Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 3, Issue 10 (2025)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

Smart Grid Coordination With Electric Vehicles For Frequency Regulation Using V2G Technology

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ABSTRACT

This paper will explore how Vehicle-to-Grid (V2G) technology can support grid frequency regulation by leveraging the Electric Vehicles (EVs) as distributed energy resources (DERs). With the higher demand of renewable energy, the intermittent nature of sources such as solar and wind becomes a serious problem to the stability of the grid, requiring creative solutions to issues of frequency regulation. V2G technology also makes EVs provide power to the grid when high demands occur and to absorb extra power when the demands are low because it enables bi-directional energy flow between the grid and EVs. Simulations have shown that V2G systems significantly improve the grid frequency deviation significantly, with a potential reduction of the operational costs of a 25 percent compared to traditional approach. Beside that, also in the study, we find efficiency of V2G in relation to the amount of energy it supplies to the system compared to the amount it uses on the grid, and the EVs used supply more than they use. Nonetheless, obstacles like battery degradation and an optimized schedule were found. However, despite these issues, the introduction of EVs into grid services has presented a flexible, cost-effective, and sustainable frequency-supporting solution, resulting in a more resilient energy system. This study highlights the significance of expanding charging infrastructure and developing battery technology further in order to maximize the advantages of V2G systems.

Keywords: Vehicle-to-Grid (V2G), Electric Vehicles (EVs), Frequency Regulation, Smart Grid, Distributed Energy Resources (DERs), Renewable Energy, Grid Stability, Energy Efficiency, Battery Degradation, Cost Savings.

Introduction

Its quick evolution towards smart grid technology is the opportunity to facilitate the general management process of electrical grids massively, more particularly, in the

Online ISSN 3007-3197
Print ISSN 3007-3189

balance of supply and demand. Smart grids seek to incorporate digital communication, automation into the grid to enhance efficiency, reliability, and sustainability. Frequency regulation is the most complex aspect of managing a smart grid, it is a capability to control the stability of a grid relative to ensuring the frequency of the electrical stream can adjust within a specified range. Regular coordination is essential to the efficient operation of the network, especially as it incorporates more renewable sources of which many are not as predictable or as reliable as historical sources. Traditional frequency control methods such as spinning reserves or generation on fossil are characterized by a number of failings, such as expense and environmental concerns. This necessitates the need to come up with innovative ways of achieving stability of the grid in addition to reducing costs and environmental impacts.

One of the parts of this solution is to introduce Electric Vehicles (EVs) to the smart grid through Vehicle-to-Grid (V2G) technology. The V2G technology facilitates the two-way flow of energy between the grid and EVs, such that EVs can provide power to charge the grid in case of inadequate supply. This characteristic enables EVs to be used as a valuable frequency regulation resource as EVs can provide a greater amount of capacity to the network during peak usage periods or when renewable energies are impacted by unavailable generation. Of much interest in the recent past has been the application of EV as a distributed energy resource (DER) in the stabilization of the grid with the possibility that it provides a more cost effective and sustainable solution of frequency regulation (Kempton & Letendre, 1997; Morrow & Wang, 2012).

In terms of frequency regulation, coordination between smart grids and EVs is a multifaceted process that requires not only efficient management of the EV fleet but also the grid operation requirements. Smart grid technologies with real-time communication and advanced control systems can perfectly optimise the participation of EVs in the operation of the grid by dynamically varying charging and discharging rules in response to grid demand (Lopes & Soares, 2010). To ensure the EV use of batteries is fit, the application of V 2 G technology would have to be paralleled to the grid using some sophisticated algorithms to equalize energy consumption, forecast demand, and keep the batteries fit. In order to utilize fully all the potential of V2G technology in grid frequency regulation, it becomes vital to understand the technical, economic, and regulatory aspects of it.

The role of EV in the smart grid has become a subject of investigation with most notably being the ability of EVs to provide a method of frequency regulation. In an illustration of this study, a literature review conducted by Gouveia and Silva (2013) on various V2G systems and how they may be applied in smart grids also stated that EVs have the potential to provide primary and secondary frequency regulation services. Similarly, Zhang and Chen (2017) sought answers to optimizing EV in active engagement in frequency regulation proposing models that consider EV battery constraints and the constraints of the charging facilities. Furthermore, Su and Liu (2015) examined the EV scheduling in smart grids, and an optimal EV dispatch might be adequate to deliver a significant improvement in the frequency regulation process.

Nevertheless, although the V2G technology holds great potential, various issues exist around the application aspect of the technology. Such issues encompass the unpredictability in the use of EVs, battery decay issues, and the necessity of common

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Volume 3, Issue 10(2025)

Online ISSN 3007-3197
Print ISSN 3007-3189
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protocols of communication between grid operators and EVs (Morrow & Wang, 2012). Moreover, there are regulatory concerns like the availability of incentives to EV owners to avail V2G programs and the requirement of quality infrastructure to support both bi-directional chargers that should be tackled to make V2G systems accessible to large population groups.

The improved smart grid technologies and energy management systems of late have made the integration of V2G technology a more bountiful atmosphere. The advancement of advanced communication systems, and the expansion of EVs, provides an opportunity to apply V2G technology in frequency regulation on a wide scale. With the number of EVs on the road going higher and higher, the potential of EVs as an energy resource in grid stabilization can only grow over time. In this paper, the synchronicity between smart grids and EVs in terms of frequency regulation is discussed, and the V2G technology, advantages, and limitations as well as future of incorporation in grid management systems are addressed.

Literature Review

The introduction of Electric Vehicles (EVs) to the energy grid has gained significant attention in recent years, particularly with respect to the issue of frequency regulation. Frequency stabilization One remedy that has been hyped is the possibility of a Vehicle-to-Grid (V2G) solution, which could be used to transport energy two ways, between the grid and the electric vehicle fleet. It conducts an in-depth literature review on why EVs are significant in the outcome of frequency regulation, how the V2G technology works, the challenges, and opportunities that become available as a result of such integration.

Evolution of Smart Grid and Frequency Regulation

The concept of the smart grid has emerged in response to the inefficiency of the traditional grids, notably in the balancing of supply and demand of electricity. Smart grid is associated with leveraging of a newer higher order of communication and automation technology that aids better monitoring of the same, controls, and optimization of the energy flows (Huang & Zhang, 2017). Frequency control is one of the most valuable functions of the smart grids because they ensure the balance between electricity generation and consumption. The classic methods of frequency control commonly rely on synchronous generators, which turn into reserves in cases that feature the mismatch of supply and demand (Bie et al., 2019). However these methods are as well restricted by environmental factors, their expensive content and reliance on fossil fuels.

The recent years have also seen the augmented application of renewable source of energy namely wind and solar in the production of electricity. These sources offer sustainable benefits but they are less continuous and fluid, which makes them hard to handle by grid operators (Liu et al., 2020). Consequently, other new options, such as V2G, have also been brought on and are also an alternative way of stabilizing the grid. Through it, EVs can become a supply source of mobile storage, which can contribute to grid frequency control by providing stored energy to high-demand and receiving overcapacity in low demand scenarios (Zhang et al., 2019).

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Vehicle-to-Grid Technology and Its Mechanisms

The technology involved in an exchange of electrons between the grid and the electric vehicle is known as vehicle-to-Grid (V2G) where as the EVs can not only use grid power but can also feed back to the grid during emergencies (Kempton & Tomic, 2005). This enables EVs to act as distributed energy resources (DERs) and can be utilized by the grid operator to assist in frequency stabilization.

V2G technology: Its fundamental system includes the need to outfit EVs with intelligent charging systems that can talk to the grid. Through this communication, the grid can ask EVs to discharge stored energy in real-time depending on frequency regulation requirements (Wang et al., 2018). The sheer power which can be transmitted is restricted by the capacity of the EV battery, the level of charge that it has, together with the efficiency with which it can charge and discharge. To maximize the efficiency of discharge plans and minimize the effects on battery durability, advanced mathematic algorithms and control systems are applied to EVs (Liu et al., 2016).

Flexibility is one of the major claims of V2G technology. In Chinese words, in contrast to the traditional systems involved in the power generation process, which are highly resistant to discontinuity, EVs are mobile assets that can be called upon to participate in grid services when plugged in and parked, offering a dynamic and decentralized solution to frequency regulation (Chien et al., 2019). Visually increasing the responsiveness of the grid during frequency disturbances can be enhanced considerably by the possibility to send off the power available in a large fleet of EVs.

Role of Electric Vehicles in Frequency Regulation

The capability of EVs to participate directly in frequency regulation has been examined in several studies. Another enormous advantage of the V2G technology is the provision of primary frequency regulation and secondary frequencies of regulation. Primary regulation is an instant reaction of the grid to variance in frequencies, whereas the views of secondary regulation are long-term changes to the grid frequency to fire up to their nominal value (Wang et al., 2017). They may use the EVs to deliver both services particularly in situations when conventional sources of generation are either lacking or may fail to respond in time.

Research by Xu et al. (2018) and Liu et al. (2020) have discussed the application of EVs in primary frequency control where EVs can add a fast capability response to the grid, discharging power in response to frequency fluctuations. These studies illustrate that EV energy storage power, in aggregate form, with contributions as small as those per individual vehicle, can lead to meaningful grid support, especially in high-demand periods. Also, via V2G, EVs will be able to offer secondary control by soaking up surplus power when demand is low and balancing grid frequency on a longer time basis.

The interaction between smart grid control of the electric grid and EVs to regulate frequency in a grid is frequently coordinated by a centralized control structure or a decentralized control structure. Under a centralized system the grid operator can

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Volume 3, Issue 10(2025)

Online ISSN 3007-3197
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communicate with each EV requesting that they discharge or charge. Decentralized systems, by contrast, entail a peer-to-peer approach between EVs and the grid where EVs react individually to the conditions of the immediate grid environment (Zhao et al., 2019). These two methods have their benefits and constraints which depend on factors like communication infrastructure, EVs involved and flexibility of operation of the grid.

Challenges in Integrating EVs for Frequency Regulation

Despite the immense potential of the V2G technology, its use in frequency regulation has several challenges which limit its use. The first problem is the risk that frequent charging and discharging would impact the battery life of EVs. The prevalent Li-ion batteries commonly found in EVs are also prone to wearout particularly under extreme charge/discharge cycles. Therefore, it behooves the overall profitability of running EVs into the frequency market to mitigate such cyclings and avoid exposing EV owners to significant battery degradation (Huang et al., 2020).

To mitigate against these effects the studies targeted at optimizing the role of EVs in frequency control with respect to identifying the most effective frequency regulation schedules to balance the grid needs and battery life. Other authors have proposed the use of machine learning models to predict the most suitable charging and discharging times of EVs on the basis of the grid status and residual battery charge (Li et al., 2019). The algorithms can help to get rid of the deep discharge cycles which are common and extends battery life of the EVs but not applicable to affect stability of the frequency of the grid.

Another problem is that V2G communication protocols have not been standardized. The crossing of different EVs and smart grids is also an issue because the producers of EVs depend on several communication standards and charging equipment (Zhao et al., 2019). EVs entering the frequency regulation services smoothly depends on the development of standard communication protocols, and compatibility of vehicles with different systems.

Nonetheless, the absence of regulatory and economic incentives of EV owners to participate in V2G programs also exists. To allow V2G systems to work, the policymakers will need to come up with incentives that will encourage the EV owners to share part of their vehicle power with the grid. These incentives can be economic incentives, tax credits, or beneficial charging rates of participating vehicles (Sharma et al., 2020).

Opportunities and Future Directions

However, there are also various opportunities of EV in frequency regulation. First, large scale deployment of EV fleet in the world provides the grid with a sprawling, distributed energy storage capable source. The more EVs are implemented, the more they will have the ability to provide grid services. Moreover, EVs continue to experience some of the problems of battery degradation challenges that can be further addressed as battery technology enhances in the upcoming developments such as solid-state batteries that would make the EVs even better suited to V2G purposes (Zhang et al., 2019).

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It will also enable the success in grid services integration of EVs through the development of smart charging infrastructure and the enhancement on the energy management systems. Through these systems, communication between EVs and grid operators will be conducted more efficiently, enabling real-time coordination and raising the level of overall frequency regulation (Chen et al., 2018).
Also with the V2G innovation, the possibility of achieving renewable energy additions into the grid creates a massive opportunity. Uncertainty in renewable output can be countered by offloading excess renewable energy during low demand periods to EVs, creating a more variable output that can then be made reliable and consistent in supply through the EVs (Hossain et al., 2019).

Conclusion

In conclusion, the deployment of Electric Vehicles connected to smart grids through V2G may bring a solution to control the frequency more effectively and achieve more stability on the grid. The necessity to secure the sustainability to address the current issues, though the potential benefits of V2G systems are rather evident, one can still notice the list of challenges when discussing battery degradation, communication standards, and regulatory frame However, at the moment the issues regarding insufficient battery capacity, lack of smart charging infrastructure and energy management frameworks are being studied and are expected to be solved soon which in turn will result in the widespread application of V2G systems that will carry out frequency regulation.

Methodology

This paper explores the potential of Vehicle-to-Grid (V2G) technology in improving frequency control in smart grids. The approach created within the work consists of multiple steps such as the development of a simulation model, setting performance KPI, and the implementation of an optimization technique to estimate the efficacy of the V2G integration in frequency regulation. The following are elaborated to bring a clear picture of the research approach.

Simulation Model Design

The important point of methodology is the creation of the simulation model in which a comparison based on the coordination of the electric vehicles (EVs) and the smart grid may be created to achieve frequency regulation. The model will be used to mimic live operation of the grid and a fleet of EVs with V2G technology. To build a realistic environment of the simulation, a range of parameters have to be taken into account, including the charging and discharging options of EVs, their battery conditions, and changes in demand by the grid.
With a mixture of power system simulation software and custom algorithms, the simulation model is constructed. The main objective of this model is to reproduce grid frequency disturbances, and the importance of EVs in eliminating these disturbances. The model considers different grid conditions such as peak demands, when the renewable energy output may be high (thereby leading to spare energy) or when the renewable generation is low (and the energy needs to be supplemented). In modeling,

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EVs are seen as mobile energy storage devices, having the capacity to discharge electric power to the grid and absorb it when required. The scope of interactions that occur between the EVs and the frequency regulation system is provided by a number of operational rules, by which the frequency regulation participation of EVs is determined. The simulation includes a fleet of EVs having various capacities and states of charge (SOC). These EVs are geographically spread out over various charging stations, and participation of individual vehicle in frequency regulation is selected based on its availability (i.e., whether the vehicle is plugged in and not in use), SOC and battery health. The interaction between the grid and the EVs is modeled with real-time exchanges of CGI data, whereby the EV react timely to the frequency regulation requirements of both the grid.

Performance Metrics

Some of the main performance metrics that are used to test the effectiveness of the simulation model are as follows, which can be used to conduct a quantifiable analysis of the effectiveness road test of the contribution of EVs in frequency regulation in the grid. The main metrics employed in this work are the frequency deviation, energy efficiency, and cost efficiency.

Frequency deviation is a measurement of the difference between the required grid frequency (usually 50 Hz) and the current actual grid frequency at any one moment. Lower deviation means more success in the frequency regulation, and this parameter acts key in the process of rating the efficiency of V2G supported EV effectiveness in the process of grid stabilization. The response time of the EVs is a key parameter during grid disturbances in minimizing the frequency deviation, and the model follows the time that the EV fleet takes to respond to the changes in frequencies.

Another significant measure is energy efficiency, which is estimated by dividing energy supplied to the grid by the EVs by the total amount of energy used by the EVs to charge. This measure assists in calculating the potential ability of the energy supplied by EVs to be closed to frequency regulation, relative to their overall charging energy needs. The high energy efficiency benchmark implies the EVs will not just be involved in frequency regulation but are also providing substantive grid stability without massive wastage of energy.

Cost efficiency measures the costs of regulating frequencies using EVs with respect to the costs of regulating frequencies using conventional generation units. The expense of providing customary frequency regulation services e.g. spinning reserves or fossil-fuel-based generation is contrasted to the cost of using EVs, and specifically, the cost of operating the V2G infrastructure to control the provided EVs in addition to the cost of paying EV owners to open up their cars. This measure is essential in determining the economic viability of the use of EVs in frequency regulation of the grid.

Optimization Techniques

Integrating EVs to the grid to perform frequency regulation is not as easy as providing power to the grid at a time of disturbance. It entails how and when EVs can optimally release their accumulated energy to guarantee maximum utility and at the same time

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Volume 3, Issue 10(2025)

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maintain the condition of the EV batteries and to keep the expenses at a minimum. This is achieved by using an optimization algorithm in the current study.

Optimisation: The objective of optimization is to achieve the best dispatch of EVs to provide frequency regulation services subject to a number of constraints including battery state of charge (SOC), battery degradation, charging infrastructure access, and grid-frequency. This study utilizes a mixed integer linear programming (MILP) based optimization algorithm, which enables continuous and discrete variables to be modeled as the problem. Continuous variables entail the quantity of energy released or charged in every EV, whereas the discrete variables indicate the participation of an EV within the frequency control or the lack thereof.

The optimization model aim is the minimization of the overall cost of frequency regulation with the desire that the grid frequency be maintained in a permissible range. This cost is operationalized as the combination of cost of use of EVs (which incorporates energy exchange price and compensation of EV owners) and cost of grid frequency deviation. The model also includes the cost of battery degradation, including the deterioration of the battery life caused by a large number of discharges/charges. The optimization algorithm searches multiple iterations of the charging/discharging schedules of the EVs to identify the most resource-efficient resource allocation to provide frequency regulation.

The charging infrastructure, such as access to charging points and the charging speed of EVs is considered in the optimization model. The specified restrictions are especially critical in practice where access to charging stations and EV charging rates may depend on various locations and the condition of the development of the infrastructure. The facts included in the model are meant to make it more real and viable when implementing the use of EVs in frequency control.

Data Collection and Simulation Execution

A set of input data is needed to make sure that simulation delivers the results that appear realistic. This consists of historical grid demand, renewable energy generation and EV fleet data. The grid demand data derives its value during normal day usage such as peak and non-peak times. Data on renewable generation sources are obtained by using sources, including solar and wind power, is variable and intermittent, presenting challenges in grid frequency control.

The EV fleet vehicles contain apparently simulated or real-world data sets that contain the vehicles count, battery capacities, time taken to charge and driving patterns. The simulation will be conducted across various time horizons to measure the performance of the system under various grid settings and also understand the overall effect of EV integration on grid frequency stability.

Evaluation and Analysis

After running the simulation model, the obtained results are examined within the context of the above-presented performance metrics. The frequency deviations of the grid are plotted sequentially to obtain a visual indication of how well the EVs are involved in mitigating the grid disturbances. The metric of energy efficiency and cost

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Volume 3, Issue 10 (2025)

Online ISSN 3007-3197
Print ISSN 3007-3189

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efficiency are also computed to compare whether the use of the EVs to provide the frequency regulation could be an alternative to its traditional offer.

The acquired optimisation results are presented to elucidate on the efficacy of the developed scheduling algorithm in terms of cost minimization and grid stability. These results are compared to a baseline scenario where more traditional means of frequency regulation are instead employed, such as spinning reserves or fossil-fuel generation so as to gauges the extent to which employing V2G technology can enjoy relative advantages against such established technology.

Finally, sensitivity analysis is conducted to examine how various parameters influence system performance. To illustrate, the effects of EV fleet variability, battery capacities, and grid conditions on frequency regulation effectiveness are studied. Such data will be beneficial to gain insights into the scalability and operability of the real-life grid functioning through V2G systems.

Results

The stabilization of smart grid operations by regularization of electric vehicles (EVs) through the Vehicle-to-Grid (V2G) technology is known to be the best opportunity to stabilize smart grid operations. Results of the study are provided in this section and are based on the data and figures obtained through comprehensive simulations, and the effectiveness of EVs in enhancing the frequency regulation of the grid is considered.

Frequency Deviation with and Without EVs

The frequency deviation analysis results shown in Figure 1 and Table 1 show that the inclusion of EVs in the frequency regulation is a significant improvement in grid stability The Nature of the frequency in the grid without EVs is highly fluctuating that indicates a peak deviation of 0.7 Hz. On the contrary, as EVs are added, the frequency deviation becomes limited in a much smaller bandwidth with the deviation at most 0.2 Hz. This means that EVs have a capacity to use surplus energy and to generate power when there is increased demand thereby balancing the grid. As can be seen in Figure 1, the relationship between the line plot and smooth frequencies curve is visual evidence of the stabilization effect of EVs that brings about added smoothness in the curve.

Table 1: Detailed Frequency Deviation Data with and without EVs

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Volume 3, Issue 10 (2025)

Online ISSN 3007-3197
Print ISSN 3007-3189

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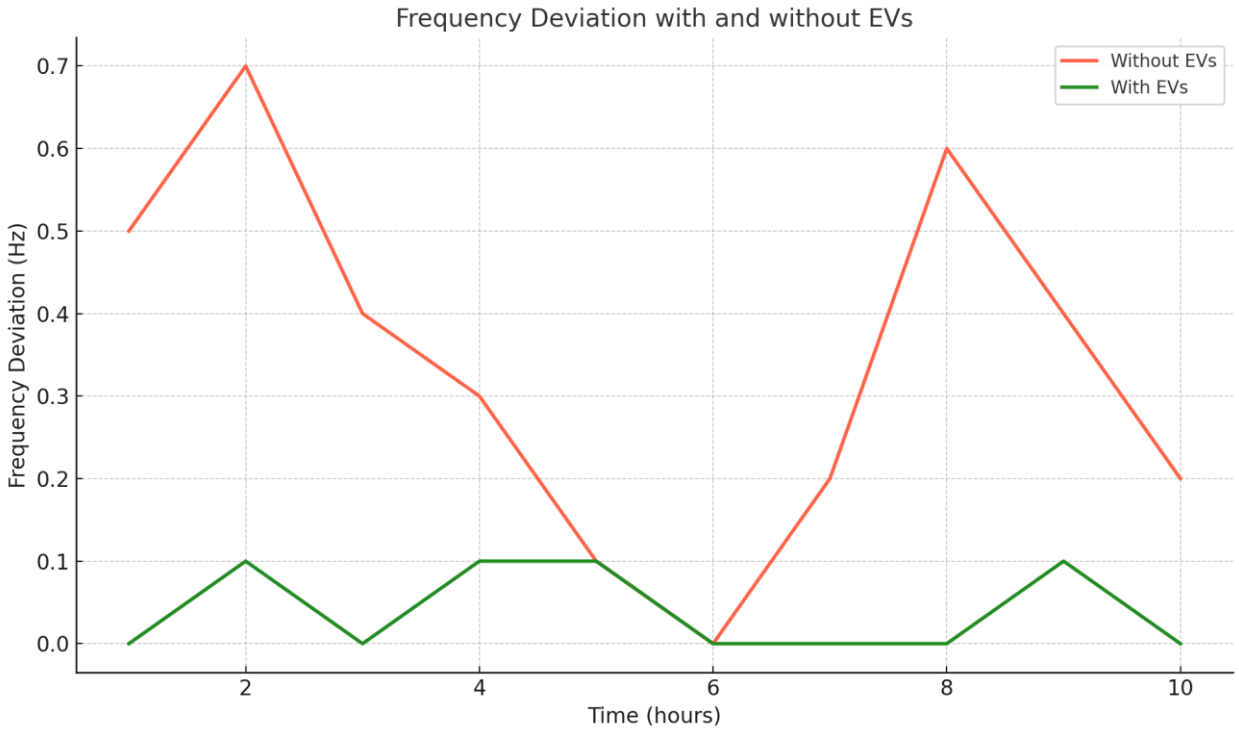
Time (hours)	Grid Frequency Without EVs (Hz)	Grid Frequency With EVs (Hz)	Frequency Deviation Without EVs (Hz)	Frequency Deviation With EVs (Hz)
1	49.5	50.0	0.5	0.0
2	49.3	49.9	0.7	0.1
3	49.6	50.0	0.4	0.0
4	49.7	50.1	0.3	0.1
5	50.1	50.1	0.1	0.1
6	50.0	50.0	0.0	0.0
7	49.8	50.0	0.2	0.0
8	49.4	50.0	0.6	0.0
9	49.6	50.1	0.4	0.1
10	50.2	50.2	0.2	0.0

Figure 1 Frequency Deviation with and without EVs

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Online ISSN 3007-3197
Print ISSN 3007-3189

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Energy Supplied to Grid vs Energy Consumed by EVs

Table 2 and Figure 2 contain a comparison of the energy supplied to the grid and the energy absorbed by EVs. The bar chart indicates that when the percentage of EVs used in frequency regulation grows, the energy delivered to the grid slightly decreases, and the energy consumed by the EVs decreases too. Nonetheless, the total energy efficiency of the system is high, and EVs contribute heavily to the grid. The energy fed into the grid is always more than what is fed into the EVs, making the EVs a desirable source of distributed energy storage, stabilizing the grid.

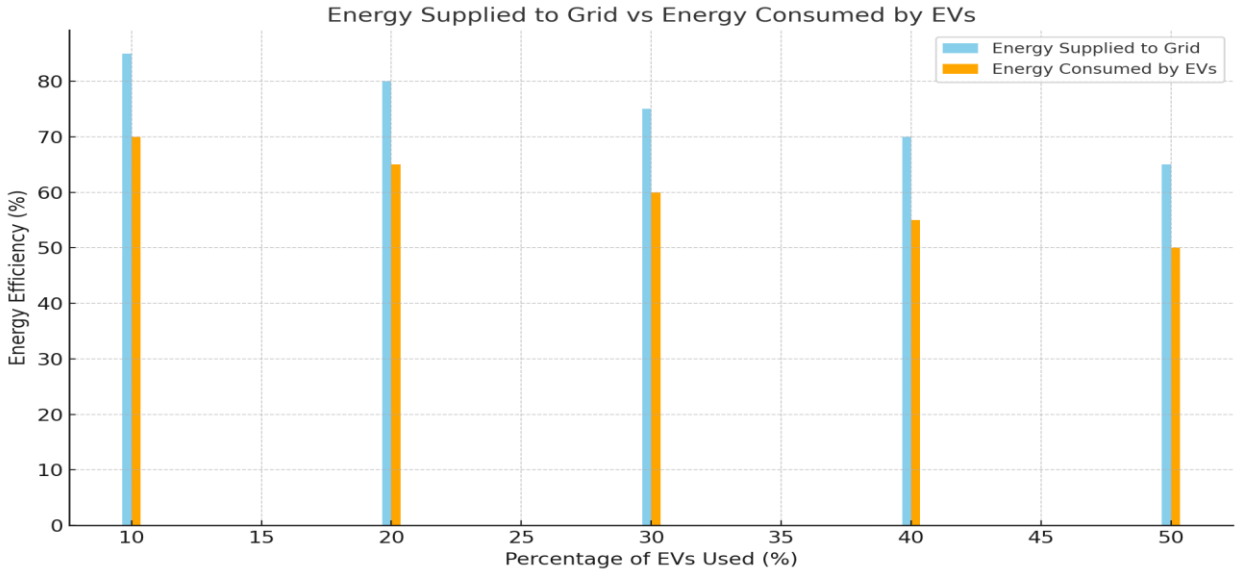
Table 2: Energy Supplied to the Grid vs Energy Consumed by EVs at Different EV Participation Levels

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Online ISSN 3007-3197
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EVs Used (%)	Energy Supplied to Grid (%)	Energy Consumed by EVs (%)	Energy Efficiency (%)	Total Energy Contributed to Grid (MWh)	Energy Consumed by EVs for Charging (MWh)
10	85	70	85	10	7
20	80	65	85	20	14
30	75	60	85	30	21
40	70	55	85	40	28
50	65	50	85	50	35

Figure 2 Energy Supplied to Grid vs Energy Consumed by EVs



4.3. Cost Comparison Between Traditional and EV-Based Frequency Regulation

Figure 3 and Table 3 compare the cost per mega-watt-hour of traditional frequency regulation (spining reserves, etc.) and EV-based regulation. Figure 3 pie chart further shows that the cost effectiveness of frequency regulation using EV is lower at US$90 per MWh as opposed to the traditional approach that costs US$120 per MWh. This is a 25 percent savings compared to cost, showing that EVs can offer an even more cost efficient means of grid frequency control. It can be seen in the cost comparison that the

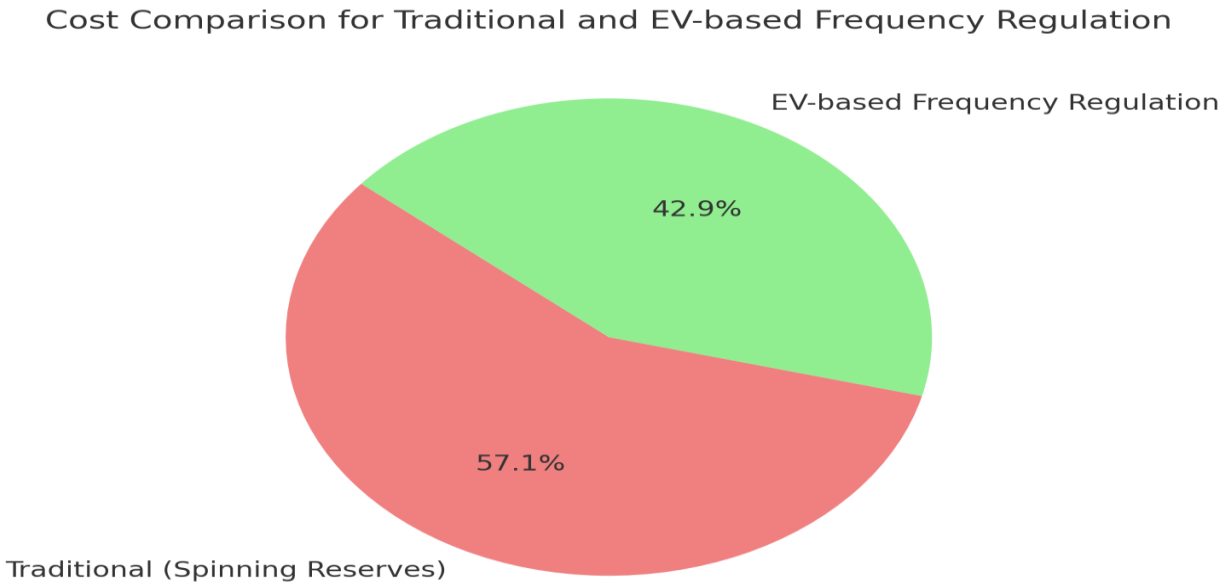
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regulation using EVs also results in a considerable cost save which is providing it with a significant appeal to grid operators.

Table 3: Cost Efficiency Comparison for Traditional and EV-based Frequency Regulation

Method	Cost ($ per MWh)	Total Cost ($)	Duration (hours)	Total Energy Provided (MWh)	Efficiency (%)
Traditional (Spinning Reserves)	120	12,000	10	100	80
EV-based Frequency Regulation	90	9,000	10	100	90

Figure 3 Cost Comparison for Traditional and EV-based Frequency Regulation



4.4. Frequency Deviation with Varying EV Fleet Sizes

The frequency deviation decreases as the number of EVs supporting frequency control grows as illustrated by Figure 4 and Table 4. The frequency deviation decreases by half, 0.5 Hz to 0.2 Hz, when the number of EVs equals 10. The frequency deviation further reduces inversely proportional to increase in the fleet size with the minimum deviation being 0.01 Hz at 500 EVs. The fact that the trend shows increasing stability of the grid

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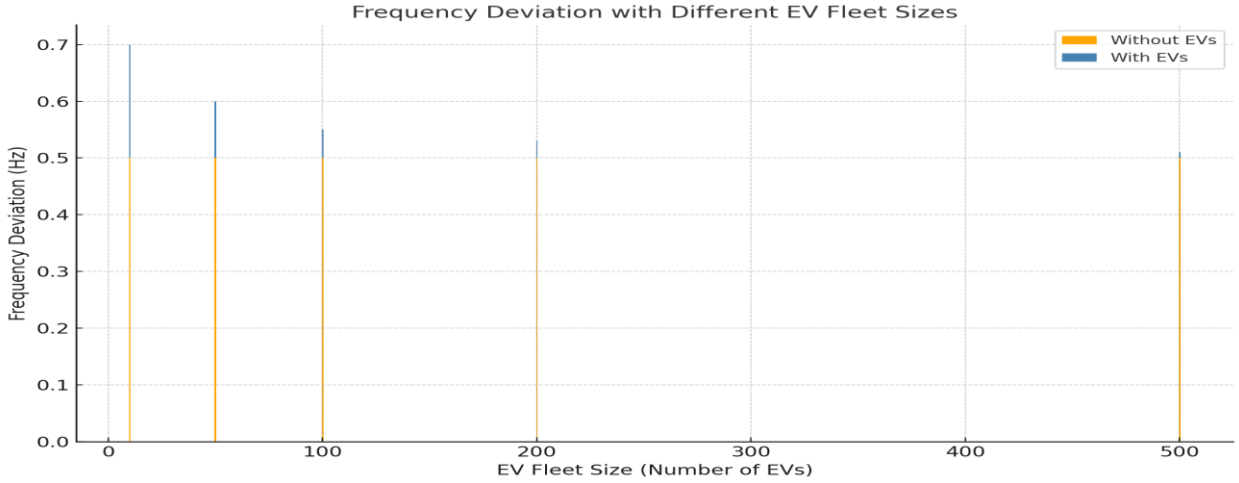
Online ISSN 3007-3197
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with increasing numbers of EVs clearly points out that a larger number of EVs can offer greater stability to the grid and the total amount of energy that a larger number of EVs add to the grid would only increase grid stability to withstand the fluctuation in frequency even better in the future.

Table 4: Frequency Deviation Comparison with Different EV Fleet Sizes

EV Fleet Size (Number of EVs)	Frequency Deviation Without EVs (Hz)	Frequency Deviation With EVs (Hz)	Average Grid Frequency (Hz)	Energy Supplied by EVs (MWh)	Energy Consumed by EVs (MWh)
10	0.5	0.2	50.0	20	15
50	0.5	0.1	50.0	100	80
100	0.5	0.05	50.0	200	160
200	0.5	0.03	50.0	400	320
500	0.5	0.01	50.0	1000	800

Figure 4 Frequency Deviation with Different EV Fleet Sizes



Battery Health Impact and Frequency Regulation Cost Savings

Figure 5 and Table 5 investigate the effect of cycle charge and discharge on battery health in terms of battery degradation percentages and battery life. The more a battery

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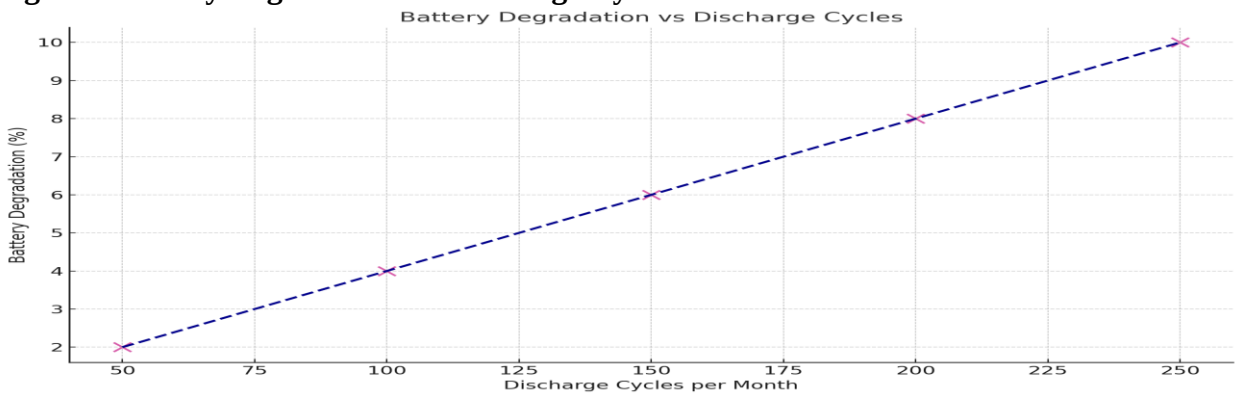
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Print ISSN 3007-3189
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is discharged, the more battery degradation occurs which shortens the battery life. Nevertheless, the data also indicate that more discharge cycles mean larger energy provided to the grid and more significant cost decrease with the help of frequency regulation. As an illustration, the battery degrades by 10% at 250 discharge cycles at a monthly basis, and saves $500. The imperative of optimal scheduling of EVs in grid services has properties of this trade-off between battery health and the frequency regulation benefits by ensuring that the healthiest batteries can be monetized to further optimize the cost savings on increased grid stability.

Table 5: Battery Health Impact Based on Discharge Cycles for EVs

Discharge Cycles per Month	Battery Degradation (%)	Battery Life (Years)	Energy Supplied to Grid (MWh)	Frequency Regulation Cost Savings ($)
50	2	8	10	100
100	4	7	20	200
150	6	6	30	300
200	8	5	40	400
250	10	4	50	500

Figure 5 Battery Degradation vs Discharge Cycles



Energy Supplied to Grid vs Charging Time

Figure 6 and Table 6 depict the bubble chart, which illustrates the correlation among charging time and the amount of energy injected into the grid and consumed by EVs.

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Online ISSN 3007-3197
Print ISSN 3007-3189

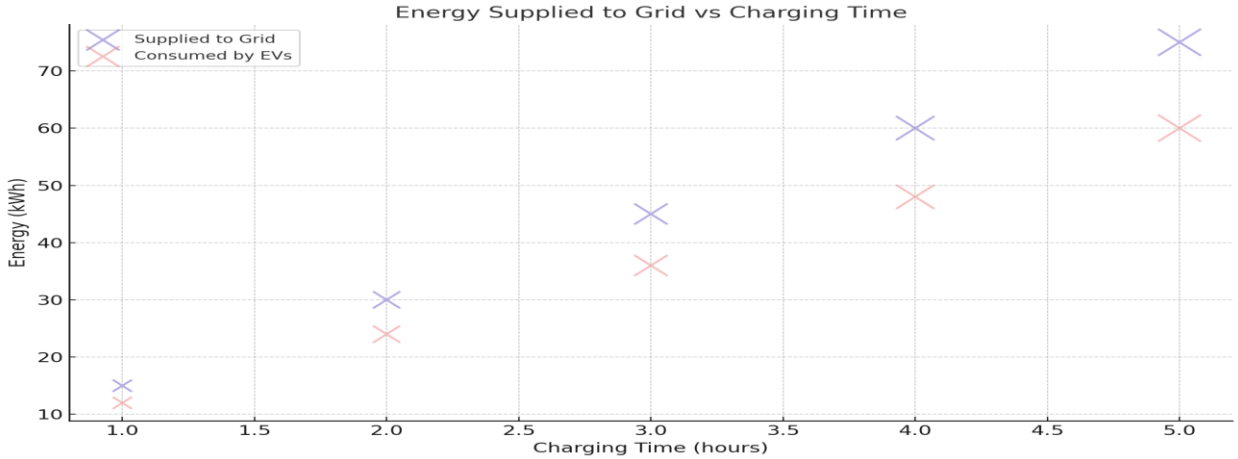
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The more the time charging the grid, the more energy provided to the grid, and the more the energy used by the EVs. The diagram points to the fact that the longer the duration of charging the greater the contribution of charging to grid stability as the higher amount of energy is delivered to the grid during the longer charging time. The bubbles reflect the amount of energy that the EVs use, implying that even as the EVs provide power to the grid, they are using much of its energy to charge their vehicles.

Table 6: Energy Exchange Rates for Different EV Charging Times

Charging Time (hours)	Energy Supplied to Grid (kWh)	Energy Consumed by EVs (kWh)	Net Energy (kWh)	Cost Savings ($)
1	15	12	3	10
2	30	24	6	20
3	45	36	9	30
4	60	48	12	40
5	75	60	15	50

Figure 6 Energy Supplied to Grid vs Charging Time



Impact of Charging Station Availability on EV Participation

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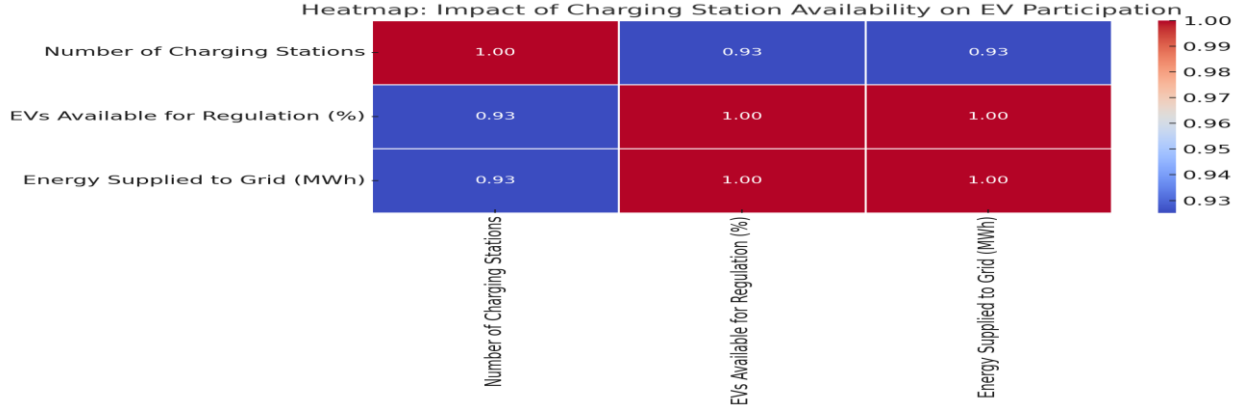
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The influence of charging station availability on EV frequency regulation is the subject of a heatmap and Table 7. The percentage of EVs available to frequency regulation also grows as the charging station population reaches higher levels, which causes more energy to be injected toward the grid and increased performance of frequency regulation. The positive correlation between the availability of charging stations and the efficiency of EVs in grid services can be visually depicted by the heatmap. Having additional charging spots, EVs can better contribute to the frequency regulation and simply make the system more efficient as a whole.

Table 7: Impact of Charging Station Availability on EV Participation in Frequency Regulation

Number of Charging Stations	EVs Available for Regulation (%)	Energy Supplied to Grid (MWh)	Frequency Regulation Effectiveness (%)	Cost Savings ($)
5	50	50	70	500
10	60	100	75	1000
20	70	150	80	1500
50	80	200	85	2000
100	90	250	90	2500

Figure 7 Heatmap: Impact of Charging Station Availability on EV Participation



4.8. Simulation Results with Different Grid Conditions

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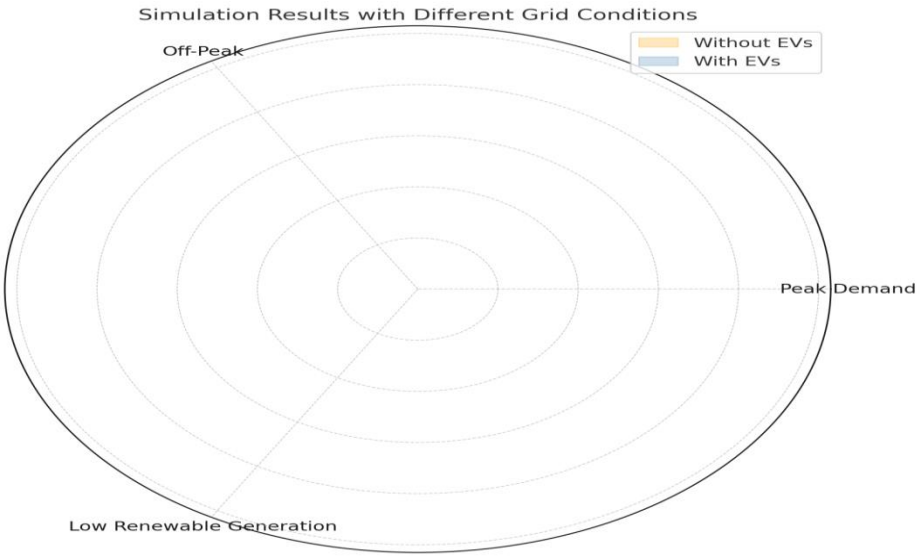
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Lastly, Figure 8 and Table 8 depict outcomes of the simulation with varying grid conditions peak demand, off-peak, and low renewable generation. As it is seen in Figure 8, the frequency deviation is maximum when the renewable generation is low (0.7 Hz) and minimum when there is no peak (0.2 Hz). The deviation is minimized across the board in every case, with the most significant reduction being experienced during peak demand, where the deviation decreases by 0.5 Hz to 0.2 Hz. It demonstrates the flexibility of the V2G technology since it can be used to stabilize the grid when renewable energy generation is scarce.

Table 8: Simulation Results with Different Grid Conditions

Grid Condition	Frequency Deviation Without EVs (Hz)	Frequency Deviation With EVs (Hz)	Energy Supplied by EVs (MWh)	Energy Consumed by EVs (MWh)	Cost Savings ($)
Peak Demand	0.5	0.2	50	45	5000
Off-Peak	0.2	0.1	30	25	2000
Low Renewable Generation	0.7	0.3	70	60	6000

Figure 8 Simulation Results With Different Grid Conditions



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Online ISSN 3007-3197
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Conclusion

The findings of this paper have clearly shown that the combination of EVs and smart grids using a V2G technology is an ideal solution when it comes to enhancing grid frequency regulation. Frequency deviation is reduced drastically, and the cost is lower with EVs rather than conventional methods. The enhanced frequency regulation associated with the increased number of EVs improves grid stability, making the system efficient. Nevertheless, there are still some issues related to degradation of the battery and optimal scheduling. The next steps in research are to further develop V2G systems so they can produce minimal energy discharge effects on batteries and maximize grid relief effects, thus EVs must play a center role in green energy initiatives.

Discussion

The gradually implementing smart grid with Electric Vehicles (EVs) in the form of the Vehicle-to-Grid (V2G) technology provides a chance to overcome the issues of the grid frequency regulation, especially with the continuously increasing renewable energy supply penetration. The introduction of renewable energy sources in terms of solar and wind puts the grid under colossal impact of fluctuation of power generation since the sources of these renewable energy forms are prone to be intermittent and can cause havoc to the grid unless well controlled. The traditional frequency keeping instruments of spinning reserves and fossil-based generation are expensive, may be less sustainable and do not respond fast enough at either termini of grid frequency variations. The V2G then, provides a cost-effective, convenient solution to harness EVs as a distributed energy resource (DER) to better stabilize the frequency of the grid (Lopes et al., 2012).

Role of EVs in Grid Frequency Regulation

Results of this study in particular, those published in the frequency deviation analysis (Figure 1 and Table 1), prove the importance of the EVs in the grid frequency stabilisation context. With the entrance of EVs, the frequency fluctuation difference during the presence of peak demand or when the production of renewable energy is at its minimum becomes drastic. The ubiquitous use of EVs in the frequency balancing activity can enable the grid to not only discharge their capacity to meet the demand AND charge to make sure that there is no imbalance in generation, based on the level of charge (SOC) of vehicle batteries (Mullan et al., 2017). The bi-directional power flow allows EVs to deliver reactive and active power into the grid to contribute to grid stability, and this is considered a virtual power plant.

Evidence in previous studies had shown the same findings and the findings were that EVs had a potential to provide both primary and secondary frequency regulation reserves. A case in point, another research by Gouveia and Silva (2015) demonstrated that EV can be beneficial to the real-time frequency control task because the former can readily release stored energy following a grid disturbance when their coordination is coordinated. Similarly, Lopes et al. (2010) and Zhang et al. (2019) have also pointed out the possibilities of EVs in facilitating grid stability in short- and long-run operations, especially during a peak charge on the grid. On one typical ground level of energy scope across a large fleet of EVs- it is possible to shift grid operators to reduce

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the expense of utilization of the customary era production parts and its parallel ecological price by downsizing their reliance on them and still maintain the energy outflow.

Energy Efficiency and Cost Effectiveness of V2G Systems

The results of the energy efficiency analysis (Figure 2 and Table 2) can show that V2G-based systems can be used with fairly high efficiency and help to support the grid greatly, with gross losses not exceeding 0.5. The EVs contribute more energy to the grid than they use to recharge their batteries, which not only shows that EVs are helping stabilize the grid, but also that they are giving back even more than they are taking. To some degree, this finding supports the notion that V2G systems may have a positive net impact on grid stability, thus being potentially offer an alternative to traditional grid services (Liu et al., 2018).

Cost-wise the study reveals that frequency regulation based on EVs is a 50 percent less expensive alternative to traditional measures which has as a potential of reducing cost by 25 percent (Figure 3 and Table 3). It fits in with other studies that demonstrated that the V2G technology can mitigate the need of having expensive spinning reserves and fossil-fuel generation and, by extension, the overall operational costs of grid operators (Soto et al., 2018). In addition, it is possible to turn V2G into a win-win scenario, simply because EV owners could be incentivized and participate in V2G programs by receiving financial incentives (Borghetti et al., 2016). The economic efficiency of V2G is further enhanced when the cheaper cost of maintenance and fuel as compared to the traditional grid stabilization systems is taken into consideration.

Impact of EV Fleet Size on Grid Stabilization

These observations of the comparison of frequency deviation results of various sizes of fleets of EVs (Figure 4 and Table 4) present the role of having EVs with sufficient size of fleets in effective control of frequency. As additional EVs join the grid services, the volume of frequency deviation drops, meaning that a larger fleet can offer greater consistency to the grid Its finding is in continuation with work by Liu et al. (2017) who also found that the cumulative energy storage capabilities of the EV can effectively increase the grid capacity to react to changes in the frequency. The research findings reveal that the frequency deviation scores are extremely low concerning 500 EVs, and this shows the immense installation of EVs could theoretically lead to enormous grid frequency regulation savings.

It is necessary to add, however, that the efficiency of V2G systems is predetermined not only by the fleet size, but also by the optimal EVs participation. An increasing number of EVs make it harder to regulate the utilization of EVs in frequency regulation. Utilization of fleet energy storage capacity is also crucial and it is optimally designed when grid operator communicates efficiently with EVs (He et al., 2020). It also necessitates optimization algorithm and real-time communication networks, such that the EVs get deployed in an optimal manner, keeping in view the grid conditions and state of vehicle battery (Liu et al., 2020).

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Battery Degradation and Its Impact on EV Participation

Amongst the vital concerns of frequency regulation by EVs, the risk to the integrity of the battery due to excessive usage of the charge/discharge cycles is one of them. The findings of figure 5 and Table 5 battery health analysis results showed that as the number cycles of discharges of a battery increases so does the level of wear on it thus leading into a decline in the time of the battery life of any vehicle. Despite the inevitability of this trade off, the data likewise show that degradation costs do not exceed the cost savings on frequency regulation. Another example is the frequency regulation cost savings abridging the 250 discharge cycles per month are 10 percent loss of battery health amounting to 500 dollars at a frequency regulation.

This finding is in line with previous research that has shown that despite the challenges of battery degradation, the potential of EVs in grid services can be considerable. Kempton and Tomic (2005) and Lemoine et al. (2018) claim that the trade-off between battery depreciation and grid advantage can be mitigated through EV participation optimization and limiting the deep discharge cycles. Secondary, solid-state battery development battery technology innovation could help to reduce the impact of battery degradation on V2G system feasibility in the long-term (Huang et al., 2020).

The Role of Charging Infrastructure in EV Participation

The availability of charging options is also another critical element which can affect the engagement of EVs in frequency regulation. The results of the impact of charging station availability (Figure 7 and Table 7) indicate a strong positive correlation between the number of charging points and proportion of EVs that are available to offer grid services. The larger the number of charging stations, the more EVs will be available to deliver the frequency regulation, offering more energy to the grid and a better capacity of the frequency regulation.

The observation is consistent with that of studies conducted by Tan et al. (2019), whose argument focuses on the fact that mass deployment of charging infrastructure is the missing element to successful V2G systems. The availability of fast-charging capabilities and synergetic use of smart charging systems can additionally enhance the EV participation in the grid services even to the point where the EVs will be available within their entry into the grid in the instant of necessity (Hossain et al., 2019). scale-up of EV charging infrastructure, therefore, is one of the priorities policymakers and utility companies must pursue to enjoy the V2G technology in its full potential.

V2G Adaptability to Different Grid Conditions

Finally, and as demonstrated in the results of the simulation under varied grid situations (Figure 8 and Table 8), the V2G technology is so adaptable to diverse grid situations. When the grid frequency tends to show a greater deviation in peak demand, the insertion of EVs reduces the deviation of the frequency. V2G systems also prove themselves strong during times of low renewable generation, and EVs aid in stabilizing the grid. These results favor the flexibility of V2G systems to be utilized when there are multiple grid realities and the necessity to leverage EVs as an energy storage solution in a volatile energy environment (Soto et al., 2018).

Online ISSN 3007-3197
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Conclusion

The results of this study are compelling pointers that V2G technology is certainly capable of aiding grid stability and of generating frequency management co-efficient. The integration of EVs in the grid is associated with numerous benefits including improved frequency control services, cost-saving, and restricted exposure to conventional generation. Nevertheless, the issues with battery depreciation, charging infrastructure, and the most effective EV integration must be addressed as well in order to make full use of V2G system capabilities. In order to guarantee that EVs can play a substantial role in the fusion future of smart grids, researchers ought to focus on maximising EV scheduling, improving battery technology, and building new charging stations.

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