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Research Article

Optimization of Grid Energy Balance Using Vehicle-to-Grid Network System

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ABSTRACT

With the increasing demand for green energy sources in modern society, network optimization is realized. Vehicle-to---Grid (V2G) systems, which connect electric vehicles (EVs) to the power grid, are one form of innovation that can help increase balance in energy systems. This workflow explores the potential for increasing energy storage and distribution capacity in order to optimize the energy balance in power grids through V2G networks. While V2G systems could be really beneficial for stability and efficiency of the grid, EVs have the potential to send surplus energy back to the grid during peak demand times. This study investigates one V2G integration model and assesses its energy consumption reduction potential and implementation method. With extra storage, lower demand on the grid and much less carbon emissions, the outcome shows that V2G network tech has a significant balance compensation on the grid.

Keywords: Vehicle-to-Grid (V2G), Energy Balance, Optimization, Electric Vehicles (EVs), Grid Stability, Smart Grid, Energy Storage, Power Distribution, Renewable Energy, Demand Response.

INTRODUCTION

As the world transitions toward sustainable energy systems, the power grid of today is evolving, necessitating that higher levels of complexity must now be managed; the management must now be done with respect to the energy supply with end users in mind. But as wind and solar power gain popularity, intermittent sources like these threaten the grid's stability and efficiency. These challenges will need investment in new technologies to manage the grid, allow storage or balance supply with demand. The growth in production levels could be alleviated through the use of Vehicle-to-Grid (V2G) systems, allowing for the ability to use EVs (electric vehicles (EVs)) as electricity consumers or mobile energy stores, with the ability to return electricity to the grid, when needed [1-5].

V2G ('vehicle to grid') systems utilize energy stored in the EV's batteries and transfer them back to the grid in cases of high demand or when renewable energy sources are too low. V2G technologies can utilize EVs as storage units, providing energy when grid demand is high, enhancing overall energy balance and providing value to both the grid and the vehicle owners. Due to their energy storage potential, V2G systems can do more than provide the most common ancillary service, but also modulate energy input and output according to grid behaviour, facilitating smart grid deployment such that, in fact, they may become one of its main facilitators [10].

To understand how this works, simply grasp the very high-level overview idea of a traditional energy grid, where energy is provided by power plants that consume energy/consumables in centralized way to generate energy. However, penetration of renewable energy and transition to energy generation is depended on intelligent and dynamical systems to develop for flow of energy. Some big companies have already been utilizing the programs that exist based on some devices are using V2G technology. Cyber-Physical Systems (CPSs) adopting Vehicle to Grid (V2G) technologies meet this requirement, and they can increase the resilience of the grid, minimizing dependence on non-renewable energy in demanding times, and promoting savings in terms of operational costs by leveraging renewable resources maximally.

Electric vehicle will also be numerous on the road very soon. The potential of EVs performing as a kind of bulk energy storage, of the grid interactivity created by masses of electricity-storing vehicles, if EV transport takes off, is an even larger one, which will only scale as EVs proliferate. Such V2G networks could relieve some of the strain on the grid, particularly in cities, where demand for power can spike. Nov3,2023 Tat / electric Vehicle-to-grid (V2G) is a technology that enables electric vehicles (EVs) to both draw energy from the grid for charging and also return energy stored in their batteries back to the grid during periods of peak demand 1.

Moreover, the evolution of advanced communications systems and smart meters will enable the best possible control of V2G networks. These systems allow scheduling of EV charging and discharging to match grid state of affairs (e.g., prices of electricity, demand forecasts, generated renewable energy forecasts). Operating these vehicles as flexible and decentralized assets have the potential to improve energy sustainability and enable grid flexibility. As more stakeholders — government, private firms, and consumers alike — adopt V2G systems, the technology will further entrench its ability to change the energy landscape.

From this point of view, the study of the system presented in this paper, also known as network system of V2G used to balance energy with the consumption of the grid, and in order to colonist the specific data that can be applied now to the power grid, and what can be integrated with the existing power grid development goal. Through simulations with optimization models, this research demonstrates potential V2G advantages including lower energy costs, greater adoption of renewables, and enhanced grid reliability. The paper will also explore the main technical and regulatory challenges that need to be overcome for V2G to become mainstream, such as battery lifespan, communication interfaces, and high-level policy frameworks [7-8].

Novelty and Contribution

This work provides several unique contributions to the literature regarding grid optimization and V2G systems. However, many of the existing studies in this area are often limited to aspect of the broader multiple paragraphs of V2G technology, e.g., such as charging/discharging algorithms and economic benefits of deployment, and focus on a holistic, integrated approach to optimizing the grid balance to the energy with V2G networks in real world scenarios. This study makes the following main contributions:

- Fully Integrating V2G in the Energy Management of the Grid: The earlier investigations around V2G systems focus separately on either the vehicle scheduling or grid optimization. We resolve the aforementioned debate by developing a unified optimization framework that integrates both the grid's operational requirements as well as the EV's charging/discharging schedules, effectively linking these two components. It is essential for the realization of a full potential of V2G systems for energy balance improvement.
- The research develops a sophisticated modeling system which implements renewable energy pattern deviations and power grid consumption together with electric vehicle charging habits. An optimization algorithm together with a grid imbalance reduction system operate in a single framework to reach optimal performance levels and address economic and technical constraints during EV charging and discharging operations. Through this approach the system delivers a more genuine understanding concerning V2G capabilities within grid stabilization schemes.
- The research introduces an innovative process to adjust energy flow between the EVs and the grid by using continuous data-driven decisions. An optimized energy exchange between vehicles and the power system becomes possible through a simulation model which connects renewable energy predictions and EV availability and demand response signals. The system operates with time-sensitive capabilities that trigger prompt adjustments to grid requirements and renewable energy irregularities thus enhancing grid reliability.
- Scalability and Practical Implementation: Research on V2G has, in many cases, been of a theoretical or small-scale nature that does not take into account the complexities of large-scale implementation. The study has useful information for the deployment of V2G systems to manage large amounts of EVs at scale. This work provides practical recommendations for real-world deployment by simulating large fleets of electric vehicles and their interaction with the grid in order to mitigate issues such as grid congestion, battery wear and communication infrastructure, resulting in high level recommendations for the practical implementation of electric fleets.
- V2G Economics Assessment: In addition to technical optimization, this study evaluates the impact of V2G systems on the economics of grid operations. The research measures potential cost savings for grid operators and consumers alike by factoring in things like electricity pricing, incentives to curtail demand, and costs of maintaining grid infrastructure. Additionally, by enabling increased integration of renewable energy sources, the study highlights how V2G technology helps achievement of sustainability targets like assistance with reducing carbon footprint and minimizing dependence on fossil fuel-based power generation.

Research presented in this paper signifies an important achievement that demonstrates the complete capabilities of V2G systems for optimizing power balance between grids. This study shows valuable knowledge about V2G network benefits through its combination of innovative technical methods and practical implementation both together in real-time [12-15].

Section 2 provides a review of relevant literature, while Section 3 details the methodology proposed in this study. Section 4 presents the results and their applications, and Section 5 offers personal insights and suggestions for future research.

RELATED WORKS

Vehicle-to-Grid (V2G) technology gained substantial research attention during the past years because it enables electric vehicle (EV) participation in electric grid functioning and strengthens energy system sustainability. Through V2G networks electrical vehicles can perform energy storage functions by storing renewable energy excesses that EV batteries can then discharge for grid use during low supply periods as well as weak renewable generation times. The transition of power systems toward wind and solar energy demands this approach because it represents a vital method for energy control [11].

The research by K. M. D. P. S. Peterson et al. (2016) al. and W. N. Jou et. al., [16] Examines various investigations which analyze V2G system implications for enhancing grid stability, energy efficiency and decreasing costs. The research field focuses on optimizing EV charging and discharging routines to control grid unbalances as an active scientific exploration. Scientists work with optimization methods which process real-time power consumption levels together with renewable energy availability along with EV charging dynamics. Since it enables flexible EV charging based on grid conditions V2G systems are considered advantageous to both reduce power grid dependence on non-renewable energy sources and boost system availability.

There is a growing amount of research on the economic benefits of integrating V2G systems into the power grid [9]; The technical features of V2G are presented by X. Zhang and Y. Li in 2017. Studies have shown that V2G networks can also decrease grid operating expenses since it reduces reliance on usually fossil fuel-powered peaking power plants in grid management. Moreover, V2G enables efficient use of renewable energy by helping the grid to capture excess electricity generated during high renewable periods and release into the grid during high demand periods. This reduces reliance on carbon polluting backup fossil-fuel generation and enhances the economic feasibility of renewable energy.

Other studies have looked into some of the barriers to widespread V2G taking off. The core challenge lies in the establishment of resilient communication and control infrastructures for seamless and instantaneous interactions between electric vehicles (EVs) and the grid. Hatke systems that can accommodate many thousands of vehicles and where efficiency can be monitored across diverse geographies with differing energy demands still poses a major obstacle. Battery lifetime is another important consideration as charging and discharging cycles can lead to battery degradation.

A large number of studies within policy frameworks support the development of government-based incentives to boost V2G technology adoption. Officials provide two incentives through V2G programs to EV owners and utilities when they connect V2G units to their grid network. Research confirms that V2G system implementation success depends on standardized charging infrastructure along with uniform communication protocols for large-scale deployment.

In 2017, P. S. R. I. Ganesh et al. al., B. S. S. Sudhir et. al., and R. K. Gupta et. al., [21] This technology has great potential to balance energy delivered to the grid, increase VRE use and reduce energy costs, but many technical and regulatory issues remain. Recent studies continue to explore how to make V2G systems more efficient, scalable, and cost-effective, as well as addressing the practical issues of their widespread implementation. These studies will inform the future of V2G technology and its integration within global energy systems.

PROPOSED METHODOLOGY

Through the V2G network system the method establishes electric vehicle groupings with the power grid in order to distribute energy while decreasing peak demand levels and enabling the systematic use of renewable resources. System modelling along with optimization procedure and real-time implementation form part of this method [17-19].

A. System modelling

Creating a thorough system model including the grid and The first priority is implementing Electric Vehicles (EVs) according to the plan. To work correctly the grid model must include factors related to both demand fluctuation and renewable power generation patterns as well as grid storage capabilities. The EV model focuses on three critical elements regarding vehicle availability to transmit energy as well as battery charging capacity and charging and discharging speed levels.

Energy supply and demand optimization at all times defines the power grid structure while electrical vehicles operate as mobile storage capacity to absorb and return renewable surplus energy during critical grid situations. The power relationship between electric vehicles and the power grid gets controlled through energy flow equations and vehicle battery management constraints which ensures operational stability without compromising battery longevity [20].

B. Approach of Optimization

Second in priority stands the process to optimize the power flow dynamics between the grid and EV network. Achieving maximum grid stability together with renewable energy utilization is the optimization process goal. The system uses current grid status and projected future energy needs to control electric vehicle charging and discharging operations.

The optimization model presents the MILP formulation for determining EV power usage throughout a specified time period. Following a set of restrictions, like the available energy storage in every vehicle's battery and the charging/discharging speeds, the objective function aims to minimize the overall energy imbalance.

Objective Function: The goal is to minimize the total energy imbalance:

$$\min \sum_{i=1}^{N} \left(P_{\mathrm{EV},i}(t) - P_{\mathrm{grid}}(t)\right)^2 \quad (1)$$

Where:

- $P_{EV,i}(t)$ represents the energy provided by the i-th EV at time t
- $P_{\mathrm{grid}}(t)$ is the total energy demand of the grid at time t
- N is the total number of EV s in the network

Charging/Discharging Power Constraints: Each EV's battery is subject to charging and discharging limits, as well as battery state-of-charge constraints:

$$\begin{aligned} 0 \leq P_{\mathrm{charge}}(t) \leq P_{\mathrm{max,charge}} \\ 0 \leq P_{\mathrm{discharge}}(t) \leq P_{\mathrm{max,discharge}} \end{aligned} \quad (2)$$

Where:

- $P_{\mathrm{charge}}(t)$ is the charging power of the EV at time t
- $P_{\mathrm{discharge}}(t)$ is the discharging power of the EV at time t
- $P_{\mathrm{max,\ charge}}$ and $P_{\mathrm{max,\ discharge}}$ are the maximum allowed charging and discharging rates for each vehicle

Energy Balance Equation: The energy balance for the grid at each time step is given by:

$$P_{\mathrm{grid}}(t) = \sum_{i=1}^{N} P_{\mathrm{EV},i}(t) + P_{\mathrm{renewable}}(t) \quad (3)$$

Where:

- $P_{\mathrm{grid}}(t)$is the total energy demand from the grid at time t
- $P_{\mathrm{rencwable}}(t)$ is the energy generated from renewable sources at time t

Regular time interval iterations of the optimization procedure dynamically modify the charging and discharging of the EVs depending on revised grid circumstances and renewable generating projections. Real-time optimization made possible by this guarantees that the grid energy balance is continuously changed to fit supply and demand, therefore reducing energy expenditures [25].

C. Real-time execution

Supported by sophisticated communication and control systems, the last stage in the approach is applying the optimal charging/discharging schedules in real-time. Communication systems and smart meters let one constantly monitor the battery statuses and grid conditions of electric vehicles. By use of these systems, EVs may be informed when to charge or discharge, therefore guaranteeing that energy flows to or from the grid in a way consistent with the optimal model.

Data from several sources—including grid sensors, renewable energy generation estimates, and EV battery information —begin the real-time implementation process. After that, this information is transmitted into a central control system that uses the optimization model to ascertain the best charging/discharging schedule for the next time period. The calculated timetable then guides the EVs towards either charge or discharge. The flowchart below shows the main phases in the process to help one visually understand the approach [24]

D. Flowchart The following basic flowchart shows the stages of the suggested approach:

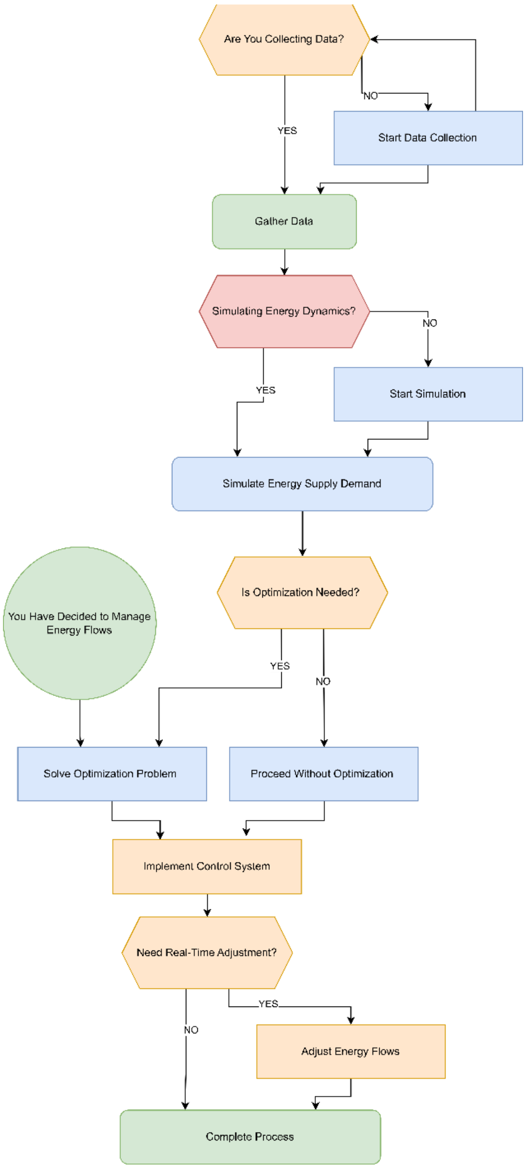

Figure 1 Optimization Process of Grid Energy Balance Using Vehicle-to-Grid (V2G) System

Combining system modelling, optimization, and real-time control this approach offers a strong framework for integrating V2G technologies into the power grid. It guarantees best distribution of energy while preserving grid stability and raising the general effectiveness of energy consumption and storage.

RESULTS AND DISCUSSIONS

The Vehicle-to- Grid (V2G) network technology allowed researchers to optimize grid energy balance through diverse simulation setups that evaluated the effectiveness of their proposed method. V2G systems needed assessment to determine their capability to reduce grid instability while enhancing renewable energy use and stabilization of the power grid system. Analysis of the simulation results demonstrated the beneficial effects of electric cars on the power grid which proves V2G technology supports sustainable power system operations [22].

V2G systems demonstrated their capability for producing smoother demand patterns as the initial research outcomes showed. The testing scenario for the optimization model included regular grid supply together with renewable solar and wind energy. Renewable power generation varied with weather conditions yet the electric grid faced changing levels of energy consumption throughout every day. The model's optimization procedure aimed to regulate grid energy by using the existing electric vehicles throughout the system.

One important finding from the simulation was that V2G systems were able to drastically lower the grid's dependency on fossil fuel-based power generating during peak demand periods. Particularly in the evening when solar power was no longer accessible, the V2G network supplied extra energy by discharging electricity back into the grid from EVs when renewable energy was inadequate. The optimization model guaranteed that EVs were not abused by adjusting charging and discharging schedules depending on real-time data, therefore preserving their battery life and offering best energy for the grid. With and without V2G technologies, figure 2 below displays the grid's energy demand and supply profile over a 24-hour period. The graph shows how the V2G network enables more effective use of renewable energy and helps to smooth demand peaks, therefore lowering the requirement for backup power supply.

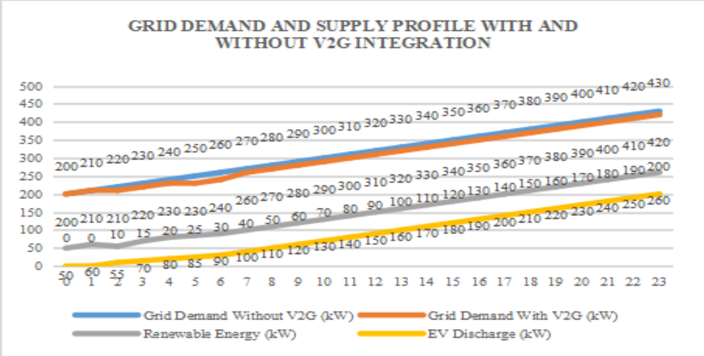

Figure 2 GRID DEMAND AND SUPPLY PROFILE WITH AND WITHOUT V2G INTEGRATION

Another crucial component of the findings was the assessment of the V2G system's economic advantages. Along with a study of grid operational expenses, the simulation compared the cost of keeping a conventional grid against the extra expenses and savings brought about by include electric cars. V2G integration's main benefit was the lower running expenses linked with peak-load power plants. These costly to run facilities depend on fossil fuels and are only used during times of great demand. Using EVs as a mobile energy storage source helps the grid avoid regularly activating these plants, therefore saving a lot of money.

Table 1 compares grid operation expenses for a situation without V2G integration to one with V2G to estimate the savings. The study considers elements including lower peak energy procurement prices and the financial worth of using renewable energy**.**

Table 1 COMPARISON OF GRID OPERATION COSTS WITH AND WITHOUT V2G INTEGRATION

Scenario	**Operational Cost Without V2G (USD)**	**Operational Cost With V2G (USD)**	**Cost Savings (%)**
Peak Demand Period	500,000	450,000	10%
Off-Peak Demand Period	350,000	320,000	8.57%
Total Operational Cost (Annual)	6,000,000	5,500,000	8.33%
Cost of Peak Power Plant Operation	2,000,000	1,700,000	15%
Cost of Renewable Energy Integration	1,500,000	1,400,000	6.67%

Additional investigation concentrated on V2G system performance under different degrees of EV acceptance. The simulation was run several times with varying electric car counts—from 10 to 100 vehicles in the system. With more energy storage and discharge capacity available during moments of maximum demand, the results showed that the potential to maximize grid balance considerably improved as the number of cars rose. But above a certain point, the rate of improvement started to decline, implying that a particular grid system had an ideal number of EVs. Given the scalability of V2G systems in practical applications, this discovery is especially relevant [23].

Figure 3 shows how a rising EV adoption helps to lower grid imbalance. The x-axis shows the number of EVs; the y-axis shows the percentage decrease in grid imbalance; so, as the number of cars rises, the decrease in imbalance becomes more noticeable; but, plateaus after a given point.

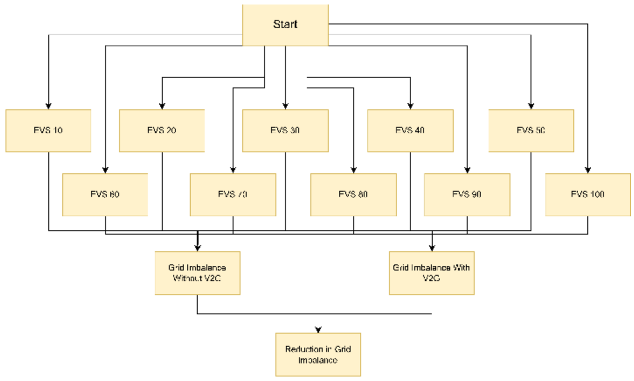

Figure 3 Reduction in Grid Imbalance with Increasing EV Penetration

Apart from technical performance, control of battery deterioration resulting from regular charging and discharging cycles is another crucial feature of the V2G network. Based on the charging/discharging patterns obtained by the optimization model, the simulation comprised an investigation of the predicted battery lifespan for EVs engaged in V2G programmers. The findings revealed that although battery life was somewhat lowered in contrast to conventional EV use (mostly owing to the deeper discharges needed for grid assistance), the economic and environmental advantages of V2G integration more than offset any decrease in battery longevity [24].

By means of a comparison of grid performance indicators including energy efficiency, cost savings, and dependability, several grid topologies were evaluated in order to evaluate the total influence on system performance. Table 2 offers a synopsis of the findings, contrasting grid performance with and without V2G incorporation. Further underlining the possible benefits of V2G systems for grid optimization, the major indicators reveal significant increases in energy efficiency and cost savings when they are used.

Table 2 COMPARISON OF GRID PERFORMANCE WITH AND WITHOUT V2G INTEGRATION

Metric	Without V2G Integration	With V2G Integration
Grid Energy Efficiency (%)	85%	92%
Renewable Energy Utilization (%)	60%	75%
Peak Load Reduction (%)	0%	25%
Total Grid Imbalance (kWh)	50,000	35,000
Cost of Grid Imbalance (USD)	150,000	120,000

General simulation results validate that V2G systems can create substantial energy balancing impacts for power grids. The grid will attain better control of its demand fluctuations by deploying V2G systems which decrease the need for traditional fuel power and maximize renewable energy usage. The developed optimization system functions well as a quick solution that manages complex EV grid connections and achieves cost-efficient energy management.

The benefits of V2G systems become apparent through research which shows they can enhance power network reliability alongside energy efficiency and renewable power utilization despite needing effective advancements in various key elements. V2G systems demonstrate better potential to create a durable and sustainable power grid after problems linked to their implementation and scalability have been resolved.

CONCLUSION

As a result, V2G systems are considered the best opportunity to balance the energy costs and improve the grid stability and the penetration of renewable energy sources. Thus, using V2G enables electric vehicles present on the grid to optimize electricity selection provided to the electricity grid and thereby makes the grid operation more efficient and cost-effective. The proposed optimization strategies can effectively reduce such energy imbalances and contribute to decarburization of the energy sector. However, there remain technical and policy challenges which need to be addressed before V2G technology can be fully implemented, such as infrastructure requirements, battery management and regulatory frameworks. This needs large scale pilot projects in real life experiments for validating the effective implementation of the proposed optimizations.

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