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Research Article

Evaluating the Effect of Electric Vehicles Charging Stations on Residential Distribution Grid

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Abstract: This article investigates the effect of electric vehicle (EV) charging on the electricity distribution grids of residential areas. With the rapid increase in EV adoption, the additional load from EV charging poses potential challenges to existing residential distribution grids. The primary focus of this research is to understand how EV charging affects grid stability, power quality, and energy losses. To this end, a detailed model of the distribution grid was developed, incorporating the variable loads induced by EV charging over different periods. Through this model, the study explores the relationship between EV adoption rates and charging patterns, particularly analyzing their effects on the voltage profiles within the grid. Furthermore, the research quantifies the extent of power losses resulting from the increased demand created by EV charging. The findings aim to offer insights into the grid management complexities introduced by EVs and suggest practical approaches for enhancing grid reliability and efficiency. The results are intended to aid utilities and policymakers in making informed decisions to accommodate the growing presence of EVs, ensuring a smoother transition towards sustainable transportation electrification.

Keywords: Residential Distribution Grid, EV Charging Effect, Grid Stability, Power Losses, Voltage Profile.

1. Introduction

Recently, the global energy landscape is predominantly reliant on fossil fuels for both electricity generation and transportation needs [1-3]. However, a confluence of emerging energy and environmental concerns, coupled with geopolitical instabilities, economic challenges, energy security apprehensions, and the impending depletion of fossil fuel reservoirs, has served as a clarion call for industries within these sectors to explore alternative energy solutions [4-6]. Consequently, there has been a discernible paradigm shift within the transportation domain towards the rapid electrification of vehicles as a viable substitute for traditional internal combustion engine (ICE) counterparts. This transition towards electric vehicles (EVs) has been primarily precipitated by the implementation of pragmatic policies aimed at curbing environmental degradation, particularly in terms of greenhouse gas (GHG) emissions, and fostering the long-term sustainability of the transportation sector [7-9].

Furthermore, the integration of EVs into the transportation ecosystem holds promise for significant fiscal savings earmarked for environmental preservation endeavours, alongside a consequential reduction in the reliance on finite oil resources [10-12]. The manifold advantages inherent in EV adoption have catalysed a global acceleration in its uptake, buoyed by supportive governmental policies such as tax incentives, the provision of EV-friendly infrastructure including parking and transit facilities, as well as toll exemptions [13-15]. Moreover, with certain nations either enacting or contemplating stringent regulations pertaining to vehicular emissions, automotive manufacturers have been compelled to recalibrate their strategies, with concerted efforts directed towards minimizing the emissions output of ICE vehicles while concurrently investing in the research and development of cutting-edge EV technologies. This adaptive response underscores the industry's commitment to aligning with evolving environmental benchmarks and reinforces the pivotal role that EVs are poised to play in shaping the future of sustainable transportation [16,17].

The burgeoning electric vehicle (EV) market has undergone a trajectory of exponential expansion, evidenced by its attainment of sales figures surpassing the 10 million marks in the annum of 2022. This ascendant trend is further underscored by the revelation that 14% of all recent automotive acquisitions in 2022 constituted electric vehicles, marking a discernible uptick from the approximate figures of 9% and less than 5% observed in the preceding years of 2021 and 2020, respectively. Within the landscape of global EV commerce, three salient markets have emerged as stalwarts. Foremost among these is the Chinese market, which, once more, has asserted its pre-eminence by commanding approximately 60% of the aggregate global electric vehicle sales. Clearly, China now harbours in excess of half of the total global EV fleet, thus surpassing its projected milestone for new energy vehicle sales earmarked for the year 2025 [18,19].

Meanwhile, in Europe, the secondary but nonetheless pivotal market for electric vehicles, a conspicuous surge of over 15% in electric car transactions transpired in 2022. Consequently, this translated to an epoch-making milestone wherein more than one out of every five automotive acquisitions in Europe materialized in the form of electric vehicles. Similarly, in the United States, which constitutes the tertiary but nonetheless substantial market for electric vehicles, the year 2022 bore witness to a striking upswing of 55% in electric car sales, thereby culminating in an 8% share of total automotive sales being attributed to EV. Anticipated to persist robustly into the forthcoming year, EV sales are poised for continued momentum throughout the duration of 2023. Evidencing this enduring trend, the inaugural quarter of the year witnessed the sale of over 2.3 million electric cars, marking a formidable surge of approximately 25% in comparison to figures recorded during the corresponding temporal span of the antecedent year. Projections indicate an envisaged culmination of sales figures at a staggering 14 million by the denouement of 2023, thereby delineating a striking year-on-year escalation of 35%, with a notable acceleration in new acquisitions anticipated particularly in the latter half of the annum. Concomitantly, it is surmised that electric cars may ascend to account for an impressive 18% share of the total automotive transactions conducted over the entire calendar year [19-21]. Furthermore, envisioned to act as catalyzing agents in fortifying the trajectory of EV sales, national policies and incentivization mechanisms are poised to play pivotal roles. Furthermore, the resurgence of oil prices to levels of exceptional elevation akin to those observed in the antecedent year could conceivably serve as an additional impetus, thereby further galvanizing the resolve of prospective purchasers towards embracing electric alternatives.

The gap in the article lies in the need for addressing of the specific impact of electric vehicle (EV) charging on the distribution grid within residential areas, particularly with regard to voltage profile and power losses. While there is existing research on the broader implications of EV adoption on the electrical grid, there is a lack of detailed analysis focusing specifically on residential distribution grids and their vulnerability to fluctuations in voltage levels and increased power losses due to EV charging activities. Furthermore, there is a dearth of studies that systematically examine the interplay between EV charging patterns and their effects on grid stability and efficiency within residential settings.

Addressing this gap is crucial for developing effective strategies for grid management, infrastructure planning, and policy formulation tailored to the unique challenges and opportunities posed by the integration of EVs into residential electricity distribution systems.

1.1 Literature Review

The literature review serves as the foundation for the current article, identifying the research gaps and building upon the existing body of knowledge. This subsection meticulously delves into an extensive examination of existing literature pertaining to the ramifications of electric vehicle charging on residential distribution grids. Table 1 serves as a valuable adjunct, providing succinct descriptions of the studies discussed within the text.

Table 1. The latest research on the impact of EVs integrated with the distribution grid.

Author	Year	Journal	Contribution	Target
Nutkani et al., [22]	2024	Willey	The burgeoning adoption of EVs is anticipated to exert a substantial influence on electrical power distribution grid (DG). Extensive efforts have been undertaken to grasp and quantify this impact on the hosting capacity of distribution networks, both with and without the implementation of network management solutions. Such a review is imperative for comprehending the breadth of existing studies, scrutinizing the datasets utilized for impact analysis, and, most importantly, elucidating the findings derived from these investigations.	EV-DG
Jiang et al., [23]	2024	Science Direct	This paper initiated by formulating a bilevel stochastic optimization model for EV charging navigation, which takes into account diverse uncertainties. Subsequently, it introduces an EV charging navigation approach predicated on the hierarchical enhanced deep Q network (HEDQN) to address the aforementioned stochastic optimization model in real-time. The proposed HEDQN encompasses two enhanced deep Q networks, each designated for optimizing the charging destination and the charging route path of EVs, respectively.	EV-DG
Singh & Kumar [24]	2024	Willey	This article introduced an innovative approach for the meticulous modeling of EVs within the framework of reliability and adequacy models for DG. The proposed technique synergistically merges forensic-based investigation (FBI) with the Archimedes optimization algorithm (AOA), aptly dubbed the FBIAOA technique. In this direction, the primary aim of this method is to enhance the profitability of rapid charging stations while simultaneously mitigating the escalating energy demand on the SG, which comprises storage systems and renewable energy generation sources such as wind and photovoltaic (PV) systems.	EV-DG
Polisetty et al., [25]	2023	Science Direct	With the escalating rate of electric vehicle adoption, there is a pressing need for the strategic deployment of charging stations to minimize loss and mitigate voltage imbalances. Several existing strategies investigated in this study for optimal charging station deployment have yielded increased power utilization, power loss, harmonic distortion, and voltage imbalances. Hence, a novel Dove-based Recursive Deep Network (DbRDN) has been devised for implementation.	EV-DG
Lai et al., [26]	2023	IEEE	EVs hold significant promise in combating greenhouse gas emissions within the transportation sector, contributing to their steady adoption in several countries. However, the increasing prevalence of EVs can pose challenges to both the power distribution network (PDN) and the transportation network (TN). Therefore, this paper introduces a dynamic pricing strategy for electric vehicle charging stations (EVCSs), aiming to enhance their profitability while mitigating potential adverse effects on both PDN and TN.	EV-DG

Wang et al., [27]	2023	Wiley	This article meticulously accounts for the diverse characteristics inherent in various vehicle models and incorporates user responsiveness, thereby rendering the model more reflective of real-world dynamics. The results underscore that the optimized charging and discharging strategy outlined in this study not only reduces charging costs for vehicle owners but also enhances revenue generation from charging stations and the utilization rate of charging piles.	EV-DG
Hartvigsson et al., [28]	2022	Science Direct	This article endeavored to scrutinize the ramifications of voltage disturbances on EV batteries and charging systems while introducing a Fault Ride-Through Capability (FRTC) mechanism aimed at enhancing voltage quality.	EV-DG

In this context, the study builds upon the knowledge base established by previous researchers in the field of the anticipated surge in electric vehicle (EV) adoption, which is driven by government incentives and declining battery costs, necessitates an examination of the ensuing load on the electricity grid. In [29], the study delves into the effects of integrating a substantial fleet of EVs on the power network, considering the spatial variations in vehicle usage, electricity demand, and network configuration. The findings demonstrate that, within Great Britain's power system, smart charging holds the capability to obviate the need for additional generation infrastructure accompanying 100% EV adoption, simultaneously reducing the percentage of distribution networks necessitating reinforcement from 28% to 9%. The implications and generalizability of these results to other power systems are also discussed.

Previous research [30] has focused on the presence of EVs that continues to grow, their potential for scheduling and dispatching offers significant benefits to both the power grid and EV users. By fully harnessing the dispatching potential, the power grid can enhance system operation efficiency, while EV users can experience cost savings and improved satisfaction. In light of this, this study presents a charging scheduling method for EVs that considers real-world scenarios, encompassing optimization targets and control strategies. To address this challenge, an enhanced multi-objective particle swarm optimization (PSO) algorithm is proposed. This improved algorithm employs maximum and minimum fitness functions based on dynamic crowding distance and rate of change, while optimizing the inertia weight coefficient and learning factor to enhance algorithm performance. Finally, the numerical examples are presented to validate the effectiveness of the proposed model.

In [31], the study aims to evaluate the potential implications of EVs, which are already widely deployed and expected to experience exponential growth, on distribution networks. The research focuses on understanding the necessary adaptations and developments that the distribution grid must undergo to accommodate the escalating energy demand posed by EVs. Furthermore, an assessment of the impact of fast charging stations was conducted. Simulations were performed using MATLAB software to create scripts, which were then implemented within the DIgSILENT PowerFactory software.

Recent study [32] discussed the rapid adoption of EVs in California has brought forth numerous challenges related to the integration of these vehicles with the electricity grid. To assess the capacity constraints faced by local feeders, this study utilizes real-world feeder circuit level data obtained from PG&E, a major utility in California. By employing a detailed modeling approach, the adoption of EVs is analyzed at the census block level, taking into account actual vehicle charging data to simulate future load patterns on circuits across Northern California. In the most ambitious scenario, where 6 million electric vehicles are adopted throughout California, the study reveals that approximately 443 circuits (nearly 20% of all circuits) in PG&E's service territory would require upgrades to accommodate the increased demand. Alarmingly, only 88 of these circuits currently have planned upgrades scheduled in the future.

According to [33], authors present a comprehensive and data-driven model that realistically captures the charging behaviors of future EV adopters in the US Western Interconnection. This analysis focuses on the critical factors of charging control and infrastructure development, which shape the charging load, and evaluate their impact on the grid using a detailed economic dispatch model that considers the generation mix projected for 2035. These findings reveal that peak net electricity demand experiences an increase of up to 25% under the forecasted adoption scenario, while a stress test involving full electrification results in a 50% surge.

1.2 Motivation

The motivation article of the effect of charging electric vehicles on distribution grid of the residential area in terms of voltage profile and power losses is to investigate the impact of EV charging on the distribution grid within a residential area, specifically focusing on two key aspects: voltage profile and power losses. The study aims to analyze how the increasing adoption of EVs and their charging patterns influence the voltage levels across the distribution grid and the overall power losses incurred. By examining these factors, the article seeks to contribute to a better understanding of the challenges and opportunities associated with integrating EVs into residential electricity distribution systems, ultimately informing decision-making processes regarding grid management, infrastructure planning, and policy development in the context of sustainable transportation electrification.

1.3 Problem Statement

The widespread adoption of EVs poses significant challenges to residential electricity distribution systems, particularly regarding voltage profile and power losses within the distribution grid. While the integration of EVs into residential areas offers numerous benefits in terms of sustainability and reduced greenhouse gas emissions, it also presents complexities related to grid stability and efficiency. The existing infrastructure may not be adequately equipped to handle the increased demand for electricity caused by EV charging activities, leading to voltage fluctuations and elevated power losses.

This research aims to address the gap in understanding the precise impact of EV charging on residential distribution grids, with a specific focus on voltage profile and power losses. By investigating the relationship between EV adoption rates, charging patterns, and their effects on voltage levels and power losses across the distribution grid, this study seeks to identify potential challenges and opportunities associated with integrating EVs into residential electricity distribution systems.

The findings of this research are expected to contribute to a better understanding of the complexities involved in managing EV charging within residential areas and to inform decision-making processes regarding grid management, infrastructure planning, and policy development. Ultimately, the goal is to facilitate the transition towards sustainable transportation electrification while ensuring the reliability and efficiency of residential electricity distribution systems.

1.4 Research Object

The primary objective of this article is to investigate the impact of EV charging on residential electricity distribution grid. To achieve this objective, the following specific research objectives are outlined:

- Design a model for the distribution grid that incorporates the anticipated load from EV charging activities, taking into account the period of time during EV charging.
- Analyze the relationship between EV adoption rates and charging patterns within residential areas with a specific focus on voltage profile within the distribution grid.
- Evaluate the magnitude of power losses incurred in the distribution grid as a result of increased demand from EV charging.

By addressing these research objectives, the study aims to contribute to a better understanding of the complexities involved in managing EV charging within residential areas and to provide practical recommendations for ensuring the reliability and efficiency of residential electricity distribution systems amidst the transition towards sustainable transportation electrification.

1.5 Contribution

The article contributes by designing a model for the distribution grid that incorporates the anticipated load from EV charging activities, taking into account the temporal aspect of EV charging. To begin with, this model provides a systematic framework for assessing the impact of EV charging on distribution grid operation. By looking at the connection between the number of EVs on the road and how they are charged in residential areas, with a focus on the voltage profile in the distribution grid, the study sheds light on how EVs affect grid performance over time. Furthermore, this analysis helps to understand the nuances of EV charging behavior and its implications for grid stability. Then, the article evaluates the magnitude of power losses incurred in the distribution grid due to increased demand from EV charging. This assessment provides valuable insights into the efficiency of the distribution grid under varying scenarios of EV adoption and charging patterns.

2. Effect of Grid-Connected EV Systems

The integration of EVs into the power grid has precipitated substantial modifications in the architecture, strategic planning, and functional operations of the network. Without meticulous analysis and strategic planning of this integration, extensive penetration of EV charging into the conventional grid infrastructure can disrupt its normal operations, leading to a plethora of technical power quality challenges [34-36]. These include, but are not limited to, voltage drops, voltage imbalances, harmonic distortions, increased system losses, equipment overloading, and issues pertaining to voltage stability. This subsection concisely examines some of these impacts, highlighting the critical need for advanced planning and adaptation in grid management to accommodate the growing influx of EVs [37-40].

A. Voltage drops

Voltage drop represents a significant constraint in the incorporation of extensive electric vehicle (EV) charging within low voltage (LV) distribution networks. The process of charging EVs directly from the grid induces voltage drops and deviations at the connection points, which can exacerbate if the penetration level of EV charging escalates significantly [41-46]. Such a scenario might result in breaches of the regulatory voltage limits set for safe network operation. Consequently, utility companies across various nations are tasked with the imperative of maintaining customer service voltages within permissible thresholds, despite differing grid specifications [47-50]. The voltage drop of the network topology is determined as following Eq. (1).

$$\Delta V_D = V_{ref} - V_{min} \tag{1}$$

Where, V_{ref} is a prespecified voltage magnitude at load bus i which is usually set to 1.0 (p.u.). V_{min} is the minimum bus voltage of the network topology.

B. Voltage unbalance

Voltage unbalance in electrical distribution systems arises when there is a disparity in phase voltages either in amplitude or phase shift, deviating from the standard 120-degree relationship, or both. This phenomenon typically results from asymmetrically distributed single-phase loads and impedances across the network and is quantified using the Voltage Unbalance Factor (VUF). VUF is defined as the percentage ratio of the absolute magnitudes of the positive and negative sequence voltage components. EVs, which often connect to low-voltage feeders predominantly loaded with single-phase demands, introduce significant power quality challenges for distribution network operators. Empirical evidence, as detailed in references, indicates a pronounced voltage unbalance attributed to EV charging within distribution systems. Consequently, to facilitate seamless integration of EVs while managing voltage unbalance, utilities must establish specific grid codes and standards [50-54]. Furthermore, comprehensive impact assessments by researchers are essential to devise effective strategies to mitigate these challenges and enhance grid stability.

C. Harmonics

Harmonics are non-fundamental frequency components of voltage or current within a power system, commonly quantified as Total Demand Distortion (TDD) and Total Harmonic Distortion (THD). TDD represents the root mean square (RMS) ratio of harmonic content, excluding inter-harmonics, to the maximum demand current, whereas THD is calculated as the RMS ratio of harmonic content to the fundamental current. The process of EV charging predominantly introduces harmonics into the electrical grid through power electronic converters [55-58].

D. Power loss

Power loss in transmission lines is an intrinsic characteristic of electrical distribution systems, fundamentally tied to the square of the current flowing through these lines. This relationship underscores how increases in current lead directly to higher power dissipation. With the rising integration of EVs into existing distribution networks, there is a significant increase in power losses, largely attributable to feeder overloads and changes in the electrical characteristics of feeder currents. As EV adoption expands, the additional demand imposed by vehicle charging exacerbates these effects, stressing the infrastructure and necessitating careful management of load distribution to mitigate increased losses [59-62]. This surge in power loss not only challenges the efficiency and capacity of power transmission but also calls for strategic enhancements in grid management and technology to accommodate the evolving demand dynamics introduced by widespread EV usage. The network topology's total real power loss is defined by the following Eq. (2).

$$P_{loss} = \sum_{i=1}^{N_{br}} R_i * \frac{P_i^2 + Q_i^2}{V_i^2} \tag{2}$$

Where, N_{br} is the number of branches; R_i is the resistance of the ith branch; P_i and Q_i are the real power and reactive power of the i_{th} branch, respectively; and V_i is the voltage magnitude at bus i.

E. Equipment Overloading

Regarding equipment overloading, the widespread adoption of EV charging places considerable demands on the distribution network. This situation necessitates the transfer of substantial amounts of power from the grid to the load, which can result in the overloading of critical network components, including transformers and cables [63-64]. As more EVs connect to the grid for charging, particularly during peak times, the cumulative load can exceed the designed capacity of existing infrastructure. This overloading can lead to increased wear and tear, reduced efficiency, and potentially shorten the lifespan of vital network elements such as transformers and power cables, posing significant challenges to grid reliability and safety [65-73]. Therefore, managing this load effectively through grid enhancements and smart charging strategies becomes essential to prevent overloading and ensure the sustainable integration of EVs into power systems.

3. Methodology

This article expounds upon the selected methodology employed in the present section, encompassing a comprehensive depiction of the research approach and process, as well as the designation of the preferred data sources and modelling technique. Certainly. The selected methodology is a critical component of any research endeavor since it outlines the systematic and logical approach utilized to achieve the research objectives. The primary objective of this article is to investigate and analyses the potential implications of electric vehicles on low-voltage grids. This article aims to develop low voltage distribution grid models in the NEPLAN program that incorporate asymmetric load-flow simulations, accounting for factors such as household load variations, EV home arrivals, and different state-of-charge scenarios. The research work further seeks to evaluate the outcomes of these simulations. Specifically, the investigation focuses on a large residential area comprising 72 houses, from which a low voltage grid model is created to facilitate the requisite simulations, including load flow analysis and time. The structured flowchart provides a clear roadmap for research work, ensuring a systematic approach to analysing the influence of EVs on the electrical distribution network as indicated in Figure 1.

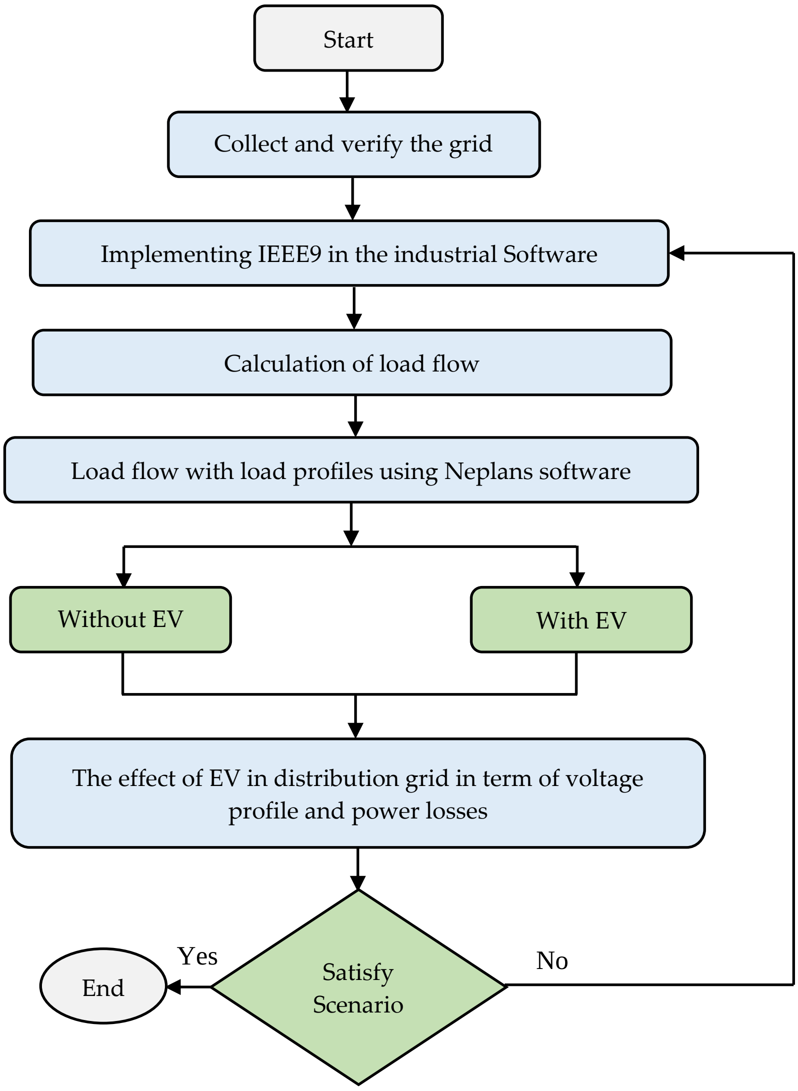

Figure 1. The flowchart of the impact of EVs in the distribution Network's voltage profile and Energy losses

The flowchart for analysing the impact of EVs on the voltage profile and energy losses within a distribution network involves a structured approach to data collection, software implementation, and simulation. Here's a detailed description of each step in the flowchart for your research work:

i. Collect and Verify Grid Data:

Objective:

- Gather all relevant data regarding the distribution network to ensure accuracy in simulations.

Actions:

- Collect grid topology, load data, transformer capacities, and line impedances.
- Verify the accuracy and completeness of collected data to avoid errors in the model.

ii. Implement IEEE 9 Bus System Using Industrial Software:

Objective:

- Set up a standard model that can serve as a baseline for further simulations.

Actions:

- Utilize a software industrial-grade tool to implement the IEEE 9 bus system.
- Configure the software settings to align with the specific parameters of the distribution network being studied.

iii. Simulation Setup in Neplan Software:

Objective: Prepare the Neplan software environment for detailed load flow analysis.

Actions:

- Import the verified grid data into Neplan.
- Set up the simulation environment corresponding to the IEEE 9 bus system adapted for the specific network characteristics.

iv. Load Flow Analysis with Load Profiles Using Neplan:

Objective:

- Conduct a comprehensive load flow analysis to evaluate the network's performance under different scenarios.

Actions (without EVs):

- Run simulations to establish a baseline of the network's voltage profile and energy losses without the impact of EVs.
- Analyze and document the results as the control scenario.

Actions (with EVs):

- Integrate EV load profiles into the simulation, representing various levels of EV penetration.
- Simulate the network's behavior with the additional loads imposed by EV charging.
- Analyze how EV integration affects voltage stability and energy losses compared to the baseline scenario.

v. Comparison and Analysis:

Objective:

- Compare the results from both scenarios to assess the impact of EVs on the distribution network.

Actions:

- Use graphical and statistical tools within Neplan to compare voltage profiles and quantify energy losses.
- Identify patterns, anomalies, or critical issues that arise from the integration of EVs into the network.

vi. Documentation and Reporting:

Objective:

- Compile the findings into a comprehensive report that outlines the methodologies, results, and conclusions.

Actions:

- Document each step of the process, including assumptions made, challenges encountered, and solutions implemented.
- Prepare detailed charts, graphs, and tables to visually represent the impact of EVs on the network.
- Conclude with recommendations for managing voltage profiles and minimizing energy losses in networks with high EV penetration.

To summarized, the research work on evaluating the impact of EVs on a distribution network's voltage profile and energy losses follows a structured and systematic approach. The process begins with the collection and verification of relevant grid data, ensuring the accuracy of the model. Using industrial software, the IEEE 9 bus system is then implemented to provide a standard baseline for simulations. The Neplan software is utilized to set up and conduct detailed load flow analyses under two scenarios: with and without EV integration. This involves simulating and analyzing the network's behavior to identify how EV charging affects voltage stability and energy losses compared to the baseline scenario without EVs. Results from both scenarios are compared to assess the impact of EVs.

4. Result and Discussion

This section addresses several key aspects of the proposed system. It begins by analyzing the parameters utilized in the modeling of grid-connected EVs. Subsequently, the section delves into the comprehensive modeling process of grid-connected EVs, highlighting the simulation methods, assumptions, and computational techniques employed. Finally, the outcomes derived from the modeling of grid-connected EVs are presented, offering insights into system performance, potential impacts on grid stability, and efficiency metrics. The discussion integrates these findings to evaluate the feasibility and implications of widespread EV integration into residential power grids.

4.1 *The Parameter of the Proposed System Modeling of Grid-Connected EV*

This subsection delves into the detailed parameters of the proposed system for modeling grid-connected EVs. As the integration of EVs into the power distribution networks continues to grow, understanding the specific parameters that influence system performance becomes crucial. Table 2 indicates the parameter of the proposed system.

Table 2. The parameter of the proposed system.

System quantities	Rating
Grid supplying two distribution feeders	115Kv, X/R ratio=6
Short circuit	500 MVA
Line impedance	0.1529+j0.1406 ohm/km
Distance of line lines are 1km long	
TRM	115 KV/12.47 KV/20 MVA
TR1, TR2, TR3, TR4, TR5, TR6, TR7, TR8	12.47 KV/0.4 KV 2 MVA
Load Energy without EV	69.289 MWh
Load Energy with EV	82.38 MWh
Maximum Load without EV	4.722 MW
Maximum Load with EV	5.489 MW
Load Loss Factor without EV	0.4351
Load Loss Factor with EV	0.383
Energy Losses without EV	0.625 MWh
Energy Losses with EV	0.839 MWh
Maximum Losses without EV	0.059 MW
Maximum Losses with EV	0.0911 MW

In the context of the proposed system for modeling grid-connected EVs, it is imperative to delineate the specific parameters that govern the dynamics of power distribution networks. As EV integration intensifies, a profound comprehension of these parameters becomes essential for evaluating system performance accurately. Notably, the grid in question is configured to supply two distribution feeders, each rated at 115 kV with an X/R ratio of 6, and a short-circuit capacity of 500 MVA. Furthermore, the line impedance is specified as 0.1529 + j0.1406 ohm/km, with all transmission lines extending for precisely 1 km. The main transformer (TRM) utilized within this configuration is rated at 115 kV/12.47 kV with a capacity of 20 MVA. Complementarily, additional transformers labeled TR1 through TR8 are configured at 12.47 kV/0.4 kV, each with a capacity of 2 MVA. These detailed specifications are critical for understanding the electrical characteristics and operational constraints of the network under the increased load conditions imposed by EV charging.

4.2 *Modeling of Grid-Connected EV*

The Neplan software program was employed, utilizing a model based on the 9-bus IEEE system Neplan software program as demonstrated in Figure 2. This tool allows for a precise simulation of how EVs interact with the power grid under various scenarios. The findings discussed herein provide insights into the potential challenges and efficiencies that can arise from high penetration levels of electric vehicles within and without urban distribution networks. The findings are critical for stakeholders in energy management and infrastructure planning to understand the dynamic changes introduced by EVs and effectively strategize for future grid enhancements.

The employment of the Neplan software in this analysis merits particular attention due to its robust simulation capabilities, as evidenced by its adoption of a model based on the well-established 9-bus IEEE system. This model features a single network feeder with a substantial capacity of 4.3 MW, which is integral for assessing the performance and reliability of the grid under high power loads. The complexity of the system is further highlighted by the inclusion of 11 distinct load points, each with varying demand loads, thus simulating a realistic diversity in consumer energy usage within the network. It is observed that the EV interfaces are connected with Bus 3, Bus 5, and Bus 8. Additionally, the infrastructure of the proposed model is enhanced by the integration of nine transformers, each designated as a 2W Transformer.

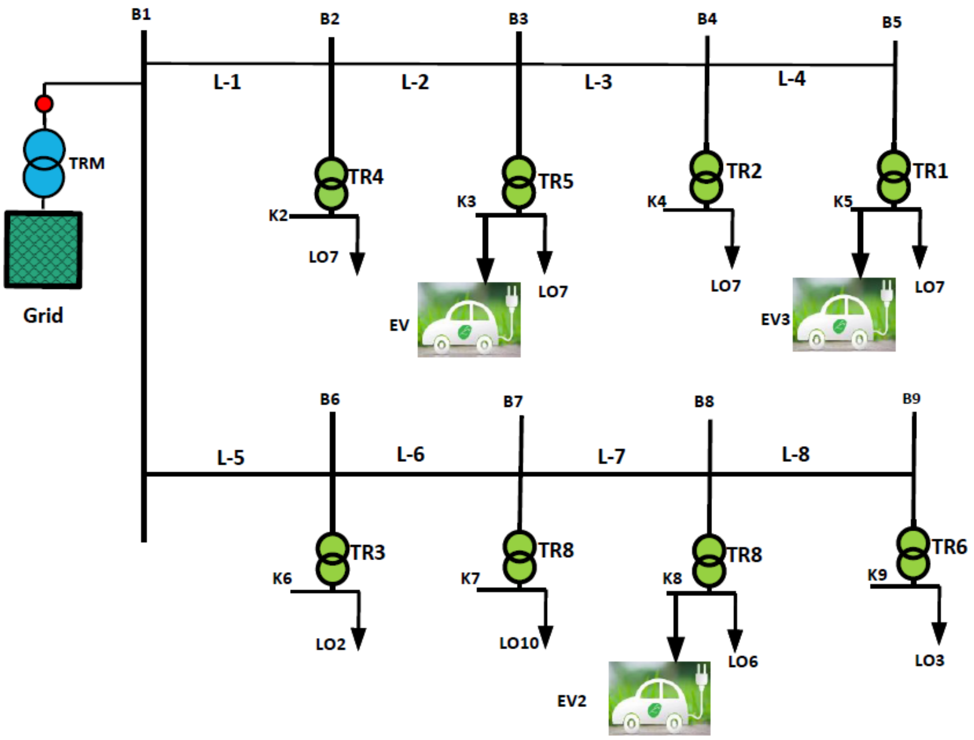

Figure 2. The diagram of proposed modeling using the Neplan software program.

These transformers are critical components, designed to handle dual-winding operations that are essential for effective voltage regulation and efficient power distribution across different nodes of the network. The presence of 18 nodes within the model allows for an exhaustive analysis of the electrical flow and potential bottlenecks or inefficiencies that may occur at various junctures within the distribution grid.

4.3 Result from Modeling of Grid-Connected EV

In the context of this article, a comprehensive network simulation incorporating a 72-household grid was executed using the NEPLAN software program. The simulation was meticulously designed to evaluate two distinct scenarios: one where no households possess EVs, and another where electric vehicles are present in 40 of the 72 homes. For each household, specific loads were configured to simulate the electrical consumption patterns both with and without the presence of EVs. Measurements were taken from various critical points within the network to assess the impact of these loads. Current readings were systematically recorded from the power transformer and network cables to monitor the flow and distribution of electricity across the grid.

Additionally, the article work involved detailed monitoring of power losses within the network, a key indicator of efficiency and network health. To further understand the dynamics of household electricity consumption, electrical energy usage data was collected over a continuous 24-hour period from each home. Voltage levels were also meticulously measured at the Puller Box, providing valuable insights into the stability and adequacy of voltage supply across the network.

A. *Voltage Profile on Different Buses without EV*

Understanding the results of voltage levels at different buses without the presence of EVs is crucial for several reasons. Firstly, it establishes a baseline or control scenario against which the impact of EV integration can be measured. This baseline data is essential for identifying how the addition of EV loads affects the stability, capacity, and operational efficiency of the power distribution network. Secondly, knowing the voltage at different buses under normal conditions without EVs helps in assessing the adequacy of the existing infrastructure. Figure 3 presents the result of voltage on different buses without EV. Figure 4 illustrates the results of voltage range (%) on different buses without EV. Figure 5 shows the results of voltage range (%) of distribution's network transformer with EV. Figure 6 illustrates the results of bus voltages (p.u) of distribution's network with EV. Figure 7 presents the results of charging voltages (MW) of distribution's network with EV.

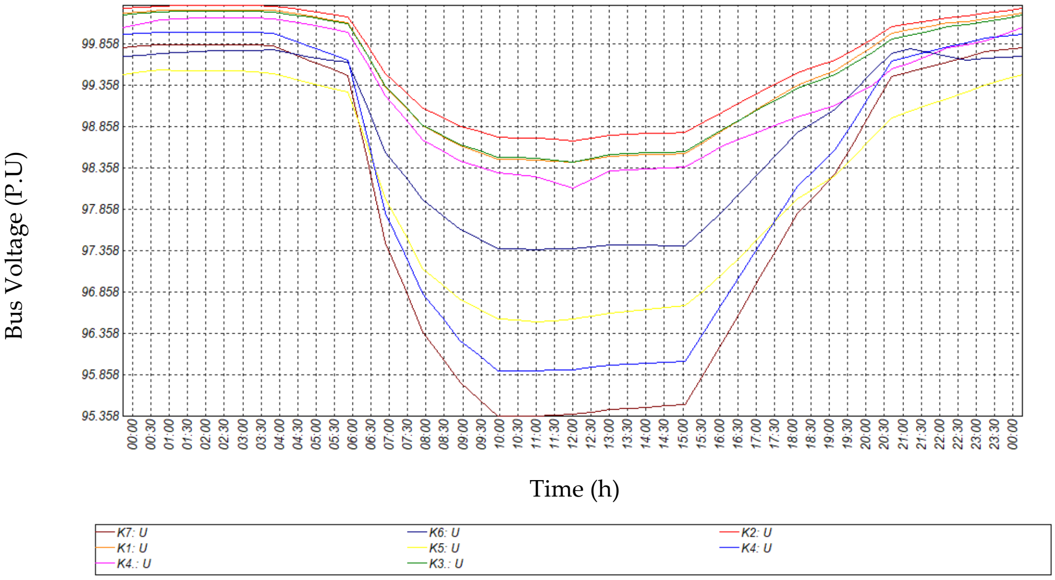

Figure 3. The result of voltage on different buses without EV.

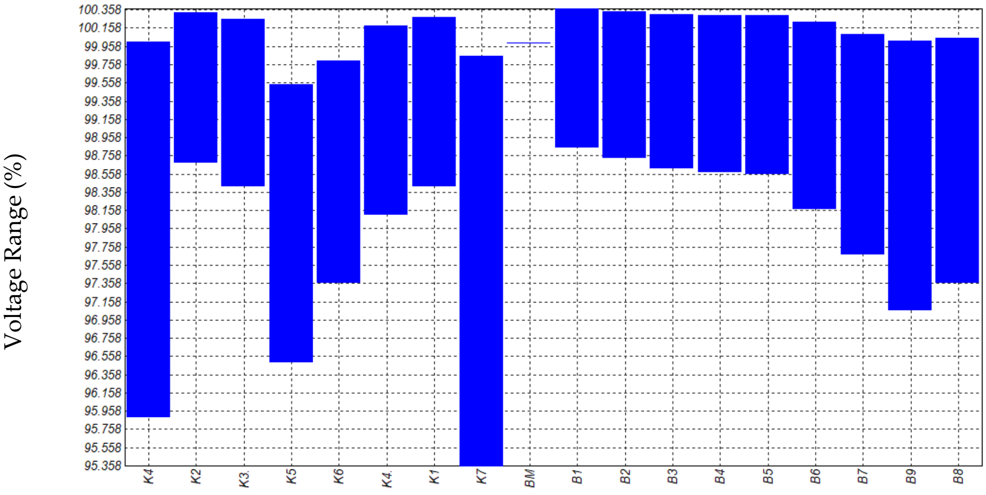

Figure 4. The results of voltage range (%) on different buses without EV.

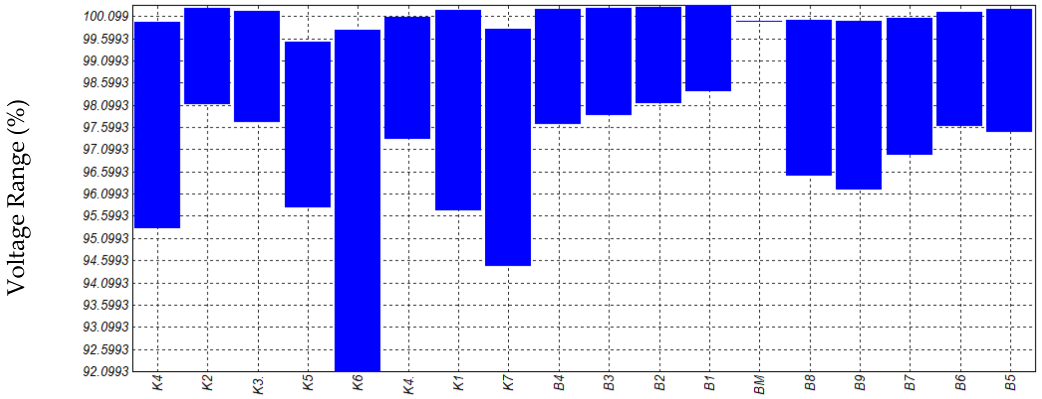

Figure 5. The results of voltage range (%) on different buses without EV.

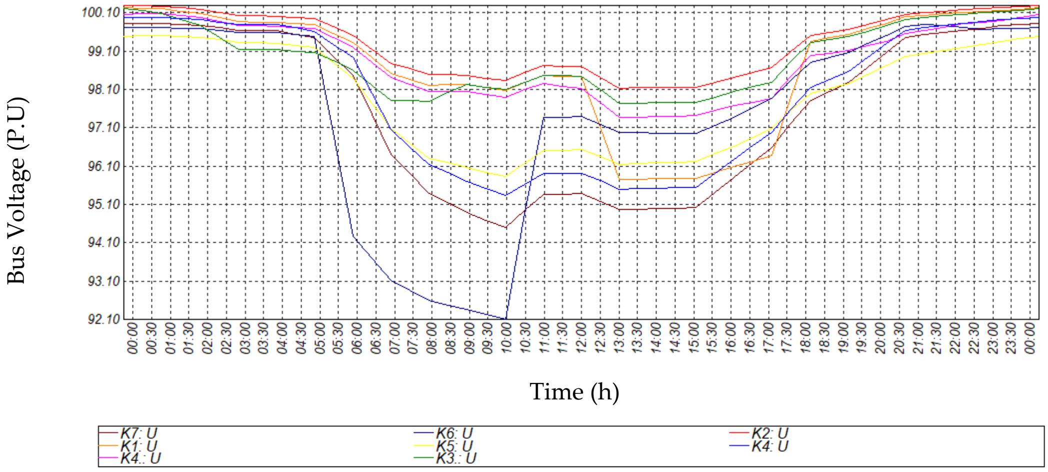

Figure 6. The results of voltage range (%) of distribution's network transformer with EV.

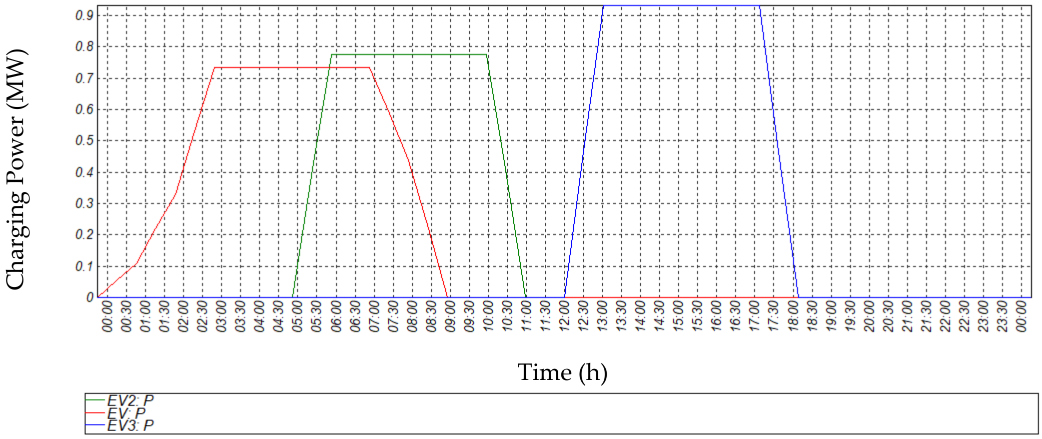

Figure 7. The results of charging voltages (MW) of distribution's network with EV.

Additionally, analyzing voltage levels at various buses provides insights into potential weak points or vulnerabilities in the network. These could be areas where voltage levels are already near critical limits or where minor fluctuations could lead to significant issues, such as voltage sag or instability. Moreover, this analysis aids in the proactive planning of grid expansion and reinforcement. By understanding the baseline conditions, utilities can more effectively strategize where to invest in grid modernization, such as adding transformers, upgrading lines, or integrating advanced voltage control systems.

B. The results of Real Power (MW) Generation

Discussing the results of real power (MW) generation during the modeling of grid-connected EVs is crucial for several integral aspects of energy management and infrastructure development. Figure 8 shows the results of obtaining Real Power (MW) based on generation. Figure 9 presents the results of Real Power loss (MW) with EV. Figure 10 presents the results of the Real power loss (MW) of the distribution network transformer with EV.

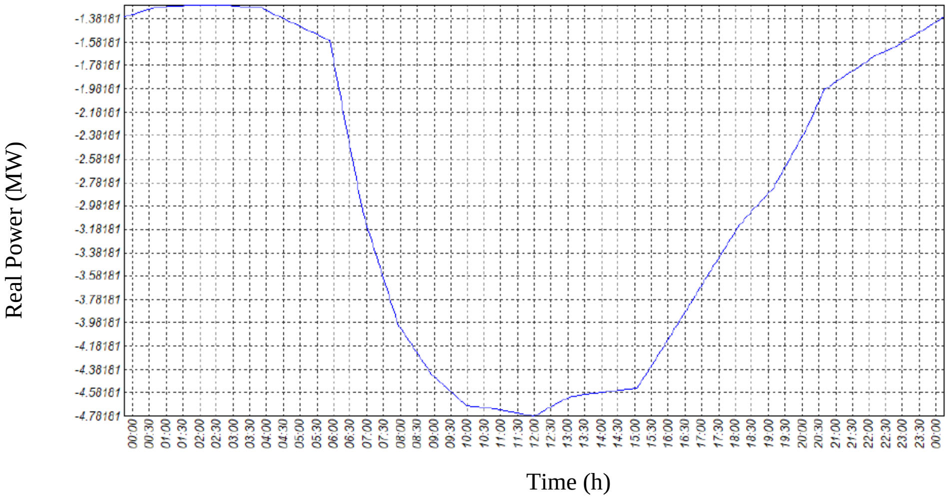

Figure 8. The results of obtaining (Real Power (MW)) based on generation.

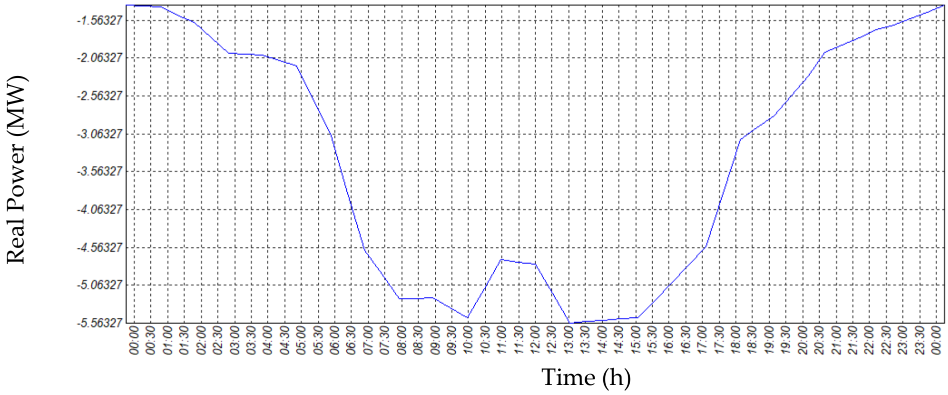

Figure 9. The results of Real Power loss (MW) with EV.

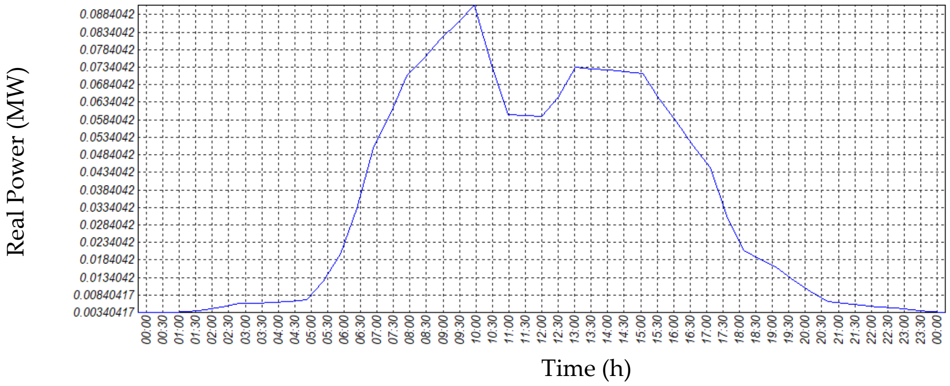

Figure 10. The results of the Real power loss (MW) of the distribution network transformer with EV.

In this point, real power measurements are essential for assessing grid stability and reliability. The integration of EVs introduces additional loads that can affect the power generation balance, and having a clear understanding of these effects is critical for maintaining reliable and uninterrupted power supply across the network. Accurate real power data allows engineers and grid operators to analyze the impacts of EV charging on the overall system and to take necessary actions to ensure stability. Moreover, accurate data on real power requirements facilitates better infrastructure planning. It provides the basis for decisions regarding the upgrading of transformers, enhancement of transmission lines, and increases in generation capacity to accommodate the expected rise in electricity demand due to widespread EV adoption. This planning is essential to support the growth in EV usage without compromising the performance of the power grid.

C. The Results of the Loading Profile of Distribution's Network and Transformer

Understanding the loading profiles of a distribution network and its transformers, both with and without the integration of EVs, is paramount for several strategic and operational reasons. With the rise of EVs, the additional demand they introduce can significantly alter load profiles. Evaluating these profiles with and without EVs allows utilities to accurately forecast the need for infrastructure upgrades, including transformer upgrades or the installation of additional units. This foresight helps in managing increased loads effectively, ensuring the infrastructure is neither underutilized nor overwhelmed. Figure 11 presents the results of loading profile of distribution's network without EV. Figure 12 demonstrated the results of the load profile of the entire distribution network transformer with EV.

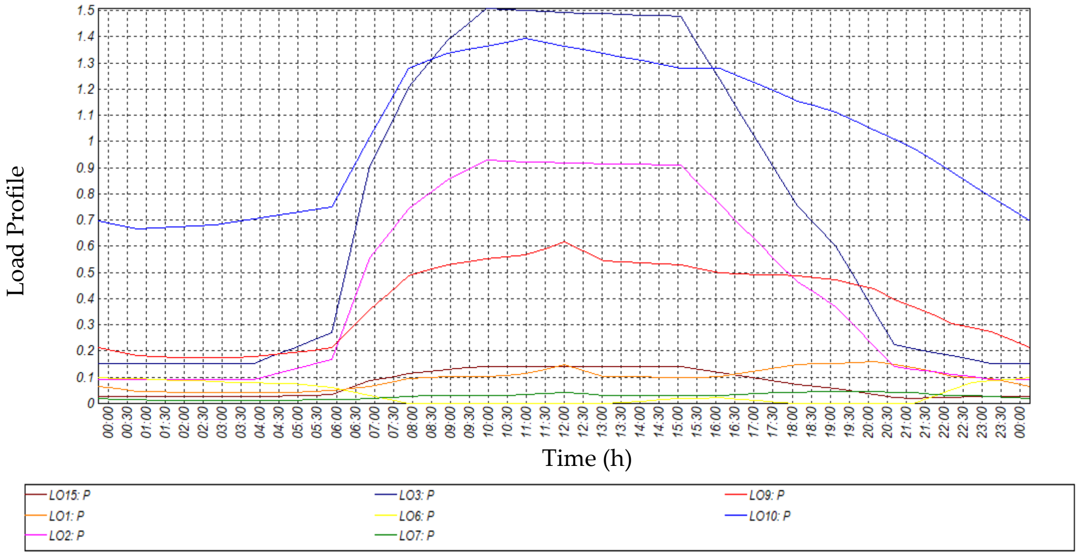

Figure 11. The results of loading profile of distribution's network without EV.

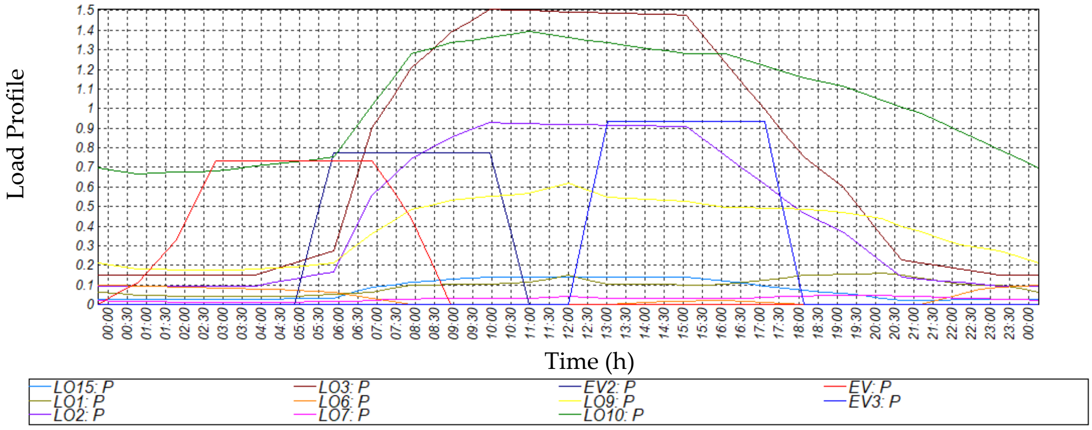

Figure 12. The results of the load profile of the entire distribution network transformer with EV.

Moreover, transformers are critical components that can be heavily impacted by the high and often fluctuating charging demands of EVs. Analyzing how load profiles change with the introduction of EVs can highlight potential risks of overloading and wear, guiding the necessary enhancements in transformer capacity and technology to handle these new loads without compromising the lifespan of the equipment. In doing so, load profiles with EVs can exhibit sharper peaks and troughs, particularly during popular charging times. By understanding these patterns, utilities can implement strategies such as demand response programs or time-of-use pricing to smooth peaks and fill valleys, thereby enhancing grid stability and reliability. Figure 13 shows the results of loading of distribution's network transformer without EV. Figure 14 indicates the results of loading of distribution's network transformer with EV.

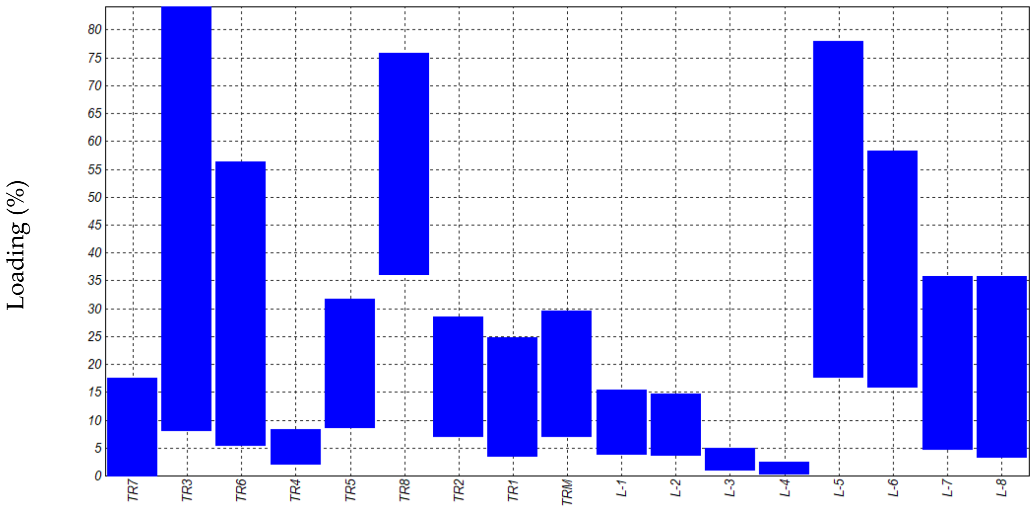

Figure 13. The results of loading of distribution's network transformer without EV.

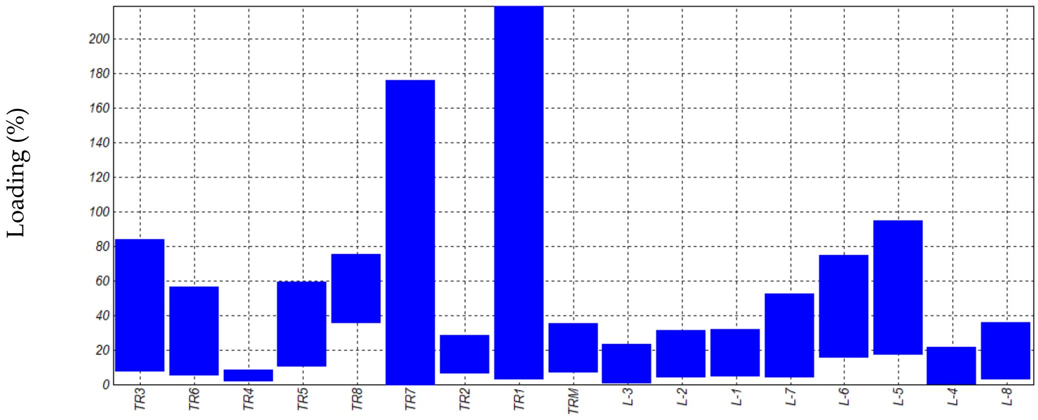

Figure 14. The results of loading of distribution's network transformer with EV.

For consumers, particularly those with EVs, understanding the impact of their charging habits on the distribution network can lead to more informed decisions about when and how they consume electricity. Utilities providing this information can enhance customer relations and potentially offer economic benefits through programs encouraging off-peak charging. In summary, analyzing the loading profiles of distribution networks and transformers with the inclusion of EVs is crucial for ensuring that the power systems are prepared to handle new demands.

4. Conclusion and Future Work

The article set out to explore the impact of EV charging on residential electricity distribution grids, a critical area of research given the increasing adoption of EVs and their potential implications for power systems. The primary conclusion drawn from this study is that EV charging significantly influences residential distribution grids in several key aspects. Firstly, the development and implementation of a model designed to simulate the distribution grid with anticipated EV charging loads revealed that time of charging plays a crucial role in grid management. This modeling demonstrated that peak charging times could significantly strain the grid unless properly managed with smart grid technologies or time-of-use incentives.

Secondly, the analysis of the relationship between EV adoption rates and charging patterns provided clear evidence that as more residents adopt EVs, without strategic management, the risk of voltage instability within residential grids increases. This underscores the need for utilities to adjust their infrastructure and management strategies to accommodate an evolving landscape where EVs are more prevalent.

Lastly, the evaluation of power losses due to increased demand from EV charging highlighted that without adequate upgrades and optimization, distribution grids might suffer from efficiency losses. These losses not only affect the economic operations of utilities but also the sustainability goals associated with reducing overall energy consumption and carbon emissions.

This article contributes valuable insights into the challenges and necessary strategies for integrating EV charging into residential distribution networks. It underscores the need for proactive grid management and infrastructure development to handle the upcoming surge in EV usage effectively. The findings advocate for a strategic approach to grid management that includes enhancing grid capacity, utilizing smart charging technologies, and possibly restructuring tariff systems to encourage off-peak charging. This will ensure that the shift towards electric vehicles aligns with the goals of maintaining grid stability, ensuring economic efficiency, and promoting environmental sustainability. However, building on the findings from this article, several avenues for future research can be explored to deepen understanding and enhance the integration of EVs into residential distribution grids:

- Advanced Grid Modeling Techniques: Future studies could develop more sophisticated models that incorporate real-time data and machine learning algorithms to predict and manage the dynamics of EV charging more effectively. Such models could enhance the accuracy of simulations and allow for more dynamic management of grid resources.
- Impact of Renewable Energy Integration: As renewable energy adoption grows alongside EVs, it is crucial to examine how the concurrent use of renewables and electric vehicle charging can be optimized. Research could focus on integrating solar and wind energy sources directly into residential areas to mitigate the additional load from EVs.
- Smart Charging Strategies: Further investigation into smart charging technologies and their implementation could prove beneficial. Research could focus on the effectiveness of smart charging in balancing grid loads and optimizing energy usage, including the development of consumer-friendly smart charging apps and devices.
- Policy and Economic Incentives: Additional studies could analyze the impact of various policy and economic incentives on EV adoption and charging behavior. This includes exploring different tariff structures and incentives that encourage off-peak charging and assessing their real-world applicability and effectiveness.
- Longitudinal Studies on EV Adoption Trends: Conducting longitudinal studies to track EV adoption and charging habits over time would provide valuable insights into how behaviors change as infrastructure and technology evolve. This would aid utilities and policymakers in planning and implementing strategies that are responsive to consumer behavior.
- Technological Advancements in Battery Storage: Research into improved battery technology could explore how enhanced battery storage systems might be integrated into the residential grid infrastructure to support load balancing and energy management, potentially reducing the strain from peak charging times.

By pursuing these areas of future work, researchers and industry stakeholders can continue to refine strategies for the successful integration of EVs into the electrical grid, ensuring that the transition to electric mobility is both sustainable and beneficial to all stakeholders involved.

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resources, author; data curation, author; writing—original draft preparation, A. G., M. Ş., A. M., A. A. A., M. M., A. A., I. I., and E. M.; writing—review and editing, author; visualization, author; supervision, author; project administration, A. G., M. Ş., A. M., A. A. A., M. M., A. A., and E. M.; author has read and agreed to the published version of the manuscript.

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