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Revolutionizing Green Transport: An Extensive Review of Hybrid Electric Vehicle Charging Stations and Electric Microgrid Integration

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ABSTRACT:

Electric vehicles (EVs), recognized as a strategic approach to reducing oil consumption and greenhouse gas emissions, rely on electricity instead of traditional fuels like petrol or diesel for battery charging, positioning them as a significant player in future energy landscapes. The anticipated decline in oil demand aligns with the increasing prevalence of EVs, making attention to charging infrastructure crucial. This paper extensively explores charging infrastructure considerations, emphasizing their significance in both urban and rural contexts, especially in regions with unstable or absent power supplies. Examining off-grid, grid-connected, and hybrid charging modes, the research delves into various EV designs, including those utilizing fuel cells or batteries.

A thorough understanding of energy-source-based charging techniques and diverse power-level charging stations is presented, catering to readers' interests. With a focus on enhancing the longevity and efficiency of electric vehicles, researchers are investigating innovative charging methods, including microgrid concepts within charging stations. Recognizing electric vehicles as multi-energy systems, the paper underscores the importance of effective power management and control for optimal energy utilization.

Additionally, the review scrutinizes the impact of electric vehicles on utility grid infrastructure & maintenance, evaluating various power management and control systems. This comprehensive review serves as a valuable resource for electric vehicle operators and research engineers, offering insights into the current state of the field and potential avenues for future exploration.

Keywords: Photovoltaic fuel Electric vehicle Charging, Solar energy, Ev traffic pattern, Solar radiance, EVCS, Micro grid.

1. INTRODUCTION

The inexorable requirement for electric energy has become indispensable for contemporary human existence. With the global population steadily increasing, the demand for energy and need for grid infrastructure resilience rises in tandem. Traditional sources shoulder the responsibility of meeting the electricity demand, but their use raises environmental concerns. The surge in electric vehicle (EV) popularity is notable, driven by the decline in fossil fuel use and subsequent urban air pollution increase. Notably, coal and fossil fuels dominate China's top energy users, constituting up to 80% of the country's electricity.

Renewable energy sources are dynamically employed to expand capacity, addressing the rising demands on the grid [2-3]. The establishment of microgrids emerges as a solution, providing a robust infrastructure for EV charging, discharging, and renewable energy generation [4-5].

1.1 GENESIS

The essentiality of electric energy for human survival is undeniable [1]. The escalating global population intensifies energy demands, predominantly met by dwindling conventional sources, posing environmental challenges [1]. This era witnesses the proliferation of smart cities and rapid urbanization, contributing to the popularity of conventional automobiles, major contributors to greenhouse gas (GHG) emissions. A discernible upward trend in CO_2 levels, particularly in the transportation sector, underscores the urgency for sustainable solutions [2]. The rise in air pollution, a consequence of urbanization and increased vehicular traffic, necessitates urgent efforts to introduce alternative fuel-based

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distributed generation (DG) and transportation systems. Microgrid-based charging stations emerge as a focal point of attention, addressing the need for sustainable urban transportation [3].

Further, As the electric vehicle market expands, there is a forecast that electric vehicle (EV) companies will transform into virtual power stations and energy storage systems. The advancement of artificial intelligence (AI) has enhanced the feasibility of this transformation, enabling smart charging and discharging during off-peak times. This not only provides the grid with increased flexibility and stability in terms of energy storage but also leads to reduced charging costs for EV owners, particularly when coupled with variable rates on their electricity bills for off-peak charging.

The growing prevalence of AI systems creates opportunities for emerging energy startups aiming to establish a presence in the market. Both competitive startups and established utilities are capitalizing on AI technologies to better meet customer needs. AI is applied for load requirement and generation capability forecasting, as well as for grid optimization and network planning. These applications play a crucial role in preventing outages, cost savings, and enhancing operational efficiency.

1.2 MOTIVATION

Historically, power flow was unidirectional, primarily from power plants to consumers. However, the integration of distributed energy sources (DESs), including renewable energy sources (RESs) and electric vehicles (EVs), has led to a bidirectional power flow, deviating from centralized generation. Consumers, armed with information and choices, play a pivotal role in the evolving electric power industry, impacting their behavior and power consumption patterns. The sector experiences a paradigm shift from government-dominated to a more transparent, responsible, and competitive environment.

The unit cost of energy generated by EVs surpasses that of centralized generators due to inherent technological features, posing challenges for large-scale electricity provision. Vehicle-to-Grid (V2G) technology becomes crucial in ancillary service markets, offering advantages in capacity and energy payment scenarios. The rising interest in electric vehicle technology brings both opportunities and challenges. Addressing electric vehicle range anxiety (EVRA), energy infrastructure constraints, charging delays, and station scarcity requires thoughtful consideration [3].

In this context, battery swapping stations (BSSs) emerge as a potential solution, offering rapid charging capabilities and addressing EVRA concerns. Battery swapping provides a straightforward procedure, enabling drivers to quickly resume their journey after a swift battery exchange.

1.3 Microgrid: Overview

It is more apt to describe a "microgrid" as a smaller, more efficient, and intelligent grid. Several national and international organizations, energy centers, and institutions, including the IEEE and the International Energy Agency (IEA), have specified the concept of microgrids. According to the US Department of Energy, a microgrid is "a cluster of electrical loads, distributed energy generation units, with some electrical boundaries and behaves as one single controllable entity and capable of being used in islanded as well as grid-connected mode" [8].

Two primary types of load systems exist in microgrids: fixed and flexible (adjustable). The permanently installed component of the load's system must function seamlessly under normal conditions, while the flexible load component must respond promptly to monitoring signals. Economic incentives or operational necessities may lead to adjustments in flexible loads, also known as shiftable loads [9]. Distributed energy producing units, comprising energy storage systems (ESSs) and distributed generators (DGs), form the foundation of microgrids. These units can be installed either at the user's site or in the electrical utility system. Microgrids are currently integrating various dispatchable distributed generation (DG) technologies, such as fuel cells (FC), gas turbines, micro-turbines, and reciprocating engines, to meet energy demands efficiently and reliably while addressing environmental concerns [10].

One significant challenge with conventional and dispatchable distributed generators (DGs) lies in greenhouse gas (GHG) emissions and fuel quantity restrictions. Consequently, there is a push towards renewable and non-dispatchable DG systems [10]. The master controller in a microgrid oversees dispatchable resource components, while non-dispatchable resource components remain unchanged. Renewable energy sources (RES), such as solar photovoltaic (PV) systems and wind energy producing units, fall under non-dispatchable generation systems due to their intermittent and variable nature. The intermittent nature of non-dispatchable production, coupled

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with power output fluctuations, necessitates energy storage devices [11].

1.4 Distributed Energy Source (DES) Technologies for Microgrids

Distributed energy sources (DESs), also known as micro-generating sources, can be located in both the central grid and nearby consumer sites. Integrating distributed energy systems (DESs), particularly renewable DGs like solar and wind power, and energy storage systems (ESSs), yields substantial economic and reliability benefits. Renewable energy generating units have gained attention due to their eco-friendly nature and minimal pollution [12].

Integrating renewable distributed generation (DG) poses a challenge as the output power relies on changing meteorological parameters. Solar power emerges as a promising option for sustainable energy, producing no hazardous emissions. Power electronic converters play a crucial role in transforming solar energy into usable forms, finding application in connecting DGs to power grids [9].

In urban and suburban areas, power outages are common, and solar power, along with other renewable energy sources, presents a solution. The cost of solar modules has steadily decreased, making solar power plants more prevalent worldwide. Power supply instability remains a concern with power systems extensively utilizing renewable energy sources [13].

1.5 Energy Management in Microgrids

Power management, essential for minimizing negative environmental impacts and maximizing economic optimization, ensures a seamless transmission of electrical energy to associated loads. Research explores grid-connected inverters for power management applications, employing multiple buses in microgrids [27]. An energy management system is crucial, and various models, methodologies, and optimization approaches are developed globally to improve power pricing, devise auction strategies, and integrate renewable energy sources into power trading markets.

Eliminating energy waste is the primary goal of smart home grid-based energy management systems. These systems utilize smart plug technology to record incoming energy and load variation, enhancing overall efficiency [36]. A proposed intelligent and cost-effective microgrid includes a distributed energy resource management system and a dynamic disaster recovery system, based on intelligent hierarchical agents. Coordination of micro combined heat and power systems (μCHPs) and vanadium redox batteries is essential for distributed energy resource management, contributing to the integration of non-dispatchable generating units [37].

The profitability of microgrids lies in the proximity of generation to load, competing with conventional generating units while reducing transportation and distribution expenses. Energy supplies, switching, protection, transformers, communication, control, site engineering, and construction contributions are analyzed in a cost breakdown [34]. Microgrid scheduling is explored through scheduling methods and architectures, incorporating energy management systems (EMS) designs for microgrids with centralized and distributed models. The development of new models and methodologies globally aims to improve power pricing, create auction strategies, and integrate renewable energy sources into the power trading market [13].

1.6 Charging Systems for xEVs

Charging systems for electric vehicles (xEVs) can be broadly classified into two types: conductive and inductive. Inductive charging systems are still in early development stages and have not yet gained widespread adoption in the electric vehicle industry. In contrast, conductive charging systems, which transfer power directly from the battery to the vehicle through physical contact, have been in use for a longer period and are more commonly employed.

Conductive charging, known for its efficiency and cost-effectiveness, can be categorized into on-board charging and off-board charging. On-board charging is often used for low-current charging processes, keeping the charging within the vehicle. In contrast, the off-board approach facilitates quick charging by allowing the charger to be moved to a different location. Electric vehicles such as the Chevrolet Volt, Nissan Leaf, and Tesla Roadster utilize conductive charging methods [9].

Inductive charging, also referred to as wireless charging, utilizes an electromagnetic field to transfer electricity to the vehicle without physically connecting it to the power source. While inductive charging is safer for electrical devices, it comes with downsides such as lower efficiency and higher power loss [1]. Wireless charging introduces three types: static charging, dynamic charging, and quasi-always charging. Static charging eliminates the risk of electric shock and is suitable for settings like residential garages and parking lots. Dynamic charging, using designated charging tracks, keeps the vehicle fully charged while on the road, potentially reducing the size of the vehicle's battery. Quasi-dynamic wireless charging occurs during short stops, enhancing the vehicle's range and reducing required energy storage. A highly efficient wireless charging method capable of 7.2 kW power at 230V AC has been developed [7].

Various groups, including SAE, IEEE, and the Infrastructure Working Council, work on creating guidelines and standards for the connection between utilities and consumers [11]. Charging requirements for electric vehicles are categorized into four modes by the International Electrotechnical Commission (IEC), with DC Fast Charging (DCFC) falling under Mode 4. SAE further divides electric vehicle charging into levels, with quick charging falling under "Level-3 DC," requiring a power supply of 90 to 240 kW [6]. The CHAdeMO standard from Japan is gaining global prominence for fast charging of electric vehicles.

1.7 Grid-Integrated Charging Stations for Electric Vehicles

Mass production of electric vehicles (EVs) has minimal impact on energy generation requirements. Even if EVs constitute 50% of all vehicles in the US by 2050, the additional eight percent of power generation and four percent of generating capacity will be more than sufficient. However, charging EVs during off-peak hours increases the demand curve for electric utilities, necessitating optimization of various EVs with different charging configurations and technologies.

A smart grid application framework is essential to enhance Grid-to-Vehicle (G2V) and Vehicle-to-Grid (V2G) management in light of widespread EV use. An aggregator of EVs could mediate between individual EVs and independent system operators (ISOs), providing operational flexibility to power markets. However, managing V2G networks presents challenges due to the unpredictable actions of individual customers and fluctuating electricity market prices. Integrating EVs into power networks has been extensively researched, leading to the development of smart charging algorithms that can prevent renewable energy curtailments, network congestion, and excessive energy losses.

Several challenges arise during the grid integration of EV charging stations, including high power consumption impacting power supply, delays in power delivery, increased distribution losses, voltage fluctuations, and potential reduction in transformer lifetime due to overloading. Charging stations, regardless of the number of slots, require megawatt-level capacity, necessitating compliance with specific requirements for operational connectivity to the grid [5, 6].

2. REVIEW OF WORKS

During peak hours, the charging of electric vehicles (EVs) contributes to an increased load curve for electric utilities. Effectively managing a large number of EVs requires optimization for various charging setups and equipment [8]. An additional benefit to the microgrid/grid is the implementation of demand response (DR), challenging the demand for EV charging during peak hours. In a preserved setting, EVs can generate or store electricity, enabling the return of power to the grid through Vehicle-to-Grid (V2G) connections. V2G is crucial as there is a global shift towards emerging green and sustainable energy sources. The investment cost of vehicle power systems is significantly lower than that of central power generation. The lower investment costs and minimal incremental expenses to convert EVs into grid power contribute to economic feasibility [5].

While EVs may not generate massive power due to the higher unit cost of energy compared to centralized generators, V2G becomes relevant in additional support markets such as turning reserves and regulation. This is particularly true when there is a capacity payment for being online and available, coupled with an extra energy payment during actual power dispatch. However, in top power markets, V2G's contribution is contingent on receiving compensation solely for energy, especially when power tariffs are unusually high [6]. The rollout of EV technologies has become a focal point of revolution in the EV industry, with stakeholders needing to consider both the upsides and downsides before investing in electric vehicle rollouts [7].

Challenges may arise from factors such as the scarcity of recharging places, threats to the underlying energy grid, prolonged recharging delays, and, most importantly, electric vehicle range anxiety (EVRA) experienced by a significant portion of EV users [3]. Various national and international organizations, energy centers, and institutions, including IEC and IEEE, have defined microgrids within specific constraints. The United States (US) Department of Energy defines a microgrid as a cluster of electrical loads and distributed energy generation units, functioning as a single controllable entity usable in both islanded and grid-connected modes. CIGRÉ describes microgrids as power distribution systems containing loads and distributed energy sources, controllable in a coordinated manner, either connected to the main power network or as an independent entity [8].

The load system in microgrids is divided into fixed and adjustable parts. Fixed loads must operate efficiently and cannot be repaired, while adjustable loads respond to monitoring signals and can be curtailed or delayed based on economic incentives or operational needs [9]. Distributed energy generation units comprise distributed generators (DGs) and energy storage systems (ESSs) that can be installed at electrical utility system sites or electricity user sites. Microgrid DGs are classified into dispatchable and nondispatchable types. Currently, various dispatchable DG systems, such as reciprocating engines, gas turbines, micro-turbines, and fuel cells, are integrated into microgrids to meet energy demand efficiently while considering environmental aspects [10].

Dispatchable resource components in microgrids are controlled by a master controller, whereas non-dispatchable components have uncontrollable inputs. Renewable energy sources (RESs), like solar photovoltaic (PV) systems and wind energy units, fall under the category of non-dispatchable generation systems due to their intermittent and volatile nature. The intermittent nature refers to the unavailability of continuous electrical energy generation, while the volatile nature signifies fluctuations in power output across different time scales. The characteristics of non-dispatchable energy-generating units introduce high forecasting errors, necessitating the use of energy storage devices [11]. Primary ESSs serve as coordinating devices to ensure a continuous power output from microgrids. During periods of high market prices, energy storage systems can be used for arbitrage by feeding back stored electrical energy to the microgrid. Standalone microgrids benefit significantly from the effective utilization of energy storage systems [12].

In [13], the significant benefits of microgrids are highlighted, emphasizing the proximity of generation to load to reduce losses and transmission and distribution expenses. A cost analysis reveals that energy resources account for 30-40%, switching, protection, and transformers for 20%, communication and control for 10-20%, and site engineer and construction contributions for approximately 30%. [14] presents energy management services demonstrated through energy grid technology, using a smart plug for home energy grid systems. The study introduces an ecosystem for smart homes with distributed energy sources, aiming for high-quality energy service with low consumption costs. The microgrid operates in grid-connected mode, with Java chosen for implementation and 10 houses considered for configuration [15]. Demand response is extensively used in residential areas, where electric vehicles can act as storage units through the options of vehicle-to-grid and vehicle-to-home. [16] discusses energy storage systems in the context of demand response. In [17], a framework for demand response is considered with minimal costs, modeling constraints for appliances and cost functions for users. An algorithm is designed that only requires the price of electricity, focusing on programmed demand response for smart grid appliances.

[19] introduces an optimization technique for determining the optimal bidding method of hybrid power station manufacturers, including wind farms and hydro storage. [20] presents a fixed bid auction scheme focusing on multi-trait security issues, utilizing the Pedersen commitment scheme to ensure bid information remains confidential. [21] explains a look-ahead bidding technique for energy storage, determining vendor bids using energy storage for continuous profit over two days. [22] describes a model for different demand-side resources, proposing a risk-averse optimal bidding method efficient for minimizing day-ahead electricity costs. [23] discusses a stochastic model used to find the optimal bidding scenario for wind power. [24] presents a game theory reverse auction model based on a multi-agent algorithm for microgrid trading operations containing both conventional and renewable energy sources (RESs) in grid-connected mode. [25] proposes a framework for evaluating demand response through strategies using Sequential Monte Carlo simulations, considering uncertainty and flexibility for short-term and long-term decisions. [26] introduces a real-time market for ramp capacity to explore and evaluate the need for generator flexibility due to the integration of RESs.

3. RESEARCH GAPS IDENTIFIED

Historically, the concept of power flow was predominantly aligned with electrical energy being generated at centralized power stations and then transmitted to consumers. Power plants were designed to produce the required electrical power based on overall load requirements. However, due to the increasing integration of distributed energy sources (DESs), particularly renewable energy sources (RESs) and electric vehicles (EVs), power flow has become directional. Generation is no longer centralized, and consumers actively participate in electric power interaction, influenced by information, choices, incentives, and disincentives that shape their power purchasing patterns and behavior. These decisions pave the way for the emergence of new technologies and markets. The government-driven energy sector is experiencing significant private investment, enhancing competitiveness, accountability, and responsibility [27-30].

Renewable energy is seen to alleviate the dependence on fossil fuels and protect the environment. Microgrids offer a practical avenue for renewable energy and electric vehicles to seamlessly access the grid. For instance, in the USA, having EVs constitute half of the total vehicles in use by 2050 would result in only an 8% increase in power generation and a 4% increase in generation capacity. This shift would substantially reduce emissions from conventional vehicles and decrease fuel consumption in the transportation sector [31]. Therefore, the integration of a large number of EVs must be carefully optimized for various charging setups and technologies [33, 34]. Demand response adds another layer of benefit to the microgrid/system by disrupting the charging of electric vehicles during peak hours. In a parked scenario, EVs can generate or store power, known as V2G power [35-38]. EV batteries connected to the charging system can act as distributed energy storage systems (ESSs) for the electrical grid, providing benefits such as grid stabilization, security, and resilience. The widespread integration of intermittent energy sources, such as wind and solar, is facilitated by the V2G system, making it a crucial enabler for the global transition to a green and sustainable energy economy. Compared to centralized power generation, the relatively lower investment costs of vehicle power systems and the small incremental cost to convert EVs into grid power imply economic feasibility [39-42]. However, V2G participation in top power markets is contingent on compensation solely for energy and is only viable when power tariffs are exceptionally high [43-46]. Charging loads connected directly to 380VDC and supplied by PV can reduce conversions, losses, and save energy. The increasing trend of urban and smart cities adopting electric vehicles as part of their transportation system is contributing to the high greenhouse gas (GHG) emissions. To mitigate the detrimental impact of GHG emissions, electric vehicles (xEVs) in smart cities are gaining significant attention [47-49]. However, the unscheduled connectivity of EVs with the traditional grid system poses challenges, leading to unreliable and interrupted power supply that may result in grid failure.

4. SIGNIFICANCE AND SCOPE OF THE DESIGN

Electric vehicles are equipped with both DC and AC charging capabilities, where DC represents fast charging, and AC represents slow charging [50]. In microgrids where the amount of DC fast charge is high, and AC loads are minimal, the microgrid experiences high harmonic currents due to numerous AC and DC conversions. This elevated harmonic content increases power usage, reduces system stability, and affects the overall wealth of the microgrid system. Consequently, the conventional hybrid AC/DC microgrid, which relies on an AC microgrid as the primary component, is not suitable for such scenarios. A hybrid microgrid-powered charging station reduces transmission losses, enhances power flow control, and improves the overall efficiency of the modern power system.

5. CONCLUSION

A stochastic model is developed for EV traffic profiles, appearances, and resource utilization patterns. It encompasses EV parking garage occupancy, EVs in a system, and resource usage in the microgrid (MG) area. Additionally, a techno-economic analysis of PV-powered EV charging stations in a microgrid under various solar light conditions in India is comprehensively discussed, and an optimal system is determined using the HOMER software. The results indicate that with higher solar illumination, the cost of NPC and COE decreases, leading to improved project efficiency for PV-powered EVCS. The ratio of PV power to grid power in the total generated power for the EVCS remains unchanged for both scenarios, emphasizing the 100 kW PV system capacity as the optimal solution. As the feed-in tariff (FIT) cost decreases, the COE of both cities slightly increases, making Kashmir a viable center for solar-powered EVCS investment due to its high solar illumination in both scenarios.

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