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A Comprehensive Review of Vehicle-to-Grid Technology Effect on Frequency Stability in Electric Power Systems

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Abstract— Vehicle-to-Grid (V2G) technology is an innovative concept designed to support frequency stability by enabling two-way energy exchange between electric vehicles (EVs) and the power grid, especially in systems with high penetration of renewable energy resources. This paper examines the battery electric vehicles' demand nature also as an ancillary support resource to address intermittency of renewable energy sources and grid frequency support through V2G technology. The study highlights technological issues such as degradation rates of batteries, communication difficulties, and scaling problems alongside issues of regulation and market that encompass large-scale implementation of V2G. Tackling the effectiveness of V2G systems in frequency regulation The effectiveness of approaches like virtual inertia emulation, enhanced control algorithms, and decentralized frameworks are discussed as ways of enhancing V2G systems. These findings reaffirm that V2G has tremendous potential in the electric grid yet, it must be noted that solving these issues remains critical through transformational research and policy strategy. The conclusions help to better understand the prospects for improving V2G towards more accurate support for frequency stability in transition to sustainable energy systems.

Keywords: V2G, Frequency Stability, Intermittency, and Renewable Energy Integration.

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1. Introduction

The global energy system has undergone profound changes resulting from the increasing use of renewable energy and the electrification of transportation facility. As the world shifts toward a low-carbon paradigm, electric vehicles (EVs) batteries have become a critical aspect of green transportation and a flexible supply chain for managing the energy grid[1]. The addition of variable renewable energy sources, such as wind and solar, lead to challenge in maintaining the power system frequency, which must be addressed. Vehicle-to-Grid (V2G) technology is one of the promising ways to enhance the robustness of electric networks [2], [3], [4]. The V2G technology enables electric vehicles to both consume energy from the grid and provide the energy back to the grid when it is needed. This feature has a potential for improving load level, peak power management, and frequency regulation, therefore, the role of V2G will be a crucial element of today's power systems [5], [6], [7]. Building on the storage capabilities of electric vehicles battery and the future opportunities for using electric vehicles battery as energy storage to support the grid, vehicle-to-grid (V2G) provides a new approach for the integration of renewable energy resources [8]. The frequency stability in power grids is the precise balance of demand and supply in real-time. If the supplied energy is more than the consumed energy or vice versa, the grid frequency deviates from its nominal value of 50 or 60 Hz, depending on the country. If not controlled, such deviations can cause power system instability and in extreme cases, blackouts [9] - [13]. Thus, frequency stability assurance is one of the critical objectives for the power grid system.

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However, the higher usage ratio of renewable energy sources like wind and solar energy increases the challenge of maintaining frequency stability [14], [15]. These energy sources are often unpredictable and incongruous, which puts a strain on energy supply. In such instances, the V2G is a fast active balancing instrument because electric vehicle batteries can quickly be discharged and charged [16], [17]. To maximizing this functionality requires coordination of grid operators and such linked V2G units, supported by elaborate systems for control that would facilitate real-time grid control [18] - [21]. There are a lot of technical and operational challenges facing the implementation of V2G in improving frequency stability. One is managing hundreds, if not millions, of electric vehicles connected as distributed generation resources. The level of battery charge, battery capacity, and usage rates differ from car to car thus making coordination of their contribution toward frequency control challenging. Sophisticated control mechanisms are required for quick and synchronized responses of electric vehicles to the imperative signals of grid frequency. The key to solving this problem therefore lies in the development of efficient algorithms that control charging and discharging cycles [22] - [28].

On the other hand, legal and market barriers are a big challenge in the deployment of V2G technology. The basic service requirements for the compatibility across electric car makers and charging solutions as well as grid operators are still unclear, and this is holding back the field [5], [29], [30]. Finally, there are still limitations in terms of gains that owners of electric vehicles could make in order to participate in vehicle-to-grid. Without such engaging and sustainable economic models within the user community, the desired engagement may not gain the necessary magnanimity to impact or stabilize grid frequency [31], [32], [33]. Thus, in the case of this technology, proactive regulatory support and the creation of incentive structures are key to the widespread implementation of the technology [34].

V2G technology has been a subject of research interest in many previous papers pertinent to some fundamental issues in today's power systems. Based on this literature, some of the areas of interest in these investigations, which mainly investigate the role of V2G, pertain to frequency control, load shifting, and handling of renewable energy [35], [36], [37], [38], [39], [40]. From the previous literature, V2G is able to function as a variable and dispersed energy resource that is capable of adapting to the grid needs. Nevertheless, its practical regulation and improvement towards frequency stability is an area of current research. V2G has the ability to control frequency fluctuations through the use of quick response method. Aggregated electric vehicles are capable of operating like the traditional frequency control reserves. These services are the primary frequency response which describes a quick and automatic reaction within seconds and the secondary frequency response, which is a restoration of balance within minutes. However, their simulations highlight the importance of better control algorithms to enable a reliable integration of curtailment signals by V2G units with the grid [41], [42], [43], [44]. The implementation of advanced V2G control strategies necessitates the integration of artificial intelligence and machine learning technologies. This integration facilitates the management of bidirectional energy processes for electric vehicle batteries. Intelligent control systems can improve V2G operations by at least 15 percent, but recommend that such systems should be well supported by communication networks and databases [16], [45] - [48]. In addition, the challenge of scalability still persists because the current models do not consider large-scale implementation of the electric vehicles [49] - [51].

The prior literature has explored the positive impacts of integrating V2G, including cuts in carbon emissions, enhanced energy usage, and storage. However, there is limited research focusing on the V2G impact on the stability of the frequency. In providing these issues and analyzing potential problems, this paper also focuses on improvements in grid dependability with an emphasis on frequency stability in relation to V2G implementation. This study is especially valuable for encouraging EV adoption in developing countries such as Indonesia, where this technological change is just beginning. The primary objective of this work is to provide a comprehensive evaluation of the same condition, considering the stability of V2G technology. It identifies major technical challenges, evaluates possible remedies as discussed in the literatures, and outlines tactical directions for further technology development. It hopes that this research will contribute to the academic community and

practitioners in renewable energy implementation and electric vehicle technology.

2. Method

To conduct this study, we searched for relevant literature on the topic of power system stability, frequency stability in EVs, and vehicle-to-grid (V2G) technology through the databases of Google Scholar, ScienceDirect, IEEE, and Scopus. The sources were selected based on the research questions: (a) What is the effects of EVs on power system distribution? (b) What is the effects of V2G on power system distribution? (c) What is the effects of V2G on frequency stability? (d) What are the challenges of V2G technology? (e) What methods are used in V2G technology for frequency stability? (f) What are the future research directions for V2G technology?

3. Result and Discussion

Power system distribution integration with electric vehicles and vehicle-to-grid (V2G) technology is a new and emerging field of study. Several studies have shown that the integration of EVs and V2G can provide significant benefits to power system frequency stability [2], [4], [38], [52]. Electric vehicles can act as distributed energy storage and provide load balancing to the grid, which can help mitigate the intermittency of renewable energy sources and support frequency regulation. V2G technology allows EVs to discharge energy back to the grid when needed, which can improve the performance and efficiency of power grid operation [53].

3.1 The effects of EVs and V2G on power system distribution

As the use of electric vehicles (EVs) increases, the distribution of power systems increases as well, with frequency stability as a major concern. EVs add an active load that is large, varying, and uncontrolled. Large changes in power demand will cause frequency differences. This load imbalance occurs because a large number of EVs charge during peak hours and may cause a deviation in system frequency, which presents a risk to the stability and reliability of power grids. This problem further intensifies in systems that contain high levels of renewable energy because the level of power generation is periodic and less predictable [14], [44], [54] - [58].

Furthermore, the charging behavior of EV users is directly affecting frequency stability. Arbitrarily charging result in fluctuations in the load and force system operators to mobilize more reserve margins or have generation units ready to ramp up or down in order to maintain the frequency [44], [59], [60]. On the other hand, this has the effect of increasing operational costs and at the same time predisposes the grid to instability, especially during sudden load spikes [61] - [63]. Besides that, managed charging strategies like time-of-use tariffs or charging systems, which include the smart charging system, are likely to reduce these risks by enabling the charging of EVs at times during which demand is low or during periods of high renewable generation. As a result of this, the use of charging loads decreases the need for extra interventions in order to maintain the grid's frequency [28], [64] - [69].

Apart from the obstacles discussed above, the use of EVs offers potential for improving frequency stability, especially when interfaced with other technology such as V2G. V2G provides a means through which reverse power flow is possible such that the electric vehicle becomes a distributed storage power supply. The good thing is that during periods of frequency deviation, EVs can actually discharge power back into the grid as well. It does not only reduce the destabilising effect caused by large penetrations of EVs on the frequency but also turn them into supportive tools for the grid. However, in order to realize these benefits, there are big challenges in the control algorithms, communication systems, rules and governance between the EV users and the grid operators [2], [4], [70] - [73]. Figure 1 depicts the V2G framework, which includes parking lots, V2H systems, intelligent buildings, energy loads, renewable energy sources, general grid components, and an aggregator.

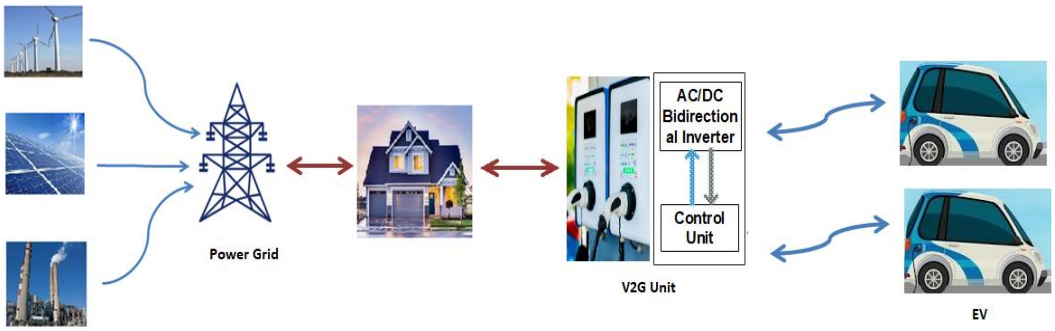


Figure 1. Vehicle-to-grid (V2G) Technology

While the integration of EVs and their charging behaviours have a direct impact on power system distribution, vehicle-to-grid (V2G) technology can provide a solution to mitigate the frequency stability issues. In essence, the design of V2G incorporates the flexibility of reverse flow, allowing EVs to not only fully draw electricity from the grid but also contribute electricity back to it [23]. This capability system transforms electric vehicles into active producers and consumers of electricity capable of responding to grid needs in real time. During periods of frequency deviation, electric vehicles that have been charged with V2G technology can also participate in ancillary services where supply is balanced in a short time. During peak load hours V2G systems dispense electricity into the grid and in off-peak hours, they draw electricity from the grid, and store [3], [19], [46], [75], [76].

However, integrating V2G into the power system distribution presents certain technical and operational challenges, which will be discussed in the following section. The charging and discharging cycler characteristic of EV batteries necessitates the development of enhanced control methodologies and communication schemes to ensure a standard response to frequency swings [28], [67], [42]. [26]. But if the bidirectional energy flow is not regulated, the structures of the distribution system can be overburdened, and voltage instability may appear and strain the network components [77]. But the degree of which V2G provides information related to the stability of the frequency depends on the level of integration of the users and rules which encourage the owners to contribute to the grid services [16], [78]. More than anything else, enough system integration of EVs and grid operators as well as the market must be set because only then will V2G demonstrate the full potential of the same for the regulation of frequency without disrupting the power supply systems [30], [43], [58], [79] - [80].

3.2 The effects of V2G on frequency stability

V2G technology is disrupting the frequency stability due its ability to allow EVs to act as adaptive resources within the grid of supply and demand. The bidirectional energy flow allows V2G equipped electric vehicles to sell stored power back into the grid when it experiences abnormalities such as frequency fluctuations at a very short time [75], [80] - [83]. This capability is most important in power systems that have high levels of installed renewable power generation from sources like wind and solar which are accumulating intermittency problems affecting frequency regulation. Battery V2G systems consuming and adding power to the grid ensures the equilibrium in real time and reduces the utilization of conventional techniques as spinning reserves that are sluggish and less efficient [83].

In addition, V2G technology based on virtual inertia control has the capability to provide the rotational inertia like that has been furnished by conventional synchronous generators. Inertia has declined as renewable plants replace those based on fossil fuels.This concept is called virtual inertia, implies the cooperation of V2G systems to mimic the stabilizing characteristics of physical inertia [85], [86] - [87]. During rapid changes in frequency, V2G systems can also discharge power immediately during oscillations in the frequency of the system a characteristic that essentially makes the system act like a virtual flywheel. This capacity is needed for operating in the new power systems

where mechanical inertia is necessarily lower and provides frequency stability after contingencies, including loads or renewable power plants failures [88] - [89].

3.3 The challenges of V2G technology

The implementation of V2G with virtual inertia source is by nature technically and operationally complex. The charging and discharging cycles that are necessary for fluctuation correction and other tasks introduce concerns for battery preservation as well as optimal control of thousands of EVs. Sophisticated communication systems and relevant policies and measures are also required in order to successfully synchronize V2G systems, grid operators and electricity markets [52] [90] - [91]. Moreover, the effectiveness of V2G in frequency stability is premised on the responses received by the consumers together with incentives to EV owners on the provision of the grid services. Nevertheless, the introduction of V2G technology along with the use of virtual inertia provides the prospect of improving the stability of the frequency and improve the factor of integration of the supply, use of power system resources with the growing intensity of using renewable sources of energy [92]. Summary of the challenges of V2G is shown in Table 1.

Table 1. Summary of the challenges of V2G

Type	**Challenges**
Technical	Grid stress [93] Infrastructure limitations Battery degradation [94]
Economic	Cost of implementation Tariff structures[95]
User Engagement	Willingness to participate Privacy and security[95]

3.4 Methods in V2G technology

The optimization of vehicle-to-grid technology for the purpose of improving the stability of the frequency in today's power systems has been considered and analyzed through many methods. One of such strategies includes the bi-directional power flow management, in which V2G systems adapt the charging and discharging rates of the EV batteries to variations in the frequency [96][97]. This technique requires high levels of algorithms such as model predictive control (MPC) and adaptive control strategies to ensure the right coordination between the V2G units and the grid [98][99]. These methods enable V2G integrated EVs to demand and offer ancillary services such as frequency containment and the fast frequency respond (FFR) where the EVs provide energy to counteract a real time imbalance [100][101]. This is also supported by research which implements decentralized control frameworks where the computational process is partitioned among several EVs ultimately to optimize scalability [102] [103].

Another important method is based on the notion of virtual inertia by which V2G systems mimic the inertial response previously supplied by synchronous generators. Using V2G systems, power is released quickly during frequency fluctuations making batteries in V2G equipped EVs function as frequency stabilising flywheels. Recent researches have examined some approaches involving droop control as well as inertia emulation methods to achieve the application of virtual inertia via V2G systems. Also, time-of-use (TOU) and other demand-side management (DSM) measures have been combined with V2G to coordinate charging times in a manner that maximize the contribution of EVs to system balancing without straining the already congested peak load periods [104][105][106]. The applicability and reliability of these methods totally rely on proper communication standardization like vehicle to everything (V2X) and a clear structure to balance the

requirements of grid operators, user engagement and fair economic signal[107][108]. Such achievements show the work capabilities of V2G technology as an innovative solution for working with the range of frequency that should be established in connection with the transition to renewable energy-driven power systems.

Table 2. Methods in EV and V2G technology

Reference	Methods used	Result
[109]	a. Model-free Actor–Critic policy optimization technique b. Three Reinforcement Learning (RL) algorithms: DDPG, SAC, TD3	a. Improved frequency stabilization with adaptive VSG control technique b. TD3 outperforms non-adaptive VSG in efficiency
[96]	Model of bidirectional onboard charger with implementation of current summation method (CSM)-derived power flow analysis for IEEE 33-Bus radial distribution system	Bidirectional EVs can improve voltage profile and frequency stability of the grid
[110]	a. Fuzzy logic controller (FLC)for adaptive coefficient adjustment b. Differential evolution algorithm for optimizing FLC gains	a. Adaptive VSG coefficients improve frequency stabilization significantly b. 7.3% less frequency deviation and 46% less frequency change rate
[111]	a. Centralized optimization using linear programming with slack variables b. Distributed optimization using augmented Lagrangian relaxation and ADMM	Centralized and distributed V2G models improve frequency regulation accuracy
[112]	a. Learning-based model predictive control (MPC) algorithm b. Deep deterministic policy gradient (DDPG)-MPC double-layer controller	a. LFC strategy improves multimicrogrid reliability and stability b. Learning-based MPC enhances frequency control and robustness

3.5 Future research directions for V2G technology

Future research focusing on V2G technology ought to consider incorporating approaches in solving its technological and operational challenges to increase the achievement of its advantages. Therefore, control algorithms that can effectively balance the bidirectional energy flows of millions of EVs with minimal impact to battery degradation . Further work should be directed towards the introduction of machine learning and artificial intelligence which can help to improve the real time decision making, for V2G systems to adjust to deviation in frequency as well as the demands of the grid. Further, the decentralized control mechanism and block chain technique can be investigated to

improve the data protection and the manageability and to create a perfect coordination between EVs, grid executives, and market stakeholders. Other battery types, which may include solid state batteries could also be explored to enhance the energy density as well as longevity which enhances the use of V2G in maintaining long-term frequency balance.

One of the other research opportunities is to advance research on the interface between V2G systems and renewable energy resources. Research must explore the design of V2G microgrids and if they are capable of functioning as virtual power plants (VPPs) to manage excess renewable generation and provide frequency response capability. This induced virtual inertia and its management through V2G systems are discussed here to provide insights into improving the grid stability in low-inertia power systems. However, researchers can concentrate on the social impact of V2G deployment, for instance, financial motivators for EV users and suitable policies that would ensure more people engage in grid services.

4. Conclusion

The comprehensive review of V2G technology emphasizes that using advanced control could significantly improve the appropriate frequency stability. The integration of renewable energy sources into the existing infrastructure, along with the electrification of transportation processes, is a topic of significant discussion in today's modern power system. By bidirectional energy flow, V2G allows electric vehicles (EVs) to act as dynamic grid resources, addressing challenges of intermittency in renewable energy and demand fluctuations. However, V2G has technical, operational, and regulatory challenges that still need innovative control algorithms, reliable means of communication, and policy incentives to mobilize EV users. Techniques like virtual inertia emulation, better control techniques and optimization using artificial intelligence have been implemented to overcome such problems. This paper points out that more research is needed to understand how V2G can be made maximally effective, safe, and cost-efficient on the scale of societies or nations through optimal use of batteries and suitable incentives. These are important developments to support a stable and low carbon emitting energy network to sustain frequency balance in the contemporary high variability power environment.

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