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Vehicle-to-Grid (V2G) Dynamics: Global Insights and Innovations

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Abstract: With the rapid construction of renewable energy power plants and increasing demands on grid performance, using onboard batteries as distributed energy storage is a highly promising solution, with the rising ownership of EVs to absorb electricity generation and balance the grid. As a consequence, this paper explores the key technologies such as bidirectional charging and smart charging algorithms and highlights the development of efficient converters and the implementation of algorithms like V2G-OLC and ICSA. Despite technological progress, challenges remain, particularly in new technology breakthroughs, public acceptance, and policy support. Public attitudes and perceptions influence V2G adoption, requiring strategies tailored to different regions. Furthermore, substantial investment in charging infrastructure is crucial for widespread implementation. Policies and innovative frameworks are important to encourage the adoption. As well as this paper provides an overview of vehicle-to-grid technologies and underlines the importance of addressing these challenges to achieve a flexible and intelligent energy future.

Keywords: Bidirectional charging, Smart charging algorithm, V2G,Energy management.

1. Introduction

As global warming becomes more and more serious, governments around the world are introducing polices to support the development of renewable energy. However, with the increasing proportion of renewable energy in the energy structure, its uncertainty impacts the grid. Since electricity must be used as it is generated and the peaks of renewable energy generation do not always align with demand peaks, the demand for energy storage is rising. Driven by policy, global electric vehicle ownership is steadily growing. Research predicts that by 2060, the use of new energy vehicles in China will reduce carbon emissions by 56.33% to 103.14% [1].

Meanwhile, using the onboard batteries to absorb new energy generation, which is seen as having great potential for development. Based on this, vehicle-to-grid (V2G) came into being. V2G means that EVs can not only store the electricity but also feed power back into the grid when needed.

This new solution is crucial for achieving decarbonization targets in the transportation sector [2]. However, charging infrastructure remains a key challenge. Countries like China, South Korea rely heavily on public charging, and the lack of infrastructure complicates the implementation of bidirectional charging [3]. Although there are few projects, initiatives like the “unlT-e2” smart charging project have shown profitability. By 2030, bidirectional charging is expected to be widely profitable, with potential saving of up to 2780€/Eva [4].

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This paper reviews the two key technologies of V2G: bidirectional charging and smart distribution algorithms. It examines how EVs charging and discharging can enhance grid stability and flexibility. The study explores the integration of these technologies, which can promote deeper integration of EVs with the grid, and provide the theoretical support for future diversified, intelligent, and flexible power grid.

2. Key technologies

To better understand V2G,in Figure 1, it is important to explore its foundational technologies. This section will mainly analyze two key technologies: bidirectional charging and smart charging algorithms. These technologies lay the groundwork for future vehicle-to-grid (V2G) interactions.

2.1. Bidirectional charging

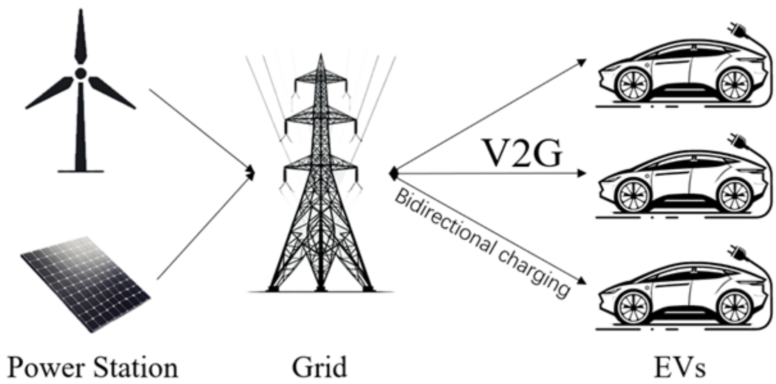

Figure 1: Diagram of a V2G system.

Firstly, the foundation of bidirectional charging is its hardware components. Currently, vehicle chargers are mostly single-stage or two-stage systems. Single-stage onboard chargers (OBC) meet the need for high power density, while two-stage OBCs are simple and efficient, which makes them a popular choice for the future. These solutions often require many switching units, which leads to a problem of power reliability. Besides, single-stage converters may have significant low-frequency output current fluctuations, which may affect battery charging efficiency. A Canadian team has suggested several topologies to address these issues to solve these problems and improve energy conversion [5].

The DAB converter, characterized by the absence of a DC link capacitor, enhances system reliability and power density. For example, the SiC DAB converter developed by Texas Instruments achieves a power level of 10 kW and a peak efficiency of 98.2%. Its benefits include no switching losses, as all MOSFETs operate with Zero Voltage Switching, reducing energy losses. Additionally, its bidirectional power flow capability supports interactions between electric vehicles and the grid.

Besides, the three-phase T-type multi-port converter is becoming increasingly important as the need for interaction between EVs and the grid grows. This topology allows connection to a three-phase grid as an input signal, featuring three AC ports and an active full-bridge DC port. Its advantages include high power density and low system losses which makes it suitable for electric vehicle charging applications.

2.2. Smart charging algorithms

Based on hardware infrastructure, the implementation of V2G mainly relies on smart charging algorithms. Researchers have proposed various integrated algorithm models. For example, the

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Optimal Logic Control algorithm (V2G-OLC) based on the French energy billing system, the Intelligent Charging Scheduling Algorithm (ICSA), which combines multiple optimization techniques including differential evolution, genetic algorithms etc. and an NLP models that minimize battery degradation while maximizing profits [6] [7] [8]. These algorithms provide the foundation for the future development of V2G.

2.2.1. V2G-OLC

V2G-OLC aims to optimize the cost of charging PEVs, especially in markets with fluctuating electricity prices. It uses a logical control strategy to optimize charging and discharging times, maximizing economic benefits when selling prices are higher than buying prices. In tests with 1000 cases, V2G-OLC reduced charging costs by an average of 47.94%, which is a significant breakthrough compared with former charging algorithms.

2.2.2. ICSA

ICSA addresses the "where" and "when" of charging for EV drivers which focuses on finding a suitable charging station with minimal wait times. ICSA uses various optimization techniques such as differential evolution, biogeography-based optimization, grey-wolf optimization, particle swarm optimization, etc. and integer linear programming to select the best charging station, ensuring an available spot upon arrival and considering battery energy use and slot availability. Studies show that ICSA is economical and robust, which can significantly reduce costs and improve charging efficiency.

2.2.3. An NLP model

NLP tackles two main issues in EV bidirectional charging: minimizing battery degradation costs and maximizing EV revenue. The model optimizes scheduling to reduce charging costs while supporting grid frequency and voltage and enhance EV economic benefits without increasing battery wear. In detail, in the first phase, research team optimize scheduling without considering battery degradation. In second phase, they incorporate the degradation into the model and input real-time data to forecasted day-ahead EV adoption. One of its biggest advantages is this model integrate several aspects such as minimize charging costs, extend battery lifespan, etc.

3. Primary issues and challenges

After discussing the key technologies of V2G, understanding primary issues and challenges can further improve people’s understanding of V2G. According to the research, most of the formal papers are focusing on technological progress, which covers 359 subjects and more than 200 design approaches [9]. However, the discussions of users’ attitudes, feeling and driving behavior is less than 2.1%. As fundamental theories advance, people face more challenges in fields like technology, public acceptance, and policy support. These issues affect sustainable development and demand better performance in practical applications. Hence a deep analysis of these issues is essential.

3.1. Technology breakthroughs

Technology breakthroughs play the most important role in the development of V2G and smart grids. In hardware, advanced bidirectional charger topologies are crucial. Devices using wide-bandgap technology and components with better thermal optimization are key research areas. Optimizing component integration to enhance system performance and exploring lower-cost, higher-efficiency solutions are essential. In the future, wireless charging technology may offer a more flexible solution [5]. On the algorithmic level, many research teams emphasize the importance of models based on real data and actual conditions as a primary research focus. Since V2G technology requires wide implementation, algorithms that are comprehensive and realistic are vital. This approach enhances their applicability in real-time complex scenarios, helping to manage fluctuations in market prices and load changes effectively [8].

3.2. Public acceptance

The public acceptance is a key factor in the development of V2G. Psychological factors, such as user attitude, perception of risks will greatly influence public acceptance, which will further influence the wide use of V2G. According to the research, optimistic outlook of the public can boost the willing to adopt the technologies. Reasonable pricing strategies are also important, which can reflect consumer economic benefits and promote the spread of V2G services. This approach can drive sustainable development and innovation [10].

A research team conducted a serious study in Taiwan to further understand user acceptance. They built a model based on UTAUT2 via analyzing 365 survey samples. Unlike previous studies focusing on single factor, this model considers risk perception and user attitude towards V2G and provides a broader perspective. Meanwhile, it shows a crucial enlightenment that the promotion of V2G in different regions should be different based on what the public mostly concern. It will help practical projects implementation and further promote new research.

3.3. Policy support

Policy innovation faces several challenges in improving V2G, particularly regarding infrastructure investment. Implementing bidirectional charging requires significant investment in charging stations and bidirectional charging points, which are essential for supporting energy flow. Specifically, investment must cover the "implementation of functional baselines" including expensive DC chargers, bidirectional charging points, etc. [11]. The installation and maintenance of these devices require substantial financial resources.

Additionally, there is a need to expand smart charging infrastructure, particularly by installing charging stations that support bidirectional energy flow at multiple locations. However, the high cost may pose a barrier to implementation. Therefore, policy support is necessary to advance these projects. Meanwhile, considering the different conditions among regions, policies should be seriously designed. Besides, to further expand the electric vehicle ownership, new vehicle purchase incentives are necessary, which can help reduce the purchase cost and stimulate the consumer markets, as several countries, such as China, France, Germany, Japan, and the United States have done before [2].

4. Conclusion

This paper focuses on examining the bidirectional charging and smart charging algorithms. Even though technologies have improved a lot, getting the public on board and having strong policy support are still big obstacles.

As V2G play a crucial role in enhancing grid stability, integrating renewable energy and many fields, the outcomes of this study are significant. V2G can contribute to a more sustainable and intelligent energy infrastructure by addressing the challenges identified.

Looking ahead, future research should focus on regional characteristics, integrating local user habits and acceptance to develop more suitable strategies and algorithm models that will help develop V2G technologies and ensure their successful implementation.

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