. The second approach takes help from the market which emphasizes operational regulations, important smart charging capabilities, tariff changes, value stacking and integration with demand side response to ensure economic feasibility and grid reliability. The first solution offers strong security and their mixed application is needed for sustainable V2G and smart charging surroundings. The second solution is more practical in the near future implementation, whereas the first solution is important for long term secure and consistent V2G deployment.

Economic Challenges

In order to implement V2G technology on large we lack critical initial infrastructure expenses and efficient business models. The experienced communication system, requirement of expensive bidirectional chargers and grid improvements creates financial boundaries for both utility companies and EV owners. The absence of practical and profitable business models reduces the user's participation since the existing advantages do not compensate for the investment costs. Due to the absence of favourable market conditions, structural system for laws and financial strategies. The inefficient adoption of V2G remains limited to its participants.[40], [41]

Proposed Solutions

1. For V2G, the solution can be upgraded that mainly focuses on aggregators in terms of technology that promotes uptrend in market economically. To fulfil the minimum biding requirements the aggregators, facilitate participation by combining several EVs, supporting frequency regulation models that depend on shallow cycling and availability payments to mitigate battery wear, and managing smart charging to alleviate peak demand and postpone expensive grid upgrades. Permitting Aggregators to act as Balance Responsible Parties to simplify the value chain to optimize revenue efficiency. To meet the bidirectional charging infrastructure there are some standards that need to be met like CHAdeMO and ISO/IEC 15118, as financial and technological risks depend on it. To compensate the expenses of EV owners there should be mechanisms such as direct payment, service agreements and warranty protection. which ensure economic safety to the aggregators. when their service revenues surpass costs related to ownership, energy and system management [42].

2. To make V2G executable government backing is essential. The creation of standardized protocol for bidirectional charging and creation of a rule-based committee that will integrate manufacturers, organizations and EV owners. Viable business models allow EV owners to generate their income by delivering energy during high demand periods by organizing market engagement. These models not only decrease the charging expenses but also earn profit from carbon trading initiatives. Distribution System Operators (DSOs) uses the EV fleets for stabilization of the grid, deploying advanced batteries with longer lifespans and data informed scheduling systems that improves the efficiency of operations. A clearly explained incentive- based model if implemented for grid operators, vehicle makers and EV owners will lead to the successful integration of V2G [43].

Critical Comparison

While both solutions improve the economic viability of V2G, their main drivers are different: the first is market- and aggregator-centric, emphasizing the role of EV aggregators in pooling resources, enabling frequency regulation through shallow cycling, optimizing revenues via simplified value chains, and ensuring technical readiness through standardized bidirectional charging like CHAdeMO and ISO/IEC 15118; the second is policy- and government-led, focusing on subsidies, standardized protocols, and incentive-based business models that allow EV owners and DSOs to Monet their integration is crucial for long-term stability and scalability through institutional support. The platform driven solution is more efficient in mature markets, whereas the strategy driven solution is better for starting stage adoption, making a mixture of both important for long term V2G deployment.

Social & Consumer Acceptance

The growth of EVs faces significant issues due to low consumer awareness and battery dependability. Many users do not have proper information about the advantages of EVs, due to these users avoids using EVs. The high costs of batteries, their limited lifespan, their performance and range make user to avoid buying. Thinking about the EVs people may like EVs but there are concern about environmental impact of battery manufacturing and disposal further reduced acceptance, due to unclear warranty guarantees reduces trust in long-term reliability [44].

Proposed Solutions

1. Consumer accepting V2G can be improved by targeting financial, communication, technical, and infrastructural measures. To improve awareness and trust among the user to compensate for battery ageing, flexible benefits schemes, and transparent reporting of earnings address cost and degradation concerns. User centric system design such as smartphone-based control which can help user to set minimum state of charge, real time notifications, and automated operation which automatically manages charging and discharging, helps reduces range anxiety. Wider adoption further depends on technical standardization through universal protocols and unified software platforms, supported by mobility-aware planning tools. Strategically deploying V2G infrastructure at long-duration parking locations such as workplaces and airports minimizes disruption to daily travel and enhances user participation [45].

2. To boost user interest in V2G through a mix of financial, educational, technical, and infrastructural strategies which include financial benefits such as tax deduction, subsidies, clear compensation which help in marketing strategies to boost consumer willingness. problem related to awareness can be deal by focusing on educational and outreach initiatives. To deal with technical issue related to range anxiety

and battery reliability can be done using ensuring minimum battery threshold and access to fast charging option and lastly development of infrastructure backed by government led pilot and demonstration interest especially in public transport sectors helps to widespread system reliability and V2G adoption to increase. [46].

Critical Comparison

The first solution is user centric and design driven, emphasizing direct compensation for battery wear, transparent earnings disclosure, intuitive smartphone based controls, technical standardization, and strategic placement of chargers at long-duration parking locations to minimize inconvenience, while the second is policy and awareness oriented, focusing on subsidies, tax benefits, market-based pricing, structured educational campaigns, independent performance validation, and government led pilot to build trust at scale. Crucially, both are complementary for long-term V2G adoption. The customer centric solution improves engagement and experience, whereas the strategy driven solution helps large scale adoption, making both important for sustainable V2G growth.

Supraharmonic Distortion in V2G Systems

Supraharmonic distortion creates challenges for power quality in V2G systems which is characterized by conducting emissions within the 2 kHz to 150 kHz frequency range that result from the high frequency switching of bidirectional EVSE. These supraharmonics are primarily not affected by the power level during charging or discharging unlike traditional low frequency harmonics which indicates their presence whenever the V2G charger is active. These emissions can be created by both narrow band components linked to pulse width modulation at the converter switching frequency and its harmonics as well as wide band components that arise from DC-to-DC converters. Frequency dependent impedance of the grid can be modified by the addition of EVSE by introducing extra capacitance from LCL filters and DC links possibly modifying resonance frequencies and increasing distortions. These interactions of impedances may result in voltage amplification due to parallel resonance or increased current distortion which is caused by series resonance with the levels of emissions being affected by the local grid arrangement. Supraharmonic voltages may result in thermal stress, shortening the life line of equipment's, generating acoustic noise and interfering with power line communication systems which is utilized in smart grids, even though their amplitudes are usually low. Due to the lack of international standardized emission limits within this frequency range and variations in measurement techniques this issue is further complicated [47].

Proposed Solutions

1.The reduction of supraharmonic distortion (2–150 kHz) in V2G systems is necessary because of the widespread use of bidirectional power electronic converters, these have a major contribution towards high frequency emissions. Converter level design, filtering methods and overall system coordination are some effective methods for mitigation. LCL filters are favoured over simpler designs because they help in reducing the transmission of supraharmonics by keeping higher network impedance whereas DC link capacitors help in reducing high frequency current ripple which is generated by DC to DC converters. Additionally, shunt active power filters may help in reducing distortion and allowing limited down rating of power factor correction stages. Multilevel inverter designs, interleaved converter configurations and refined modulation techniques such as zero dead time and random PWM at the converter level decreases emission peaks and spectral concentration. Reduction at the system level depends on smart V2G coordination with real time communication facilitating adaptive power which is based on grid conditions therefore reducing distortion during operating periods. Controlled V2G operation using advanced active rectifiers helps in sustaining near to unity power factor while reducing low order harmonics. Lastly improved grid monitoring and design of the interactions among multiple chargers are essential for addressing resonance, intermodulation and combined emission impacts. The absence of standardized supraharmonic emission limits the need for updated regulations and immunity testing that guarantees dependable operation in grid environments characterized by high frequency distortions [48].

2.Current research majorly focuses on low frequency harmonic distortion whereas supraharmonic emissions from the EV chargers are gaining recognition as an important issue in smart charging and V2G systems. The research tells us why we need improved standardization, as the existing harmonic cutoffs are implemented only at rated operating points and do not address the increased distortion observed at limited loads. Therefore, it is suggested that future standards apply classifications particularly to chargers, execute regulatory testing at multiple operating points and set clear limits for controllable loads such as EV chargers. Smart charging strategies which are aware of harmonics are recommended to support regulations, where charging and V2G set points considers harmonic emission profiles along with grid demands. Charging scenes which involves multiple vehicles, the coordination of charging can harness harmonic phase angle cancellation to reduce total distortion at the point of common coupling. Additionally, it is proposed to employ probabilistic and predictive modelling methods, including Monte Carlo simulations, to assess the combined harmonic effects of diverse EV fleets interacting with existing nonlinear loads. Lastly, progress in bidirectional charger technology and control indicates that managing charging and discharging power levels is important for maintaining harmonic emissions within limits while ensuring reliable V2G functionality [49].

Critical Comparison

The first solution focuses on technology and infrastructure, aiming to directly reduce supraharmonic emissions through advanced converter designs, filtering techniques and real time coordination between vehicles and the grid. It prioritizes immediate technical efficiency, working to minimize emissions at their source and during operation, which makes it particularly suitable for current V2G and MV2G setups. Its effectiveness however is limited by the absence of established emission standards and consistent testing methods, which may restrict its scalability across different grid systems. Whereas the second solution takes a regulatory and system planning approach. It emphasizes improved standardization, smart charging strategies that account for harmonics and the use of probabilistic modelling to manage aggregated emissions on a larger scale. While this method offers better long-term compatibility with regulations and systems, its dependence on future standards and coordinated management at the fleet level reduces its immediate practical impact. To conclude, the first solution provides short term technical mitigation whereas the second establishes a foundation for scalable and regulation compliant V2G integration. Combining both strategies is essential to ensure effective power quality management in the short term and the long-term sustainability of V2G systems. The first solution is better for instant The first solution is more efficient for instant technical control, whereas the second is better for long term, scalable and compliant with regulations integration.

Conclusion

This review paper demonstrates that, when V2G technology deployed with proper planning, V2G technology can get significant advantages in peak shaving, renewable energy integration, grid flexibility. Moreover, it enables economic value creation which makes it crucial for future smart grids. However, there is a lack of business models, insufficient cyber security designs, lack of standard communication protocols and underdeveloped bidirectional infrastructure. New reports also shows that new technological issues need more attention than other conceptual studies such as battery degradation, harmonics and supraharmonics and electromagnetic interference. To scale V2G on large it requires AI-enabled predictive control and advance energy management, battery health management system, strong communication and authentication frameworks and regulatory frameworks that match utility incentives with user participation. The rapid electrification without the synchronization of grid planning causes localized network stress. These conclusions are supported by the Indian E-bus context. Overall, the assessment shows that rather than being implement it in existing infrastructure, V2G should be integrated as active component of grid. Future work must focus on cyber security, resistant to power quality issues, Large-scale and cost-effective implementations backed by real world use, standardized frameworks, and integrated policy with technical ecosystems moving beyond theoretical implementation.

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