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Analyzing the Impact of Electric Vehicle Charging On Grid Congestion and Load Management- A Review

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Abstract – *This review paper explores the increasing adoption of electric vehicles (EVs), it is imperative to comprehend their influence on the power grid for efficient load management and grid stability. This pepar employs a comprehensive approach to examine the ramifications of EV charging on grid congestion. Utilizing real-world data from charging stations, grid operations, and EV usage patterns, we model and simulate the charging behavior of a diverse fleet of electric vehicles.*

The review Our findings reveal distinct patterns of grid congestion during peak charging periods and identify potential challenges in load management. We explore the implications of different charging strategies, such as smart charging and time-of-use pricing, in mitigating grid congestion. Additionally, we assess the role of energy storage systems in optimizing load distribution and enhancing grid resilience.

The growing body of knowledge on sustainable transportation and provides a foundation for stakeholders; this enables policymakers and utilities to make well-informed decisions in response to the growing adoption of electric vehicles.

Keywords: **Electric Vehicles, Grid Congestion, Load Management, Impact Of Electric Vehicle Charging On Grid Congestion And Load Management**

I. Introduction

The widespread adoption of electric vehicles (EVs) is ushering in a transformative era in the automotive industry, promising reduced greenhouse gas emissions and a shift towards sustainable transportation. However, as the number of EVs on the roads continues to rise, it brings forth new challenges, particularly in the realm of energy infrastructure. One of the key concerns is the impact of electric vehicle charging on grid congestion and the necessity for effective load management strategies.

This paper provides the conventional power grid was designed to handle predictable and centralized energy consumption patterns. The integration of large numbers of EVs introduces a dynamic element, as their charging patterns are often influenced by individual preferences and real-time factors. This has the potential to strain local grids, leading to congestion during peak charging times.

Comprehensively examine the multifaceted impact of electric vehicle charging on grid congestion and explore innovative strategies for effective load management. By understanding the intricate relationship between EV charging behavior and grid dynamics, we can develop solutions that optimize energy distribution, ensure grid reliability, and minimize the need for costly infrastructure upgrades.

A. Electric Vehicles

The imperative to reduce CO2 emissions from the transportation sector has driven a significant increase in the adoption of electric vehicles (EVs). Presently, the global market is witnessing a substantial surge in the sales of plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs). In Sweden, the growth of PHEVs has outpaced that of BEVs. Between 2018 and 2021, the number of PHEVs increased from 36,000 to 146,000, while BEVs increased from 12,000 to 80,000 [7]. Globally, BEVs have experienced greater growth compared to PHEVs. According to the International Energy Agency (IEA) 2021 Outlook, there was a 14.54% rise in BEVs and a 1.41% increase in PHEVs in 2020 compared to 2019. As per stated policy scenarios, it is anticipated that EVs (excluding two/three-wheelers) will constitute 7% of the on-road vehicle fleet globally by 2030 [8].

The escalating number of EVs results in increased demand on the current power transmission network, as all BEVs require recharging. Uncontrolled charging can lead to high load peaks and grid congestion, especially since most BEV owners have similar driving patterns [9]. This simultaneous charging behavior contributes to elevated peak loads. Several articles have proposed solutions to address this issue [9]–[12]. The most commonly suggested solution is the implementation of a smart charging algorithm aimed at minimizing load variation, encompassing peak shaving and valley filling. These smart charging algorithms often leverage the flexibility of BEVs, allowing them to shift their charging times without compromising daily driving needs [9][13]

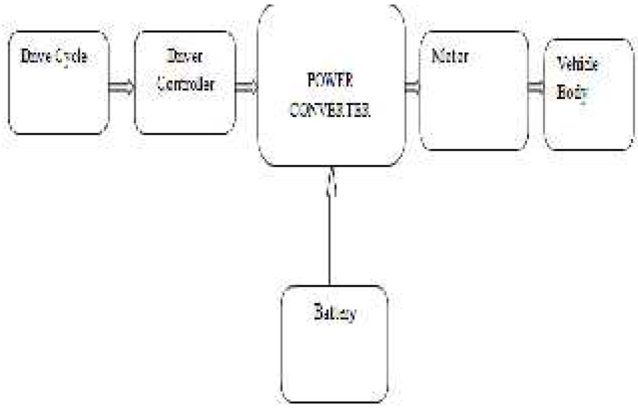

Fig 1 Electric Vehicles [27].

II. LITERATURE REVIEW

Junze YU et. al. (2024) - As the shift from traditional fuel vehicles to new energy vehicles gains momentum, the strategic layout and planning of charging infrastructure become increasingly crucial to meet the rising demand for charging new energy vehicles in urban areas. Utilizing real order data from charging platforms, this study proposes charging facility evaluation indices based on charging behaviors. It conducts a cluster analysis of electric cab charging behaviors, aiming to explore dependency relationships among these charging characteristics [01].

Madhav Kumar et. al. (2023) - Electric vehicles (EVs) are widely recognized for their high efficiency in reducing gas emissions and decreasing dependence on oil for transportation. Instead of traditional fuels like gasoline or diesel, EVs predominantly rely on electricity as their primary energy source for battery recharging. The anticipated surge in EV adoption is expected to contribute to a decline in future oil demand. Recent research in EV technology has particularly focused on the robust development of charging infrastructure.The article delves into intricate details of energy-source-based charging systems and the utilization of charging stations at different power levels. To enhance the longevity and efficiency of EVs, the study thoroughly investigates charging methods and stations integrated with microgrid architectures. Recognizing EVs as multi-energy systems, effective power management and control are imperative for optimizing energy utilization. The review also provides an assessment of several power management and control strategies, along with an analysis of the impact of EVs on the utility grid [02].

Jin Yi Yong et. al. (2023) - The widespread adoption of electric vehicles (EVs) has generated an increasing demand for charging infrastructure and efficient smart charging coordination for EVs. In addition to residential and public charging, destination charging has emerged as a crucial component, holding the potential to address remaining public charging needs. Understanding the factors and coordination strategies contributing to the sustainability of destination charging businesses is crucial. Despite the substantial growth in literature on EV smart charging and coordination, there is ambiguity in the terminology used to describe coordination strategies. Therefore, this paper aims to systematically categorize the literature, specifically focusing on destination charging. The analysis presented in this paper underscores the need for future research on destination charging coordination to consider user behavior and the potential challenges faced by the intended scale of destination charging to determine suitable coordination strategies. Moreover, the paper acknowledges the understudied nature of implicit charging coordination strategies, suggesting an exploration of these strategies as they may offer solutions to challenges encountered by real-world EV charging coordination programs [03].

M. Secchi et. al. (2023) - Encouraging the adoption of Electric Vehicles (EVs) powered by renewable Distributed Energy Resources (DERs) is vital for achieving climate neutrality. However, integrating EVs and Photovoltaic (PV) generators into the power grid can introduce unpredictable fluctuations, potentially destabilizing the system. This study presents an optimization algorithm for intelligent EV charging, designed to mitigate overall net-load variance by efficiently utilizing available PV power, implementing EV charging shifts, and employing vehicle-to-grid (V2G) strategies. Key aspects of this approach include: (i) formulation as a quadratic programming problem; (ii) facilitation of V2G charging policies; (iii) incorporation of specific constraints related to EV availability, owners' charging preferences, and, to some extent, voltage stability; and (iv) an examination of the combined impact of EV and PV integration on bus voltages, line currents, district self-sufficiency, and EV battery lifespan. The proposed approach is evaluated under both ideal conditions and scenarios involving a basic persistence forecasting model for load and PV generation over consecutive days [04].

Pranoy Roy et. al. (2023) – As the adoption of electric vehicles (EVs) grows in both residential and commercial sectors, accompanied by the rapid deployment of EV charging stations, it becomes essential to evaluate the potential impact of intensive EV charging on the operation and planning of power distribution systems. This research focuses on the rural area of west Kentucky and employs the Distribution Resource Integration and Value Estimation (DRIVE) and HotSpotter software tools to analyze the potential effects of EV charging on the operation of regional distribution systems and the lifespan degradation of power transformers.

The study aims to identify potential risks of distribution system overload and proposes mitigation solutions to address the anticipated demand for intensive EV charging in various adoption scenarios. The research assesses possible overloading in distribution systems and examines undervoltage violations. Furthermore, it investigates the overload impact of EV charging through a multi-physics reliability analysis of distribution transformers. The findings of this research contribute to understanding and managing distribution system challenges associated with the increasing demand for EV charging infrastructure **[05].**

Muhammad Bashar Anwar et. al. (2022) - Driven by technological advancements and a growing global emphasis on sustainability, the adoption of electric vehicles (EVs) is experiencing remarkable growth. This widespread integration of EVs has the potential to revolutionize the transportation sector and has substantial implications for energy and electricity systems, presenting new opportunities for significant load growth. However, unregulated EV charging poses challenges to existing grid infrastructure, potentially resulting in operational, reliability, and planning issues at both bulk and distribution levels.This article summarizes the advantages of managed EV charging, provides an overview of existing implementations and costs in the United States, critically evaluates the methodologies used in analysis and modeling studies, and quantifies the costs and benefits based on the findings of these studies. In conclusion, key insights are distilled, outlining the factors influencing the value of managed EV charging. Additionally, critical gaps and remaining challenges are identified, underscoring the need for comprehensive efforts to fully realize the effective integration of EVs into the grid **[06].**

Suresh Chavhan et. al. (2022) - This study introduces a space-efficient, multi-level charging station infrastructure designed for metropolitan cities, featuring seamless integration with the smart grid. A comprehensive 33-bus simulation is conducted, employing a Multi-Agent System (MAS) for each bus to effectively manage the grid's stability. The findings of the 33-bus simulation with MAS support demonstrate the sustained stability of the system.

A detailed cost analysis is undertaken for the innovative multi-level charging station infrastructure design. Additionally, stress analysis of the proposed structure is conducted, confirming that the maximum stress within the structure is 68.53 MPa, with a corresponding maximum displacement of 0.06716 mm.

Furthermore, a mathematical model for the multi-level EV charging station infrastructure is developed using the M/M/S/K queuing model. Critical analysis of the results is performed to gain insights into the system's performance. It is essential to note that this study focuses on densely populated metropolitan areas, specifically targeting cities in India. A limitation of this approach is its applicability to high-density urban settings. Future research could explore adapting the proposed methodology for less densely populated areas, thereby expanding its potential scope and applicability **[07].**

Sridevi Tirunagar et. al. (2022) - The swift integration of Electric Vehicles (EVs) into the transportation sector is significantly influencing the electricity and energy industries. While EVs offer numerous advantages, they also pose challenges for power grid operators, with uncoordinated EV charging emerging as a critical issue that demands attention to mitigate potential adverse effects on power grids. Smart charging and Vehicle-to-Grid (V2G) technologies play a pivotal role in facilitating intelligent power transfer between EVs and the grid, taking into account network conditions and requirements.

Addressing the challenges posed by unmanaged EV charging is crucial, and the implementation of smart charging and V2G technologies can help alleviate adverse effects. However, the widespread adoption of these technologies necessitates supportive policies and regulatory frameworks. This paper conducts a thorough review of the impacts of unmanaged EV charging, as well as the benefits associated with smart charging and V2G, drawing on insights from published research studies and real-world field trials.

Simulation case studies presented in this paper illustrate the detrimental effects of uncoordinated charging, such as increased peak loads leading to high power losses, voltage violations, voltage imbalances, reduced transformer lifespan, and harmonic distortion. Conversely, the study establishes that smart charging mitigates these network issues and brings about a range of economic, social, and environmental benefits. Notably, the role of smart charging as a mandatory requirement for achieving the net-zero decarburizations target in the transportation sector is emphasized **[08].**

Jose David Alvarez Guerrero et. al. (2022) - This article delves into the impacts of Electric Vehicle (EV) charging on the RTS-GMLC power system, employing the PCM PSO approach. The baseline scenario involved no inclusion of EVs in the RTS-GMLC model. The study incorporated two charging strategies, namely uncoordinated and coordinated, considering three levels of EV penetration: 10%, 20%, and 30% of light-duty vehicles (equivalent to 1%, 2%, and 3% of the annual energy load). To assess the impacts, the model was employed for representative on-peak and off-peak weeks throughout the year. The results are presented in terms of power system loads, operational costs, Locational Marginal Prices (LMPs), EV charging costs, Variable Renewable Energy (VRE) curtailment, and the influence of the two charging strategies.

Concerning reliability metrics such as unsaved energy and maintaining reserve margins, the EV charging scenarios did not result in an increase in unnerved energy or a violation of reserve margins. The integration of electric transportation amplified power system load, operational costs, and electricity prices. However, the magnitude and nature of these effects varied depending on the charging strategy. Under uncoordinated charging, the overall system operation cost was consistently higher compared to coordinate charging, regardless of the level of EV penetration. The operation cost correlated with the net load served by the conventional fleet, reaching notably higher levels during peak load weeks in the summer.

During summer weeks, the savings in production costs between coordinated charging and uncoordinated charging remained consistently at 1% for all three EV penetration scenarios tested. Conversely, during off-peak weeks characterized by lower load and high VRE production, the savings in production costs ranged from 4% to 8% when using coordinated charging **[09].**

Mohammad Ali Sayed et.al. (2022) - Our analysis has uncovered vulnerabilities within various components of the Electric Vehicle (EV) ecosystem, indicating potential entry points for attackers to gain control of Electric Vehicle Charging Stations (EVCS). Such control could be exploited to launch attacks on the power grid by orchestrating large-scale charging and discharging activities..

To address these vulnerabilities, we have proposed patches based on industry best practices and recommended two potential detection strategies to counter EV-related attacks [10].

III. Method

The methods used in this study is based on studies presented in [10] and [68]. In order to identify the potential effects of smart charging, the work was built based on previous case studies where the data is analysed from [69] and [13]. Building on that, this thesis investigates how the model changes in different charging scenarios. This section describes data modelling, residential load, charging schemes and model implemented in Matlab.

This model is written in MATLAB. In this model, EVs are handled as objects for efficient sorting and storing. A general representation of the model is shown in Figure 2. The inputs to this model are number of EVs, price of the electricity, forecasted load from the local distribution network, plug-in and plug-out times of the EVs, and battery capacity. These inputs are processed through a smart charging algorithm yielding to the output of balanced load on the local distribution network while charging to 100% SoC during the times when the electricity price is the lowest. The model also allows to alter the weight between load balancing and price of the electricity.

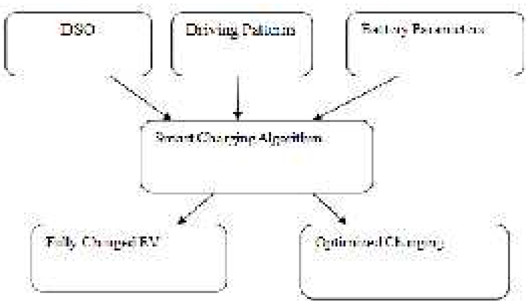

Figure 2: Representation of model configuration showing the inputs and outputs of the smart charging algorithm

IV. CONCLUSION

In this paper has provided a An EV charging load on the utility grid is explored. On the circuit level, firstly, commercially popular EV topologies are discussed, which provided the background for segregation of grid problems introduced by different EV chargers. Secondly, problems related to power quality and heating introduced by the harmonic current of EV chargers are discussed. On the component level, the impact of generalized EV load on the two key performance parameters of utility grid, i.e., voltage profile and load curve of the distribution line are explored. This helped in realizing the characteristics difference between different grid connections and the need for impact analysis for each case. Finally, studies and analysis proposed in the existing literature to account for improved EV load modelling, peak load management of load curve and enhancement of grid performance with bidirectional power flow are explored.

The impact of electric vehicle charging on grid congestion and load management requires a multi-faceted approach. Combining technological innovations, policy interventions, and community engagement can create a sustainable and resilient energy ecosystem that supports the transition to widespread electric vehicle adoption. Proactive planning and collaboration among stakeholders will be essential to address the challenges and harness the full potential of electric mobility.

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