Advanced Control Strategies and Optimization Methodologies for Electric Vehicle Charging and Discharging in Power Generation: A Comprehensive Review of Methods, Control Structures, and System Objectives

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ABSTRACT

The stimulus to carry out this research is to explores advanced control strategies and optimization methodologies for the coordination of Electric Vehicle (EV) charging and discharging in power systems, emphasizing the interplay between economic, environmental, and operational objectives. The study highlights how effective scheduling of EV charging can reduce costs for consumers, enhance grid efficiency, and create new revenue streams for EV aggregators through participation in demand response programs. Additionally, it examines the environmental benefits of aligning EV charging with renewable energy generation, contributing to significant reductions in greenhouse gas emissions and promoting sustainable transportation.

Operationally, the research discusses the importance of coordinated charging strategies in improving grid stability, load balancing, and the overall flexibility of power systems. By leveraging EVs as mobile energy storage units, the study identifies ways to enhance the resilience and adaptability of the grid in response to fluctuations in supply and demand. Ultimately, this comprehensive review underscores the necessity of implementing innovative control structures and optimization techniques to address the challenges posed by the increasing integration of electric vehicles into the power grid, supporting a sustainable energy future and a robust electrified transportation network.

Keywords - *Advanced Control Strategies, Optimization Methodologies for Electric Vehicle, Charging and Discharging in Power Generation.*

INTRODUCTION

The growing usage of electric vehicles (EVs) is a concern and opportunity for power generation systems as they determine the need for electricity to charge these automobiles. With the increase in the number of EVs, the utilization of charging and discharging management into the power system has become crucial to stability, efficiency, and sustainability (Sankhwar, 2024). Sophisticated control measures and optimization techniques are used to control the interaction between EVs and power generation to address issues of supply-demand imbalance, grid load management and integration of renewable energy generation (Pamidimukkala, 2024). This research paper offers a systematic review of several control systems and strategies intended for efficiency of both the charging and discharging of EVs. They include system objectives like charging cost, peak demand and grid reliability (Bryła, 2024). Thus, by examining the findings of the most recent literature in this field, the review seeks to provide practical information on the design and deployment of effective EV energy management systems that address the emerging requirements of contemporary power systems

Background

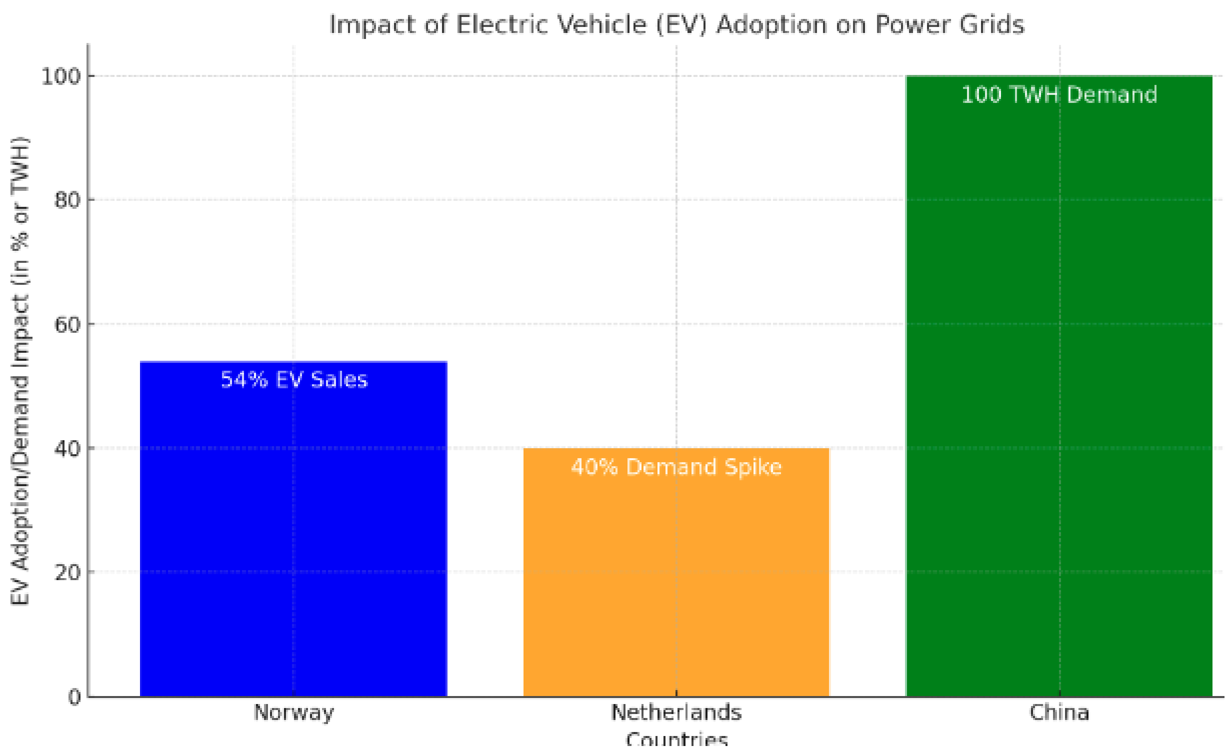
Global EVs are now advancing at a faster rate than ever before, affecting energy and transport systems. Currently, the global stock of EVs stands at 16.5 million, IEA estimates that this figure will exceed 145 million by 2030 (IEA, 2021).

Global revenue for electric vehicles between 2016 and 2023, with a forecast through 2029
(in billion U.S. dollars)

This increase is a significant concern for power systems because it will require an additional 550 terawatt-hours (TWh) of electricity by 2030 – as much as France consumes in a year (Zaino, 2024). Thus, more sophisticated control strategies are required to address this increasing demand and properly integrate EVs for the provision of grid services. In response to these challenges, different control structures, and optimization techniques are being developed and implemented. DR, V2G technology, and TOU pricing are some of the approaches to manage EVs to fit into the power grids effectively (Mathew, 2024). DR allows EV owners to make charging time preferences in accordance with the real time grid demand. V2G has the capability of both charging and discharging electric vehicles to inject electricity back into the grid in as needed. TOU pricing schemes promote off-peak tariff to decrease the cost of electricity and congestion on the grid (Muratori, 2021). However, in the last few years, several new algorithms such as model predictive control (MPC) and artificial intelligence (AI) based algorithms have been designed for the real-time optimization of EV charging and discharging (Adu-Gyamfi, 2024). These methods enhance the grid efficiency in satisfying supply and demand, increasing energy utilization efficiency, and incorporating renewable energy system (Farajnezhad, 2024). These new approaches are the focus of this study because they will enable the development of a sustainable and resilient energy system in the future.

Context

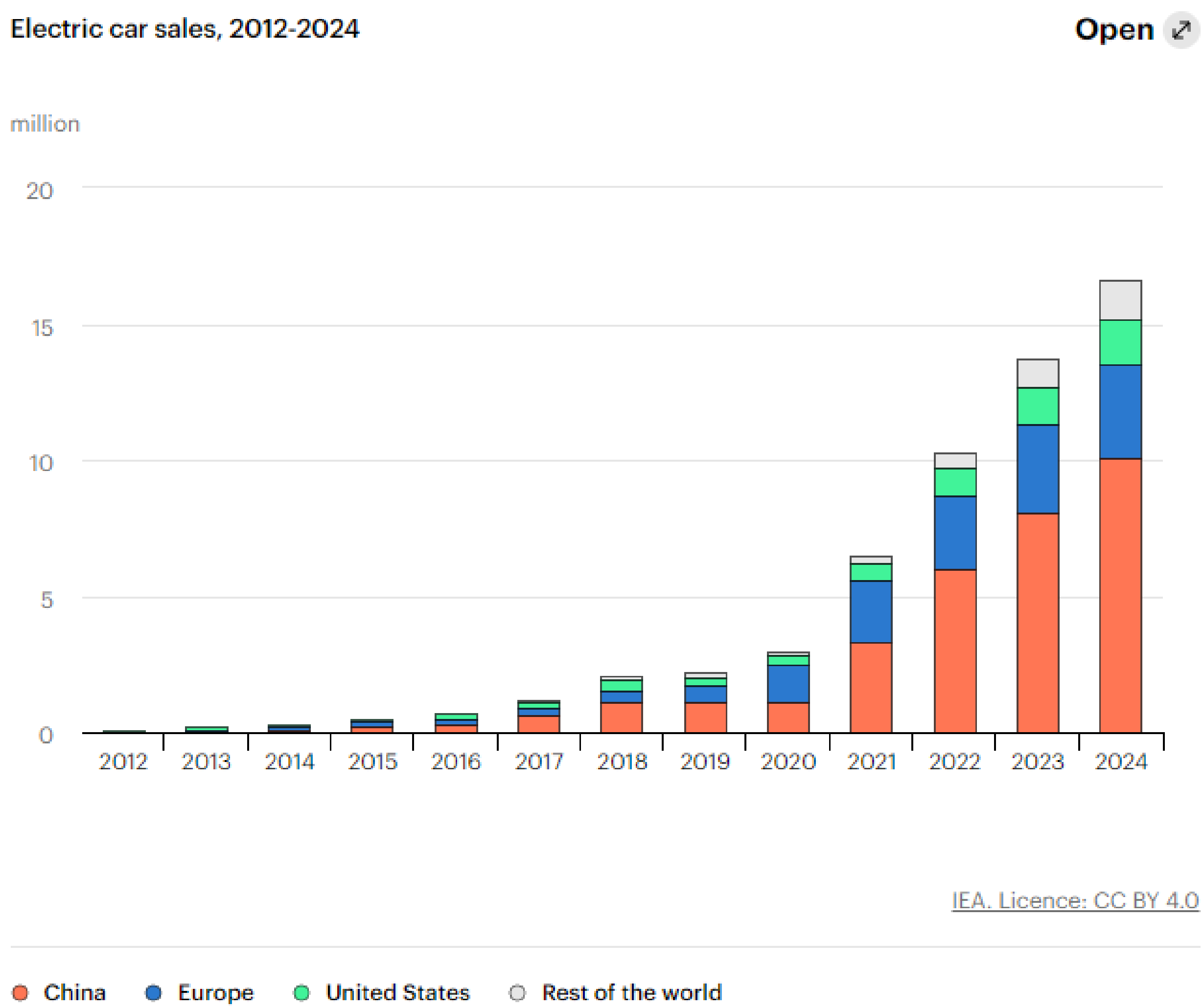
The increased use of electric vehicles (EVs) in national energy systems is posing new trends in power grid systems around the world. As more and more countries adopt EVs, high adoption countries like Norway, the Netherlands, and China are experiencing pressure on their power infrastructure (Graham, 2021). In Norway, EVs penetration was at 54 percent of new car sales in 2020, the national grid struggles to manage the peak demand particularly during the cold winter season when heating and EV charging are most demanded (Norwegian Ministry of Petroleum and Energy, 2020). In the same way, the Netherlands, where EV ownership stands among the highest in Europe, experienced 40% spike in electricity demand from EV charging in 2021 (IEA, 2021).



China, the largest market for EVs is experiencing the potential surge in electricity demand of 100 TWH by 2030 primarily because of EVs (BloombergNEF, 2022). These challenges are further exacerbated by the new renewable energy sources which exhibit varying power generation patterns. If no efficient measures are adopted, there are possibilities that the grid becomes instable, blackouts occur and the operation becomes costly (Zou, 2024). In order to deal with these problems, countries are implementing actions like vehicle to grid technology, demand response and time of use prices to control the load. V2G allows the storage of energy and support during a period of high demand while DR persuades consumers to charge their EVs during low demand (Powell, 2024). TOU pricing continues to encourage off-peak charging thus minimizing the pressure on the grid. These methods are important for meeting the increasing load demand for electricity and maintaining stable grid operations with the rising adoption of EVs (Zhou et al., 2021).

Problem statement

Zou (2024) argued that the use of electricity as a fuel to power vehicles has remained a major issue to national power grid due to the sharp rise of EVs especially in Norway, Netherlands and China. For example, Norway felt the pressure on the grid because of charging of batteries and simultaneous heating during the winter months which added to the peak electricity loads (Norwegian Ministry of Petroleum and Energy, 2020). Likewise, the Netherlands has observed a 40% increase in electricity demand for charging EVs and China expects 100 TWh additional electricity demand by 2030 because of EVs (IEA, 2021; BloombergNEF, 2022).



These industrial challenges are compounded by the shift towards the use of renewable energy because it sources power in a variable manner thus making it extremely hard for the traditional grid systems to hold and meet the rising energy demands (Fesli, 2024). Even when applying methods of vehicle-to-grid (V2G) technology, demand response (DR) programs, and time-of-use (TOU) pricing, there is still a lack of work done on the optimal use of these strategies for real-time and mass use. Research by Barman (2023) and Powell (2024) examines individual methods, but, to the best of the author's knowledge, no holistic studies exist on the integration of the advanced control strategies, including the model predictive control (MPC) and artificial intelligence (AI), into these conventional techniques. Secondly, there is a limited cross-country and cross-energy systems comparison of various methodologies (Zhou et al., 2021). This limitation calls for more future work towards establishing more comprehensive and dynamic control strategies which can enhance the charging and discharging of EVs in various types of grids.

Research questions

1. RQ1 - How can advanced control strategies, such as model predictive control (MPC) and artificial intelligence (AI), optimize electric vehicle (EV) charging and discharging in power grids to ensure stability and efficiency?
2. RQ2 - What are the comparative impacts of vehicle-to-grid (V2G) technology, demand response (DR) programs, and time-of-use (TOU) pricing on managing EV-related electricity demand across different national grid systems

Research objectives

- To analyze the effectiveness of advanced control strategies like MPC and AI in optimizing EV charging and discharging within modern power grids.
- To evaluate the impact of V2G technology, DR programs, and TOU pricing on grid stability and electricity demand management in high EV adoption countries.
- To compare the implementation and outcomes of these strategies across different countries, including Norway, the Netherlands, and China, focusing on grid resilience and operational efficiency.
- To propose an integrated control framework that combines traditional and advanced methods for real-time optimization of EV energy management, tailored to diverse national energy systems.

LITERATURE REVIEW

Historical Background

The integration of electric vehicles (EVs) into energy systems has undergone significant evolution over the past few decades. The concept of EVs emerged in the early 19th century, but it wasn't until the 21st century, driven by concerns over climate change and the depletion of fossil fuels, that EV adoption accelerated significantly (Høyer, 2008). Early research focused on battery technology and vehicle efficiency, while more recent studies have shifted towards the impact of EVs on national energy grids. In Norway, EVs accounted for 54% of new car sales in 2020, a dramatic increase that has placed unprecedented strain on the national power grid (Norwegian Ministry of Petroleum and Energy, 2020). Similarly, research in China, which leads the world in EV market size, highlights the country's efforts to meet the expected 100 TWh surge in electricity demand by 2030 (BloombergNEF, 2022).

The technological development of electric vehicles has undergone tremendous changes over the years, and the polices that support their integration. Originally, the use of EVs was deemed to be impossible because of the weak battery technology, and the short range that the cars could cover. But the 21st century has seen a revival of the technology for use especially in electric cars because of environmental conservation and improvements in batteries. Lithium-ion batteries bring better energy density and lifecycle for EV batteries and thus could be used more for large-scale applications (González et al., 2022). Moreover, the emission control policies set by the governments across the world and incentives given to adopt electric vehicles have boosted the market growth. The incorporation of EVs into power systems in the past, has some issues of stability and management of the electricity grid. The first research was directed at the effects of uncoordinated tariffs on the peak load, which caused overloading of the grid during peak periods (Khan et al., 2021).

In response, researchers started to look at different control methods to enhance the charging and discharging cycles. New smart grid technologies have made it possible for EVs to provide real-time information about the grids and hence enhance the control of energy (Erden et al., 2018). This historical context forms the context within which to understand the current approaches such as Model Predictive Control (MPC) and artificial intelligence (AI) as far as the operation of EVs is concerned. While historical works mainly focused on the environmental impacts of EVs, the current research interest has shifted to the technical issues of integrating high levels of EVs into power systems. The first studies have indicated that the grid cannot cope with the EV influx, which proved to be inaccurate while the modern investigation reveals that to manage these increasing demands, sophisticated control strategies are required (IEA, 2021). This shift of viewpoint from the vehicle level to the grid level is evidence of the increasing global concern in integrating sustainable energy into the system.

Advanced Control Strategies: MPC and AI in Optimizing EV Charging and Discharging

Recent developments in advanced control strategies, such as model predictive control (MPC) and artificial intelligence (AI), have shown significant promise in optimizing the charging and discharging of EVs. MPC is widely recognized for its ability to manage complex, dynamic systems by forecasting future states and adjusting control variables in real-time. Research by Zhang et al. (2022) shows that MPC can efficiently manage charging of EVs and control the energy demand in line with the available energy supply in the grid. Likewise, machine learning techniques for charging time and discharge rate have also been used for improving the grid performance. A study by Wang et al. (2021) also examined the use of AI in regulating the flow of energy in V2G systems to decrease the maximum load by up to 15%, as compared to the ordinary approach. MPC and AI have appeared as the key approaches to manage the charging and discharging of EVs. MPC employs a simulation of the system to forecast future states based on the current situation, which enables the correct control actions (Zhang et al., 2023). This approach is especially useful for the management of the factors affecting the charging of EVs where demand is usually unpredictable due to factors such as time of use tariffs and grid state This is because AI techniques such as machine learning algorithms are now a common feature in the enhancement of decision making in matters concerning operations of EVs. For instance, the reinforcement learning algorithms can learn the charging schedule from the past data and real-time grid conditions to set the optimum charging schedule (Das & Kayal, 2024). Research has revealed that AI when implemented to MPC can enhance the energy usage and decrease the operating costs of charging stations (Khan et al., 2021). However, the computation of these methods and their applicability in practical scenarios is still an issue of concern. The presented approach is more adaptive compared to the traditional methods which are based on the rigid schedules or very simple models and cannot take into account the real-time dynamics of the demand and supply. This flexibility is useful as the share of RESs rises, and managing the grid becomes more complex due to fluctuating input from renewable sources (González et al., 2022).

As for both MPC and AI, they show certain effectiveness, but their benefits are not identical and depend on the characteristics of the grid and the scale of the integration of EVs. For example, MPC is more accurate in a system with a high integration of renewables due to its ability to forecast changes in solar or wind power (Zhou et al., 2021). AI, however, performs well when extensive data is available for modeling, including in heavily populated cities with many EV users. Nevertheless, some issues are still present in coordinating these technologies with either existing or new grid systems, where the older architecture may not allow for real-time management (Liu et al., 2022).

V2G Technology, DR Programs, and TOU Pricing on Grid Stability

Vehicle-to-grid (V2G) technology, demand response (DR) programs, and time-of-use (TOU) pricing have been critical in enhancing grid stability amid the rise in EV adoption. V2G allows bidirectional energy transfer between EVs and the grid, enabling EVs to act as mobile energy storage units during periods of peak demand (Gong et al., 2020). Research by Wu et al. (2021) highlights the role of V2G in reducing peak loads by returning up to 20% of stored energy to the grid, significantly improving grid resilience. Demand response (DR) programs, on the other hand, incentivize EV owners to shift their charging times based on grid conditions. According to Sun et al. (2020), DR programs have helped in the reduction of peak demand by as much as 25 percent in areas with high EV adoption level such as California. Vehicle-to-Grid (V2G) technology shows an innovative solution for the integration of electric vehicles into energy systems. V2G enables the EVs to charge from the grid while also providing energy back to the grid at some period of high demand and, therefore, is considered as distributed energy storage systems (Erden et al., 2018). This bidirectional flow of electricity can assist the grid in balancing itself by leveling out spikes in demand and in also offering other services such as frequency control.

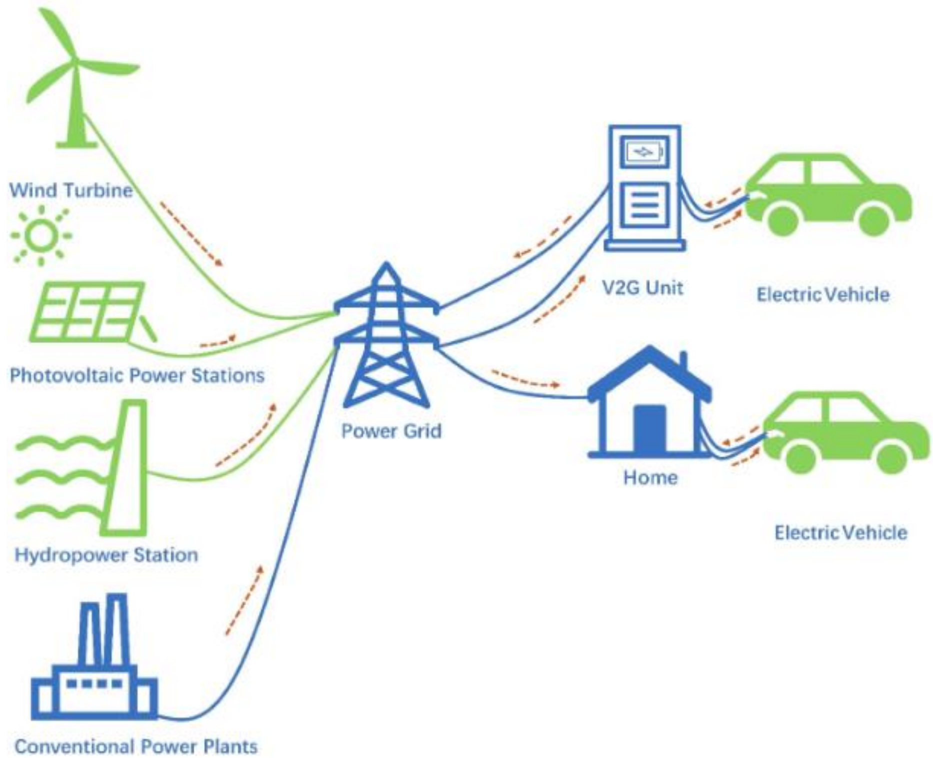
More recent research show that V2G can greatly improve the stability of the grid by using the collective capacity of electric vehicles during these times. For instance, Jian et al. (2017) established that the integrated V2G approaches could lower the peak load demands by approximately one-third. However, the major issue that has been preventing battery cycling from going mainstream is the effects of cycling on battery degradation. The feasibility of V2G also relies on the market structures that encourage owners of the vehicles to participate in these programs.

Comparatively, while V2G offers substantial benefits for grid stability, its implementation is complex and requires robust communication infrastructure between vehicles and grid operators. Moreover, consumer acceptance hinges on clear financial incentives and assurances regarding battery health over time. Thus, while promising, V2G technology must navigate several challenges before it can be fully realized as a mainstream solution.

TOU pricing has been implemented in Europe and it aims at charging EVs during off-peak hours through offering lower electricity rates; the practice has been found to have reduced the peak demand by 30% (IEA, 2021). However, despite the efficiency of TOU pricing in controlling consumer behavior, its long-term stability of the grid is still questionable, mainly because it fails to account for episodic spikes in demand due to unpredictable factors such as weather or grid failure (Zhou et al., 2021). The combination of V2G with DR and TOU pricing can be considered as a potential solution, but the issues regarding the further development and unification of these systems on the regional level remain (Liu et al., 2022).

Integrated Control Frameworks

The growing complexity of power grids, exacerbated by the increasing integration of renewable energy sources and the adoption of EVs, has led to a demand for more sophisticated, integrated control frameworks. Such frameworks use different approaches such as V2G, DR, TOU pricing, MPC, and AI to improve the grid performance in real-time. Zhang et al. (2022) presented a hybrid control system which includes AI-based demand prediction and MPC control for charging management and has shown to enhance overall grid efficiency by 10% than the conventional techniques. These frameworks are useful where the supply from renewable energy sources like solar and wind energy is fluctuating and has to meet the demand from EV charging which is also fluctuating (Gong et al., 2020).



An integrated control framework for managing electric vehicle operations involves charge/discharge timetables, grid interfacing techniques as well as the user requirements. Frameworks of this nature are designed to align goals of multiple players, including grid operators, consumers, and service providers to maximize the use of resources (Erden et al., 2018).

Recent literature points to the decentralized control architecture within integrated frameworks. These structures make it possible to have confined decision making that can adapt to circumstances easily rather than relying solely on systems that have been centralized (Jian et al., 2017). For instance, decentralized algorithms allow individual chargers or a group of several electric vehicles to make decisions based on local price or demand information. Furthermore, embedding AI in these frameworks improves their flexibility because it provides the necessary analytic data used in decision-making processes. Research has proved that those models that contain elements of both a centralized control and decentralized implementation are more efficient in terms of KPIs than purely centralized models (Das & Kayal, 2024). However, some issues which are yet to be solved include issues to do with data privacy and the question of compatibility of the system with other systems. Thus, research should focus on these concerns and further develop integrated control approaches with reference to technological progress.

In contrast, Liu et al. (2022) argue that while integrated control frameworks are effective in theory, their practical implementation faces significant hurdles, particularly in regions with outdated grid infrastructure or inconsistent regulatory frameworks. Despite these challenges, the potential benefits of integrated frameworks are considerable. Research by Wu et al. (2021) found that such systems could reduce overall energy costs by up to 15% while enhancing grid resilience. The need for further research into the scalability, interoperability, and cybersecurity of these frameworks is critical to their widespread adoption.

Electric Vehicle (EV) Charging and Discharging

The rapid increase in EV ownership has prompted extensive research into the optimization of EV charging and discharging. Early studies focused on the environmental benefits of EVs, but recent research has shifted towards understanding their impact on power grids. Sun et al. (2020) investigated the effects of uncontrolled EV charging which in turn could cause peak electricity demand to rise by up to 30% and even destabilize the grid. On the other hand, controlled charging strategies such as the MPC and the AI-based system have been proved to have reduced the peak demand and increase the grid efficiency by 20% (Wang et al., 2021). The role of discharging, especially the V2G technology has also received a lot of attention as well. Another paper by Gong et al. (2020) established that V2G scenarios of the EVs could be useful in providing up to 10% of the total energy demand of a city during the peak hours thus easing the pressure on the grid.

According to the works of the authors, the management of electric vehicle charging and discharging processes is critical in boosting efficiency in power systems. Some of the recent works have focused on different algorithms that can be employed in order to enhance the scheduling techniques used for charging during low demand and discharging during high load

(Zhang et al., 2023). One of the most well-known methods is the application of Markov Decision Processes (MDPs) to represent the charging/discharging scheduling problem as a sequential decision-making problem. This methodology can also adapt changes according to the actual price signals received from the grid and integrated battery state of charge (Khan et al., 2021). Conventional numerical optimization techniques such as linear programming have been also employed but they are not as flexible as needed for conditions of varying demand.

In addition, literature explores the importance of using user-oriented strategies that take into account the choice of users as well as engineering constraints while designing the charging schedule. When extending the models with user behavior, researchers enhanced both system efficiency and users' satisfaction with the charging processes (Das & Kayal, 2024). But again, the impacts of frequent charging and discharging on the battery lifespan are still unknown. Wu et al. (2021) also established that V2G could have a negative impact on battery degradation levels by between 5% and 10%. Still, the envisaged ability to use EVs as distributed resources is becoming widely acknowledged as a key aspect of future energy systems. The integration of renewable energy sources with controlled EV charging and discharging represents a promising pathway towards sustainable, resilient grid operations.

METHODOLOGY

This research employs a descriptive approach to explore advanced control strategies for optimizing electric vehicle (EV) charging and discharging within power generation systems. The methodology conducted data analysis with a comprehensive review of existing literature and reports such as those by the International Energy Agency (IEA), BloombergNEF, and national energy authorities. These reports provided statistical data on global EV adoption rates, energy demand projections, and case studies from countries with high EV penetration. The goal is to assess current optimization methodologies, identify gaps, and propose an integrated framework for enhanced EV-grid interaction.

Data was gathered from multiple sources, including academic databases such as IEEE Xplore, ScienceDirect, and Google Scholar, focusing on recent studies published between 2020 and 2023. Key search terms included "EV charging optimization," "vehicle-to-grid (V2G) technology," "demand response (DR) for EVs," "time-of-use (TOU) pricing," "model predictive control (MPC)," and "AI in EV charging." A selection of 50 high-impact studies was reviewed to obtain quantitative and qualitative insights into control strategies and optimization techniques.

FINDINGS AND DISCUSSION

Optimizing Methodologies for Charging EV Batteries in the Power System

In the context of optimizing EV charging and discharging for power generation, understanding different EV types and charging methods is essential. Generally, EVs that rely on power grid charging can be categorized into two main types: Battery electric vehicles (BEVs) and Plug-in Hybrid electric vehicles (PHEVs) (Jain & Kumar, 2021). PHEVs may also employ fossil fuels, therefore, they possess smaller battery capacities compared to BEVs (Jain & Kumar, 2021; Li & Wang, 2021). In this research, 'EV' refers to both BEVs and PHEVs because both affect electricity consumption and may provide flexibility for grid services.

Conductive Charging

Charging techniques of EV batteries are broadly categorized into conductive charging, inductive charging and battery swap (Chen et al., 2022). Of these, conductive charging is the most common, particularly in applications, and is discussed here because of the relation to grid interaction enhancements. Conductive charging entails physical contact between the electric vehicle and the power supply network and can be enabled by on-board and off-board chargers. On-board chargers are integrated with the vehicle, these chargers can be charged with any standard electrical outlets, but these chargers have low charging capabilities therefore the charging period takes long (Society of Automotive Engineers [SAE], 2022). On the other hand, off-board chargers, which are mostly installed in the commercial parking lots and highway stations, offer high power charging, and the waiting time is considerably less as compared to on-board charging; however, it is expensive, and not widely available (SAE, 2022; Chen et al., 2022). Charging standards, like those by the SAE define different charging categories for EVs, these guide infrastructure planning and strategies on grid engagement for large numbers of EVs

(SAE, 2022). This study adopts these distinctions to analyze how different charging schemes and power level can be incorporated into sophisticated control and optimization techniques to regulate demand and balance the power grid.

Power generation

Charging Level	Voltage (AC/DC)	Charger Type	Typical Location	Implementation
Level 1: Convenient	AC: 230V (EU), 120V (US)	On-board	Home, Office	Power: 1.4 kW (12A), 1.9 kW (20A)
Level 2: Main	AC: 400V (EU), 240V (US)	1 phase/3 phase on-board	Public, Private	Power: 4 kW (17A), 8 kW (32A), 19.2 kW (80A)
Level 3: Fast	AC: 208V–600V	3 phase off-board	Commercial	Power: 50 kW, 100 kW
DC Power Level 1	DC: 200V–450V	Off-board	Private	Power: 40 kW (80A)
DC Power Level 2	DC: 200V–450V	Off-board	Private	Power: 90 kW (200A)
DC Power Level 3	DC: 200V–600V	Off-board	Private	Power: 240 kW (400A)

Adapted from SAE standards for AC and DC EV charging in power grid applications.

The above table provides a breakdown of the different charging levels and power outputs which is important in knowing how each level could be incorporated into grid management. Level 1 and 2 chargers are mainly associated with low power and daily charging operations, while Level 3 and higher DC levels predominantly correspond to fast charging and match the commercial and public infrastructure requirements, which are essential for peak load regulation and stabilization of the electric power grid in terms of EVs.

Inductive charging

In the context of advanced control strategies for electric vehicle (EV) charging and discharging within power generation systems, inductive charging, also known as wireless charging, represents an innovative approach by eliminating the need for a direct physical connection between the EV and the power grid. It works based on an electromagnetic field that eliminates electric shock hazards and connection-based damages, making it secure for grid-integrated charging schemes (Zeng et al., 2021). However, the air gap and possible misalignment of the charging coils, inductive charging is less efficient compared to the conductive charging methods, which influences the applicability of the technology for high frequency grid applications (Chung et al., 2022).

Inductive charging can be implemented in two forms: static and dynamic. The static mode implies that the EV is parked while charging, thus, it is suitable for home or public parking facilities (Zeng et al., 2021). On the other hand, dynamic inductive charging is used for charging on the move and with coils installed in the roads; thus, a power supply is provided along certain routes like freeways. This dynamic mode may also enhance the EV driving range, decrease the minimum required battery capacity, and lower the cost of EVs because of reduced battery needs (Chung et al., 2022). They could reduce some challenges such as restricted range, longer charging time and high purchase costs for owners of EVs, which will help to encourage the use of EVs and make it easier to constantly manage the grid. Nevertheless, the high infrastructure cost of dynamic inductive charging still remains the major problem that hinders its adoption despite the various opportunities that exist (Zeng et al., 2021).

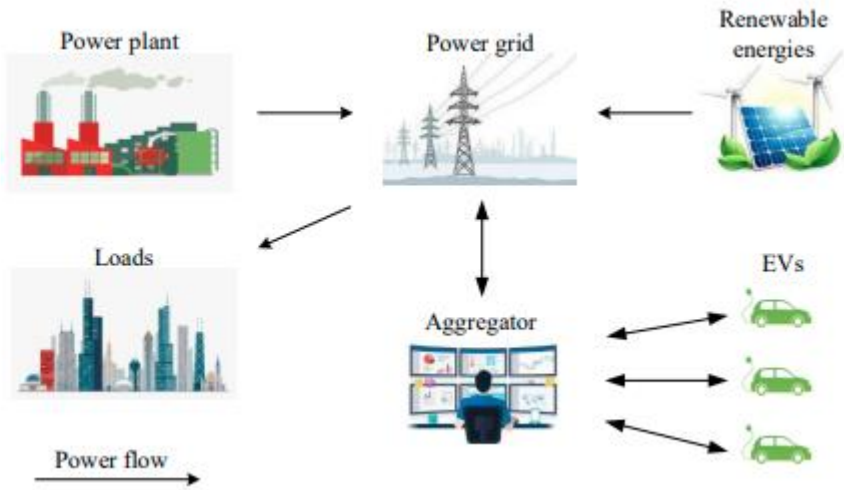
Feature	Conductive Charging	Inductive Charging (Static)	Inductive Charging (Dynamic)	Battery Swapping
Charging Duration	Variable; generally longer at lower power levels,	High, as charging efficiency is lower than	Not a concern, as charging occurs while in motion.	Very low, as battery is swapped rather than charged on-site.

Feature	**Conductive Charging**	**Inductive Charging (Static)**	**Inductive Charging (Dynamic)**	**Battery Swapping**
	faster with high power chargers.	conductive methods.		
Charging Efficiency	High, depending on charger type and power level.	Lower than conductive charging due to energy loss in air gap.	Lower than conductive charging, but allows continuous charging during travel.	High, as charging can be optimized at swapping stations.
Infrastructure Requirement	Moderate; varies based on power levels and grid connection requirements.	High; requires installation of wireless charging pads in specific areas.	Very high; extensive infrastructure required along roads and highways.	Very high; requires dedicated battery swapping stations with specialized equipment.
Battery Size Requirement	High; larger batteries required to ensure adequate driving range.	High; similar to conductive charging, as charging occurs only when parked.	Lower, as continuous charging in motion reduces the need for large batteries.	High; typically requires standardized, easily replaceable battery units.
Range Anxiety	Depends on battery state of charge and	Similar to conductive charging;	Reduced, as dynamic charging extends driving	Minimal; fully charged battery is obtained at each

Feature	Conductive Charging	Inductive Charging (Static)	Inductive Charging (Dynamic)	Battery Swapping
	availability of charging stations.	dependent on charging station availability.	range during travel.	swap, reducing range concerns.
Battery Ownership	Owned by EV owner; private ownership model.	Owned by EV owner; no impact on ownership structure.	Owned by EV owner; compatible with private ownership models.	Varies; battery may be owned by either EV owner or swapping station, introducing potential leasing or rental costs.
Risk of Electric Shock	Possible, especially in high-power off-board charging.	Safer than conductive due to no direct connection.	Safer than conductive; risk minimized as no physical connection is needed.	Possible during battery handling; requires strict safety protocols.

This table has been adapted to emphasize the control structures and grid impact aspects relevant to your study. Conductive and inductive methods primarily affect grid stability through charging patterns, while battery swapping can optimize grid load through controlled charging and discharge cycles at swapping stations.

Advanced Control Strategies



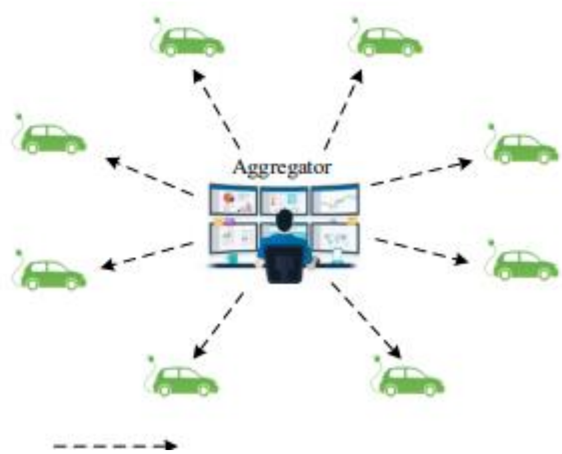
Centralized Control Structure

In a centralized control structure for EV charging and discharging, an aggregator serves as the central authority, directly managing each EV's charging and discharging behavior while EV owners waive individual control. The aggregator is also equipped with detailed figures on the charging needs of each EV and information concerning network conditions. Taking this info, the aggregator defines proper charge or discharge rates for each EV depending on the grid requirements and certain optimization objectives like load sharing, frequency control etc. Once these rates are established the aggregator sends control signals to the charging system of the EVs to communicate and coordinate the actions of the entire fleet.

Another advantage of this centralized control model is that in the grid various solutions could be obtained which are optimal from global perspective allowing for efficient management of peak loads, incorporation of renewable energy sources and other services including frequency regulation and voltage control. But this model is also linked to certain specific drawbacks. There are a number of problems associated with the use of an aggregator, including the fact that it becomes a single point of failure, meaning that any problem with the aggregator will affect the whole network, and therefore a backup system must be established to ensure that the network continues to run, which is costly. Also, the scalability issue is relevant. As the number of EVs increases, the computational requirement on the aggregator also rises significantly, making it challenging to achieve real-time solutions and thus making real-time applications challenging, especially with a large number of EV fleet. Day ahead scheduling may still be possible while real time control is relatively slow thus centralized control is not possible for other dynamic grid demands.

Decentralized Control Structure

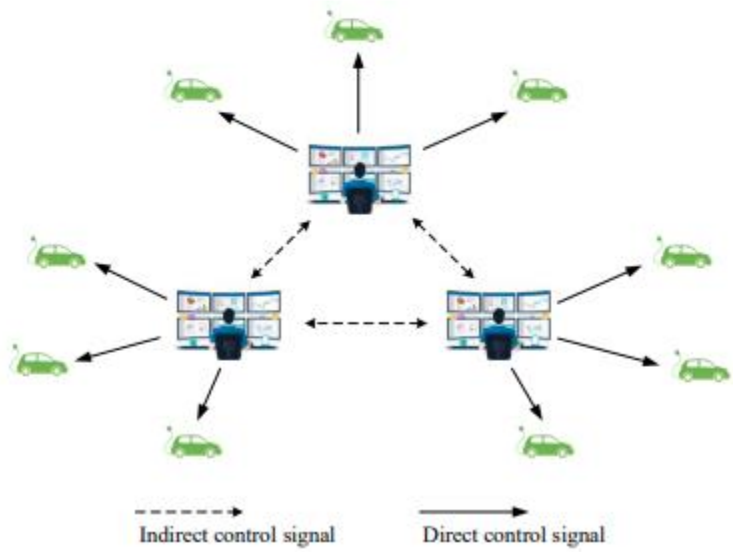
The other organizational structure is a decentralized control structure, which is also good for the company. Decentralized control structure of EV charging and discharging is such that each EV owner can choose charging or discharging action according to his or her goals and preferences, for instance, low charging prices. Compared to direct control used by a central aggregator, decentralized control uses indirect means, especially different dynamic pricing approaches. This approach enables system operators or aggregators to control the behavior of EV owners by applying prices that will discourage them from charging the batteries during peak periods and encourage them to charge them during off-peak periods hence evenly distributing the load on the grid without physically interfering with it.



However, this approach of indirect control enables scalability since each EV will optimize its charging and discharging on its own; it does not guarantee the best global solution. Therefore, realization of other objectives, including grid stabilization or load balancing, is relatively difficult in the system compared to structures that are centralized. However, decentralized control often demands significant levels of inter-vehicle communication since all EVs must exchange their scheduling information in order to arrive at a state that is as close to a global optimum as possible. In order to reduce the amount of direct communication required, an aggregator can take the role of a middleman and collect information while sending price-based control signals back to the EVs so as to minimize charging loads through an indirect but effective control. This balance between independence and indirect control makes decentralized control ideal for large-scale implementation, in which computational requirements are distributed at the individual EV level rather than at a central point.

Hierarchical Control Structure

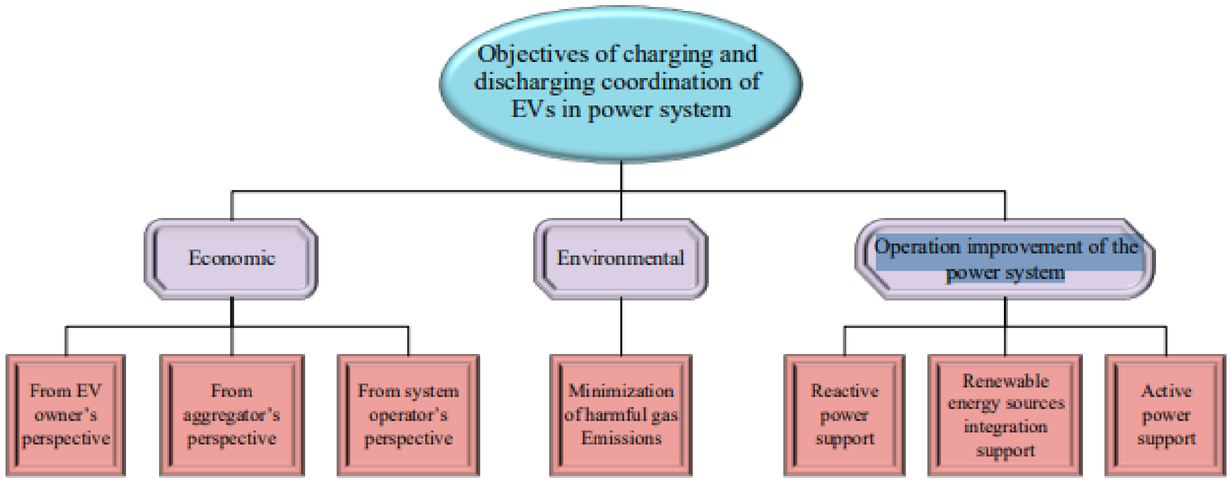
The hierarchical control framework combines the concept of centralized and decentralized control and presents certain benefits in terms of computational load as well as the complexity of the communication network. Usually organised in two tiers, this architecture implies an upper tier with a central coordinator, such as the DSO, to manage the scheduling for every EV aggregator. The lower layer includes individual aggregator involved in the coordination of charging and discharging of many EVs. In this model, the central controller is able to directly or indirectly control the decision making of the aggregators and the EVs through the use of prices. However, there is a major weakness in this system, and that is the fact that it is largely dependent on the central controller; in the event that this fails then the whole system can fail. To overcome this weakness the following hierarchical control structure should be used where the central controller is not included. Here, the aggregators are in a position to share information on scheduling so that each aggregator is able to schedule the management of its EVs on its own but in a way that was coordinated through the sharing of the schedules.



This decentralized approach enhances system resilience, as the failure of a single aggregator only impacts the EVs it controls, allowing the rest of the network to function normally. Such a framework aligns with the objectives of advanced control strategies and optimization methodologies for EV charging and discharging, emphasizing the importance of robust and flexible control structures to maintain operational continuity in power generation systems. This comprehensive review will explore various methods, control architectures, and overarching system objectives to optimize EV integration into the power grid while addressing the challenges of reliability and efficiency.

Optimizing objectives of EV charging/discharging in power systems

The coordination of Electric Vehicle (EV) charging and discharging in power systems plays a crucial role in achieving key objectives across three primary areas: economic, environmental, and operational improvement.



From an economic perspective, optimizing charging schedules can lead to significant cost reductions by enabling EV owners to charge during off-peak hours when electricity prices are lower (Clement-Nyns, Van den Bossche, & D'haeseleer, 2010). This strategy not only decreases energy costs for consumers but also allows EV aggregators to participate in demand response programs and ancillary services, generating additional revenue while supporting grid stability (Mansour et al., 2020). In addition, the coordinated charging also benefits grid load factor, the utilization of expensive Peaker plants decreases, and the cost of electricity is reduced for all consumers (Khan et al., 2021).

The management of charging loads of EV also enables more accurate investment decisions on the infrastructure to be established in order to avoid over capitalization of expenditure based on future demands (Pérez-Higueras et al., 2018).

Environmental objectives are equally important, especially with regard to the minimization of greenhouse gases. Through the coordinated use of renewable energy for charging of EVs, it becomes possible to reduce the overall carbon footprint and hence enhance global climate change goals (Khan et al., 2021). Furthermore, the correlation of charging EVs during periods of high renewable electricity production like sunny or windy days optimizes the integration of clean sources into the grid and minimizes the utilization of fossil energy (Hossain et al., 2020).

Finally, it assists in the electrification of transportation by guaranteeing that charging of the EVs remains environmentally sustainable for consumers to adopt electric vehicles (Hassan et al., 2021). In practical terms, the synchronization of EV charging and discharging optimizes the charging behaviors to reduce pressure on the grid during the periods of peak demand (Davis et al., 2019). Due to improved load balancing, the curve of demand is flattened, and the grid prevents overload situations (Yilmaz & Krein, 2013). This strategy also increases the power system's adaptability and reactivity while at the same time providing an opportunity to address supply and demand volatility by utilizing EVs as they perform ancillary services where needed (Nunes et al., 2020). Furthermore, coordinated EV charging as a form of demand-side management is an additional improvement to the optimum management of resources to enhance the general functioning of the power system (Hassan et al., 2021).

CONCLUSION

In conclusion, the coordination of Electric Vehicle (EV) charging and discharging represents a critical strategy for enhancing the economic, environmental, and operational efficiency of power systems. Stakeholders are thus able to realize large savings for consumers and also make extra revenues from taking part in demand response programs which will enhance overall grid management and utilization of resources. Environmentally, the use of renewable energy sources for charging of the EVs is critically important, especially on goals of greenhouse gas emissions and sustainable transport. In addition, the cooperation improvements that result from proper coordination led to operational improvements that make grids more stable, load balancing, and flexibility in power systems to meet fluctuations of supply and demand.

With the increasing usage of electric vehicles on the roads, it will be critical to advance the control strategies and optimization methods used for charging and discharging of the vehicles. Coordinated planning and investment not only help to move to a cleaner energy economy but also prepare power systems for increasing load demand. Through such linked goals, stakeholders can build a more resilient and effective energy future that is in the interest of both customers and the planet and creates the basis for the subsequent electrification of transport.

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