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A Review on Dynamic Prioritization Strategy for Grid Support Using Plug-in Electric Vehicles

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Abstract

The increasing adoption of Plug-in Electric Vehicles (PEVs) and the integration of renewable energy sources into power grids necessitate dynamic strategies to optimize grid stability. This review explores cutting-edge dynamic prioritization strategies that manage PEV charging and discharging based on real-time grid conditions. Key findings highlight how advanced control systems, predictive algorithms, and decentralized communication protocols enable PEVs to function as distributed energy resources. These strategies enhance grid flexibility, facilitate demand response, and support peak load shaving while optimizing the integration of renewable energy. The study identifies significant challenges, including scalability, data security, and user participation, and suggests future directions such as leveraging machine learning, blockchain technology, and incentive programs. By addressing these challenges, dynamic prioritization strategies can unlock the full potential of PEVs, fostering a more resilient and sustainable energy system. This review provides critical insights for researchers, policymakers, and industry stakeholders aiming to advance PEV-grid integration.

Keywords: Dynamic Prioritization, Plug-In Electric Vehicles (Pevs), Real-Time Energy Demand, Grid Support, Energy Supply Management, Charging and Discharging Optimization.

1. Introduction

1.1 Background

The global energy landscape is undergoing a significant transformation, driven by the growing adoption of renewable energy sources such as wind and solar. While these energy sources are key to reducing carbon emissions and combating climate change, they also introduce challenges related to grid stability due to their intermittent and unpredictable nature. To ensure a reliable and stable power supply, grid operators must find ways to balance the variability of renewable energy with real-time energy demand [4, 5]. One promising solution to this challenge is the integration of Plug-in Electric Vehicles (PEVs) into the power grid. PEVs, with their inherent energy storage capabilities, are not only clean transportation alternatives but also mobile energy storage units that can provide critical support to the grid. By leveraging Vehicle-to-Grid (V2G) technology, PEVs can draw power from the grid during periods of low demand (charging) and return power to the grid during periods of high demand (discharging). This bidirectional flow of energy presents an opportunity to enhance grid flexibility, manage peak loads, and better integrate renewable energy into the grid.

1.2 Motivation

The ability of PEVs to support the grid depends heavily on how effectively their charging and discharging operations are managed. Given the dynamic nature of grid conditions, traditional static strategies for PEV management fall short of optimizing their full potential. What is required is a dynamic prioritization strategy. This approach continuously adjusts PEV charging and discharging in real-time based on current grid conditions, such as energy demand, supply, and the availability of renewable energy sources. Dynamic prioritization not only ensures that PEVs contribute to grid support when it is most needed but also maximizes the economic and environmental benefits for both grid operators and PEV owners. However, developing and implementing such a strategy presents several challenges, including real-time data management, ensuring scalability, and encouraging user participation in grid support programs.

1.3 Objective

This review aims to provide a comprehensive analysis of existing dynamic prioritization strategies for using PEVs to support the grid, with a specific focus on real-time energy demand and supply. By examining current research, methodologies, and technologies, we will identify the strengths and limitations of these strategies, discuss their practical applications in real-world grid operations, and highlight the challenges that need to be addressed to ensure their successful implementation. Furthermore, this paper will explore future research directions that could help improve dynamic prioritization strategies for PEV-grid integration, including advances in predictive modelling, machine learning, and blockchain technology for secure and decentralized energy transactions. The ultimate goal is to enhance the efficiency and reliability of grid support systems, particularly in grids with a high penetration of renewable energy sources. In summary, the growing integration of PEVs into the power grid offers a unique opportunity to enhance grid stability and optimize energy usage. A dynamic prioritization strategy driven by real-time energy data holds the potential to unlock the full value of PEVs as decentralized energy resources, contributing to a more flexible, sustainable, and resilient energy system.

2. Plug-in Electric Vehicles and Grid Support Potential

Plug-in Electric Vehicles (PEVs) are electric vehicles that rely on rechargeable batteries to store energy, which can be obtained from the power grid. PEVs not only offer an environmentally friendly alternative to fossil fuel-powered vehicles but also have the potential to play a critical role in supporting grid operations through Vehicle-to-Grid (V2G) technology. V2G enables a two-way energy exchange between PEVs and the grid. During periods of low electricity demand, PEVs can charge their batteries by drawing power from the grid. Conversely, during periods of high demand, PEVs can discharge stored energy back to the grid, acting as mobile energy storage units [6]. The ability of plug-in electric vehicles (PEVs) to charge and discharge based on grid conditions provides several essential grid support functions. First, PEVs enhance grid flexibility by helping balance supply and demand, particularly in grids with a high penetration of intermittent renewable energy sources like solar and wind. By charging during periods of surplus renewable energy and discharging during shortfalls, they play a key role in adapting to fluctuating energy supplies. Second, PEVs contribute to peak load shaving by supplying stored energy during peak demand periods, reducing grid strain and minimizing the need for additional power generation from non-renewable sources, which helps prevent blackouts. Third, they can participate in demand response programs by adjusting their charging schedules based on grid signals aligning energy usage with the availability of low-cost or renewable energy. Lastly, PEVs support frequency regulation by quickly modulating their charging or discharging rates to maintain the real-time balance between supply and demand, ensuring grid stability. By leveraging their distributed battery storage capacity, PEVs have the potential to function as decentralized energy resources, supporting grid operations and promoting the efficient and sustainable use of electricity as renewable energy sources become increasingly integrated into modern power grids.

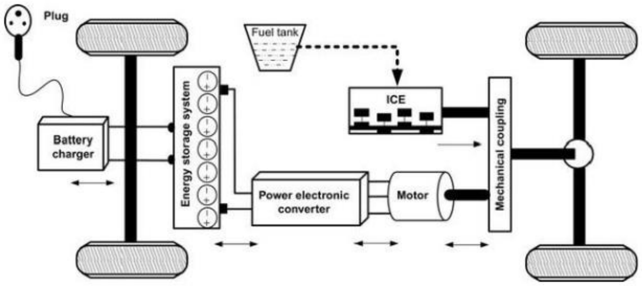

Fig. 1 Plug-in Electric Vehicle

3. Dynamic Prioritization Strategies

Dynamic prioritization strategies refer to real-time, adaptive methods that optimize the charging and discharging of Plug-in Electric Vehicles (PEVs) based on fluctuating grid conditions such as energy demand, supply, and renewable energy generation. Unlike static or scheduled charging strategies, dynamic prioritization is designed to respond flexibly to real-time data, allowing PEVs to function as distributed energy resources that can contribute to grid stability, demand response, and peak load management. These strategies maximize the value of PEVs in supporting grid operations, particularly in grids with high renewable energy penetration[7, 8].

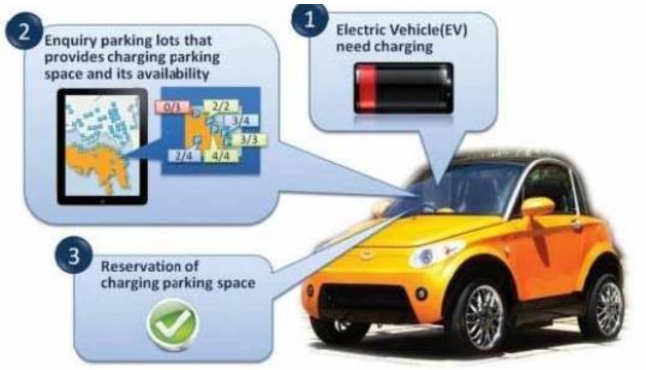

Fig. 2 Importance of Electric Vehicle

3. 1. Concept of Dynamic Prioritization

Dynamic prioritization involves continuously adjusting the charging and discharging priorities of plug-in electric vehicles (PEVs) based on real-time grid requirements. This approach relies on advanced control systems that collect, analyze, and act on data related to energy demand, energy supply (including renewable generation), electricity price signals, and grid frequency and voltage stability. By dynamically managing PEVs, these systems ensure that vehicles charge during periods of excess energy, such as when solar or wind power generation is high, and discharge energy back to the grid when demand exceeds supply, particularly during peak load periods. This strategy not only helps maintain grid balance and stability but also optimizes the integration and utilization of renewable energy sources, promoting a more sustainable energy ecosystem.

3. 2. Key Elements of Dynamic Prioritization Strategies

Real-Time Data Analysis:- Real-time data from the grid plays a pivotal role in optimizing the charging and discharging of plug-in electric vehicles (PEVs). Advanced metering infrastructure (AMI), Internet of Things (IoT) devices, and smart sensors collect real-time information about energy demand, supply, and grid conditions. This data is then processed by dynamic control systems, which determine the priorities for PEV charging or discharging based on the current grid status. Such systems enable a decentralized approach, which enhances scalability by minimizing the reliance on central computing power and extensive communication infrastructure. Additionally, PEVs can provide localized grid support by addressing specific areas experiencing demand spikes or fluctuations in renewable energy generation, improving the efficiency of energy distribution and ensuring grid stability.

Advanced Communication and Control Protocols:- Effective dynamic prioritization relies on robust communication between plug-in electric vehicles (PEVs), grid operators, and other stakeholders, such as utilities. This is made possible through advanced control protocols that support real-time data exchange and decision-making. Internet of Things (IoT) devices integrated into PEVs and grid infrastructure enable seamless communication, allowing the grid to send signals about demand or supply conditions and prompting PEVs to adjust their charging behaviour in real time. Vehicle-to-grid (V2G) communication systems further enhance this process by allowing the grid to request energy discharge from PEVs during periods of high demand or instability. These requests are transmitted over secure channels, and PEVs respond by delivering energy back to the grid to help stabilize it. In order to ensure the security and integrity of these interactions, blockchain technology is being explored as a means to facilitate secure communication and decentralized transaction management, thereby enhancing trust and efficiency in PEV-grid interactions.

3. 3. Applications of Dynamic Prioritization

Dynamic prioritization strategies are crucial to demand response programs, enabling plug-in electric vehicles (PEVs) to adjust their charging schedules based on grid signals. For example, during periods of high electricity demand, the grid can instruct PEVs to delay charging or discharge energy back into the grid, alleviating stress on the system. These strategies often utilize time-of-use pricing, which encourages PEV owners to charge during off-peak hours when electricity rates are lower and renewable energy supply is abundant. Additionally, load shifting allows PEVs to charge during times of low demand or high renewable energy generation, thus supporting grid stability and enhancing the integration of clean energy. By aligning charging behavior with grid conditions, these approaches optimize energy use and decrease reliance on non-renewable power sources. Furthermore, PEVs can contribute to frequency regulation by quickly adjusting their charging or discharging rates to maintain the grid's frequency stability (e.g., at 50Hz or 60Hz), ensuring overall grid stability. During peak demand periods, PEVs can also engage in peak load shaving by discharging stored energy, reducing grid strain, helping utilities avoid costly peaker plants, and lowering the risk of grid overload or blackouts.

3. 4. Challenges in Implementing Dynamic Prioritization Strategies

Scalability and Complexity:- Managing thousands or even millions of PEVs in real time is a complex task that requires significant computational resources and efficient communication networks. Ensuring scalability while maintaining system efficiency remains a key challenge.

Data Privacy and Security:- Real-time data exchange between PEVs, grid operators, and utilities raises concerns over data privacy and security. Ensuring the secure transmission of sensitive information (e.g., energy consumption, location data) is crucial for widespread adoption.

User Behavior and Participation:- Dynamic prioritization relies on PEV owners participating in grid support programs. Convincing users to allow their vehicles to discharge at certain times or delay charging requires well-designed incentive programs. Ensuring user trust and engagement is a significant challenge. Dynamic prioritization strategies for PEVs are a key solution to managing the variability of renewable energy sources and maintaining grid stability. By leveraging real-time data, predictive models, decentralized control systems, and advanced communication protocols, PEVs can effectively support the grid through demand response, peak load shaving, and frequency regulation. However, challenges such as scalability, data security, and user participation must be addressed to realize the potential of PEV-grid integration fully. Future advancements in machine learning, blockchain technology, and decentralized energy management could further enhance the efficiency and scalability of dynamic prioritization strategies, making them a critical component of future smart grids.

4. Challenges in Implementing Dynamic Prioritization

Scalability and system complexity present significant challenges in managing millions of Plug-in Electric Vehicles (PEVs) in real-time, as this requires substantial computational power, advanced algorithms, and a robust communication infrastructure. Achieving scalability while maintaining system efficiency is a critical issue that demands innovative solutions [9]. Furthermore, data privacy and cybersecurity are major concerns due to the exchange of sensitive information between PEVs, grid operators, and utility companies. Ensuring the secure transmission of this data is vital for the successful implementation of dynamic prioritization strategies [10]. Additionally, user participation and behavioral challenges arise from the difficulty of convincing PEV owners to participate in grid support programs and adjust their charging or discharging behaviors in real-time. Effective incentive mechanisms and fostering user trust are essential to address these challenges and ensure widespread adoption.

5. Related Work

Celebi and Fuller (2012) have proposed a time-of-use tariff scheme for regulatory bodies and the electricity market. With the flexible pricing mechanism for the customers, a cost efficiency-based metric system proposed by Ma Jinghuan, He Henry Chen *et al.* (2016) showed that load shifting appreciably affects the cost of electricity with the integration of RES. Akhavan-Rezai *et al.* (2016) have discussed online charging of PEV, where the fuzzy system has been used to allocate scores to the vehicles aiming for optimal charging and to maximize the benefit of the owner without violating the grid operational constraints. Intelligent control strategies are required in order to effectively utilize PEV storage capacity with V2G technology (Khayyam *et al.*, 2012). Better exploitation of PEVs will result in the perfect scheduling of PEVs' charging and discharging in accordance with the fluctuating RES and load demand. It is always preferable to have ESS along with RES, especially for those of an intermittent nature. There are so many energy storage technologies available in the present market: Battery Energy Storage Systems, Fly Wheel Energy Storage Systems, and Super Conducting Magnetic Energy Storage Systems. For wind energy conversion systems, an electric double-layer capacitor or static synchronous compensator can be used to smooth power output. Pumped storage plants can be used for bulk power management. To schedule the excess power generated by the wind or solar at below half peak load periods, the excess power generated by these RES can be utilized to pump the water. As the hydro plants are usually far away from load centres, it is not economical to pump the water using main grid power. Rather, it would be a better choice if there were a wind plant near the hydro (Ren, Zeng, *et al.*, 2012). Solar PV, along with ESS, are designed to supply power to the home and also to/from the grid, depending on operational constraints and economy (Sechilariu *et al.*, 2013). While deploying ESS and DGs, the size and location are major concerns as they affect the operation of the grid. Ellingsen et al. (2017) clarified that when taking into account the entire life cycle of the vehicle, the current European generation mix enables battery electric vehicles to deliver roughly 30% of emission savings compared with ICE vehicles. EVs offer only limited advantages with respect to ICE vehicles in terms of CO2 emissions, and they may even result in net increases when considering their lifecycle emissions in countries with a high carbon-intensive power generation mixture. Hence, the amount of CO2 emission per kWh energy generation is the key factor that matters a lot when we talk about emission reduction due to electric car's arrival in the market. R. Godina et al. (2016) claim that the uncoordinated or dumb charging of PEVs leads to drastic fluctuations in power demand from the main grid and, more importantly, overloads the local distribution transformers. Here, the word 'dumb charging' means that the vehicle will be plugged in for charging as soon as the vehicle arrives from the trip. The good news about PEVs is that they can be used as virtual/mobile storage units for grid support with smart charging strategies. J. Barton and D. Infield's (2004) study has estimated that the probability of PEV's (vehicle used for general/commute purposes) availability at home during mid-day is 0.9, and that of staying at home during weekdays is 0.5. It shows that most of the time, PEVs are staying at home. Hence, they can be used as storage units for grid ancillary services such as energy management voltage regulation, as a substitute for spinning reserves and in demand side management. Adil Amin et al. (2020) summarize a critical review of EVs' optimal charging and scheduling under dynamic pricing schemes. A detailed comparison of these schemes, namely, Real Time Pricing (RTP), Time of Use (ToU), Critical Peak Pricing (CPP), and Peak Time Rebates (PTR), is presented. Globally, the intention to reduce carbon emissions (CO2) has motivated the extensive practice of Electric Vehicles (EVs). The uncoordinated charging and uncontrolled integration of EVs to the distribution network, however, deteriorates the system performance in terms of power quality issues. Therefore, the EVs' charging activity can be coordinated by dynamic electricity pricing, which can influence the charging activities of the EV customers by offering flexible pricing at different demands. Recently, with developments in technology and control schemes, the RTP scheme has offered more promise than the other types of tariffs because of the greater flexibility for EV customers to adjust their demands. However, it involves a higher degree of billing instability, which may influence the customer's confidence. In addition, the RTP scheme needs a robust intelligent automation system to improve the customer's feedback on time-varying prices. In addition, the review covers the main optimization methods employed in a dynamic pricing environment to achieve objectives such as power loss and electricity cost minimization, peak load reduction, voltage regulation, distribution infrastructure overloading minimization, etc., [1]. Jin Yi Yong et al. (2023) show that further research work on charging coordination for destination charging should account for user behaviour and the potential obstacles faced by the intended scale of destination charging to determine a suitable coordination strategy. It is also recognized that implicit charging coordination strategies are understudied and should be investigated because they may circumvent problems encountered by real-world EV charging coordination programs [2]. Shanmugam, P. K., and Thomas, P. (2024) exhibited a deep review of the various EV optimal scheduling techniques and adopted algorithms, which are the emerging best practices like predictive analytics, dynamic routing, user-centric planning, multi-objective optimization, etc. that reflect the industry's focus on leveraging advanced technologies, data-driven decision-making, and collaborative approaches to enhance the efficiency and sustainability of electric vehicle routing and charging scheduling [3].

6. Problem Statement

The increasing integration of renewable energy sources like wind and solar into power grids presents significant challenges due to their intermittent and unpredictable nature. This variability in energy supply complicates the balancing of electricity demand, leading to grid instability, especially during peak load periods. Traditional grid management approaches struggle to manage this variability efficiently, and the need for more flexible, real-time solutions has become critical. Plug-in Electric Vehicles (PEVs), with their dual capability to charge from the grid and discharge power back to it using Vehicle-to-Grid (V2G) technology, offer a promising solution to these challenges. However, realizing the full potential of PEVs as distributed energy resources requires an efficient and dynamic prioritization strategy. Such a strategy must continuously adjust PEV charging and discharging operations based on real-time energy demand, supply, and grid conditions, ensuring that these vehicles provide optimal grid support while maximizing the use of renewable energy. Despite the promise of dynamic prioritization strategies, several challenges hinder their widespread adoption. These include the complexity of managing large fleets of PEVs in real time, ensuring scalability, maintaining data privacy and security, and encouraging user participation in grid support programs.

Moreover, developing predictive algorithms that can accurately forecast grid conditions and integrating decentralized control systems for PEV management remains an ongoing technical challenge. This paper aims to review existing research on dynamic prioritization strategies for grid support using PEVs, focusing on real-time energy demand and supply management. The goal is to identify the strengths, limitations, and practical applications of these strategies, as well as highlight future research directions to address the existing challenges and improve PEV-grid integration for a more stable and sustainable power grid.

7. Conclusion

The integration of Plug-in Electric Vehicles (PEVs) into the power grid offers a unique opportunity to enhance grid stability, particularly in systems with a high penetration of renewable energy sources. PEVs, through Vehicle-to-Grid (V2G) technology, can serve as decentralized energy storage units that charge during periods of excess supply and discharge during times of peak demand. However, unlocking the full potential of PEVs for grid support requires the development of dynamic prioritization strategies—real-time, adaptive systems that optimize PEV charging and discharging based on fluctuating grid conditions, such as energy demand, supply, and renewable generation. This review has highlighted several critical aspects of dynamic prioritization strategies, including the use of real-time data analysis, predictive algorithms, and decentralized control systems. These elements enable PEVs to contribute to grid support functions such as load shifting, peak load shaving, demand response, and frequency regulation, making the grid more flexible and resilient. Dynamic strategies help mitigate the challenges posed by the variability of renewable energy, ensuring that the grid remains stable and that PEVs provide maximum economic and environmental benefits. Despite the advantages, several challenges remain, including the complexity of scaling up these systems, maintaining data security and user privacy, and encouraging widespread user participation. Addressing these challenges requires ongoing research and technological advancements, particularly in areas like machine learning, blockchain for secure transactions, and improved communication protocols for real-time PEV-grid interactions.

In conclusion, dynamic prioritization strategies hold great promise for the future of smart grids, enabling the effective use of PEVs as critical resources in energy management. However, the successful implementation of these strategies will depend on overcoming existing technical, operational, and user-related challenges. Future research should focus on refining predictive models, improving decentralized control, and developing robust incentive programs to ensure broad adoption. By doing so, PEVs can become a cornerstone of a more sustainable and resilient energy system, effectively balancing real-time energy demand and supply while supporting the global transition to cleaner energy sources.

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