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*Ozan Gül*

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# Navigating Power Paths: Assessing Line Losses in the IEEE 14-Bus System amidst Electric Vehicle and Renewable Energy Integration

**Ozan Gül**[1*]
[1]Electric and Electronic Engineering, Bingol University

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## Abstract

**Purpose:** This study thoroughly investigates the impacts of Electric Vehicles (EVs) and Renewable Energy Sources (RES) on line losses within the IEEE 14-Bus System, with a particular emphasis on addressing challenges and optimizing power system planning. The primary purpose of this study is to assess and understand the intricate relationships between EVs, RES, and line losses within the IEEE 14-Bus System. The research aims to provide insights that contribute to the development of tailored strategies in power system planning, addressing challenges posed by EV adoption and RES integration. By exploring the impact on grid efficiency, sustainability, and reliability, the study aims to guide future power system planners in optimizing the integration of EVs and RES.

**Materials and Methods:** The study utilizes load flow analysis, specifically the Newton-Raphson method, to model and simulate scenarios reflecting EV charging and discharging dynamics alongside intermittent RES integration within the IEEE 14-Bus System. A 24-hour dynamic load flow analysis is conducted to capture the diverse and dynamic impacts under varying load conditions. This comprehensive approach allows for a detailed assessment of line losses in the presence of EVs and RES.

**Findings:** The study reveals nuanced impacts, indicating higher EV adoption and increased RES integration result in notable escalations in line losses. This highlights challenges associated with grid efficiency, emphasizing the need for tailored strategies in power system planning.

**Implications to Theory, Practice and Policy:** The study advances theoretical understanding of dynamic interactions between EVs, RES, and power systems. In practice, it underscores the importance of adaptive control mechanisms and optimized strategies for accommodating EVs and RES while minimizing line losses. On a policy level, the findings suggest the need for regulatory frameworks incentivizing sustainable energy practices and technological research to mitigate challenges posed by EV adoption and RES integration.

**Keyword:** *Electric Vehicles, Renewable Energy Sources, Line Losses, Power System Planning, Newton-Raphson Method*

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## 1.0 INTRODUCTION

The global push toward sustainable energy solutions has spurred the increased adoption of Electric Vehicles (EVs) and Renewable Energy Sources (RES) in the power grid, presenting a transformative paradigm shift in the dynamics of electricity distribution systems. This study addresses the in-depth exploration of the individual and combined impacts of EVs and RES on theIEEE 14-Bus System, a critical benchmark in power system research. The integration of thesetechnologies prompts a comprehensive investigation into their effects on line losses within the electrical grid.

### Problem Statement

As the world transitions toward sustainable energy, the integration of EVs and RES introduces challenges related to the dynamic nature of these technologies. EVs, with their diverse charging patterns, and RES, characterized by intermittent generation, pose complexities for power systems. The overarching problem is understanding the implications of their integration on line losses within the IEEE 14-Bus System. The variability introduced by EVs and the intermittency of RES can disrupt traditional power flow patterns, potentially leading to increased line losses and impacting grid efficiency. Addressing this problem is crucial for devising effective strategies in power system planning that accommodate the increasing prevalence of EVs and RES.

## 2.0 LITERATURE REVIEW

### Theoretical Review

The integration of Electric Vehicles (EVs) into power systems has garnered significant attention in recent literature. Yao et al. (2018) discuss the challenges and opportunities associated with integrating EV charging infrastructure into existing power grids, emphasizing the need for advanced load management strategies. Liu et al. (2013) explore Vehicle-to-Grid (V2G) technology, investigating how bidirectional capabilities can reduce line losses by utilizing EVs as distributed energy resources. Zhang et al. (2020) analyze EV charging patterns and their impact on load profiles, offering insights into optimal charging strategies to mitigate line losses during peak demand periods.

Kene & Olwal (2023) focus on coordinated charging strategies for large-scale EV fleets, highlighting the importance of intelligent algorithms for minimizing line losses. Additionally, Mohammed et al. (2024) investigate integration challenges in urban areas with rapid EV growth, exploring strategies for optimal charging infrastructure placement and grid reinforcement. This collective body of research underscores the complexity of EV integration, emphasizing the need for innovative solutions to optimize grid performance, reduce line losses, and ensure the seamless incorporation of EVs into the evolving energy landscape.

The impact of Renewable Energy Sources (RES), particularly solar and wind power, on power grids is a subject of extensive research. Benti et al. (2023) emphasize the need for accurate forecasting models to predict renewable energy generation, enabling grid operators to manage fluctuations effectively and minimize line losses. Worku (2022) highlights the critical role of energy storage systems in addressing the intermittency of RES, enhancing grid stability, and reducing line losses.

Shair et al. (2021) further explore the challenges associated with high-penetration levels of RES, providing insights into power system stability and recommending adaptive control mechanisms. Thirunavukkarasu et al. (2023) contribute by investigating hybrid renewable energy systems, combining solar and wind power, to optimize grid performance and minimize line losses.

Load flow analysis, a fundamental tool in power system studies, has been extensively used to assess steady-state conditions. The Newton-Raphson method, outlined by Tinney & Hart (1967), has proven effective in solving nonlinear equations associated with power flow. Load flow analysis enables the examination of voltage magnitudes, phase angles, and power flows across the network, offering insights into how EVs and RES impact the overall system. . The charging profiles, ranging from slow overnight charging to fast charging during peak periods, create varying demands on the grid, leading to fluctuations in power flow and, consequently, affecting line losses to be investigated by Theodoropoulos et al. (2022). By simulating diverse scenarios of EV integration, this study aims to capture the nuances of these impacts under different load conditions and EV penetration levels.

The IEEE 14-Bus System has been widely adopted as a benchmark for power system analysis. Its simplicity and representation of real-world scenarios make it an ideal platform for evaluating different integration scenarios. Zhong et al. (2021) employed the IEEE 14-Bus System to study false data injection in power smart grids, showcasing its relevance in contemporary power system research.

### Research Gaps

While existing literature provides valuable insights into the individual impacts of EVs and RES on power systems, a comprehensive examination of their combined effects, specifically on line losses within the IEEE 14-Bus System, remains limited. There is a research gap in understanding how the interplay between EVs and RES, each with its unique characteristics, contributes to line losses in a realistic power system setting. This study aims to fill this gap by conducting simulations and analyses that consider both EV and RES integration scenarios, providing a holistic understanding of their implications on line losses within the IEEE 14-Bus System.

In conclusion, the integration of EVs and RES introduces transformative dynamics in the power grid, necessitating a thorough exploration of their impacts on line losses. Recognizing the IEEE 14-Bus System as a benchmark, this study aims to address the complexities arising from the diverse charging patterns of EVs and the intermittent generation of RES. The literature review establishes the current state of knowledge, highlighting gaps that this research seeks to fill. The subsequent sections will delve into the methodology, findings, and implications of integrating EVs and RES within the context of the IEEE 14-Bus System.

## 3.0 MATERIAL AND METHODS

### Load Flow Analysis Using the Newton-Raphson Method

The study utilizes load flow analysis, specifically the Newton-Raphson method, to model and simulate scenarios reflecting EV charging and discharging dynamics alongside intermittent RES integration within the IEEE 14-Bus System. A 24-hour dynamic load flow analysis is conducted to capture the diverse and dynamic impacts under varying load conditions. This comprehensive approach allows for a detailed assessment of line losses in the presence of EVs and RES.

Load flow analysis, employing the Newton-Raphson method, is a widely utilized technique in power systems engineering for determining steady-state operating conditions within an electrical network. Particularly effective in solving nonlinear equations modeling power flow in complex systems, this method facilitates the calculation of voltage magnitude, phase angle, and active/reactive power in each transmission line and bus.The power system is typically represented by a single-line diagram operating under well-balanced conditions. Key factors at each bus include voltage magnitude (|V|), voltage phase angle (δ), active power (P), and reactive power (Q). Buses are categorized into three groups by Tinney & Hart (1967):

Oscillation Bus (Reference Bus): This bus calculates active power (P), reactive power (Q), voltage magnitude (|V|), and phase angle (δ), evaluating discrepancies resulting from power system losses between generated power and expected load.

Load Buses (P-Q Buses): In these buses, sought-after parameters include phase angle (δ) and voltage magnitude (|V|), along with active (P) and reactive power (Q). Power values become negative when power is consumed.

Generation Buses (P-V Buses): Reactive power (Q), voltage phase angle (δ), and active power (P) are calculated at these buses.

The Newton-Raphson method, an iterative technique for load flow analysis, aims to find steady-state operating conditions. The objective is to determine voltage magnitudes (V) and phase angles (θ) at all buses. The process involves nodal power equations, including real and reactive power equations. The Jacobian matrix is constructed to contain partial derivatives, and update equations are derived to find corrections to initial voltage estimates. The convergence check evaluates changes in voltage magnitudes and phase angles against a predefined tolerance.

The iterative process involves updating voltage magnitudes and phase angles, recalculating power injections, and building the Jacobian matrix for updated estimates. Convergence is assessed, and if not met, the iteration continues. This method provides a systematic approach to achieving steady-state conditions in power systems, ensuring accuracy and reliability in power flow analysis.

**Objective:** Find the voltage magnitudes (V) and phase angles (θ) at all buses in the power system.

Steps:

1) Nodal Power Equations:

Real Power Equation: $$P_i = \sum_{J=1}^{n} |Y_{ij}||\, V_i \,||V_j\,| \cos(\, \Theta_{ij} - \delta_{\mathrm{i}} + \delta_j) \quad (1)$$

Reactive Power Equation $$Q_i = \sum_{J=1}^{n} -|Y_{ij}||\, V_i \,||V_j\,| \cos(\, \Theta_{ij} - \delta_{\mathrm{i}} + \delta_j) \quad (2)$$

2) Jacobian Matrix: Construct the Jacobian matrix (J) that contains partial derivatives of the power equations with respect to voltage magnitudes and phase angles.

3) Update Equations: The update equations are derived from the Newton-Raphson method, aiming to find corrections to the initial voltage estimates

$$\varDelta P = Pcalculated - Pmeausered \quad (3)$$

$$\varDelta Q = Qcalculated - Qmeausered \quad (4)$$

$$\Delta X = J^{-1}\left(\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix}\right) \tag{5}$$

$$Xnew = Xold - \Delta X \tag{6}$$

4) Convergence Check: Assess convergence by evaluating changes in voltage magnitudes and phase angles (ΔV and Δθ) against a predefined tolerance.

5) Iteration: Iterate until convergence:

Update voltage magnitudes and phase angles using the update equations.

Recalculate power injections and build the Jacobian matrix for the updated estimates.

Check for convergence criteria. If not met, continue iterating.

### Load Flow Analysis Using the Newton-Raphson Method

Dynamic load flow assessments spanning 24 hours were conducted utilizing the Newton-Raphson load flow analysis method, as briefly discussed earlier. The computational process involved several steps: 1) Definition of models for the power system, load, and resources. 2) Application of the Newton-Raphson approach to analyze hourly load flow. 3) Calculation of line losses. 4) Completion of calculations marked the conclusion of the 24-hour period.

This investigation categorized distributed resources into two types: continuous and discontinuous. Continuous resources, exemplified by dams and thermal power plants, were characterized by nearly constant active and reactive power values, maintaining an average over the 24-hour period. In contrast, discontinuous sources, including wind and solar power, exhibited variable 24-hour active and reactive power production profiles represented by 24-component $G_P$ and $G_Q$ vectors.

Two load profile types were modeled to align with power demand characteristics at buses: low-variable and variable. Low-variable loads, such as industrial districts with minimal changes over 24 hours, were assigned load models with small variations. On the other hand, variable power demand profiles were attributed to loads with significant 24-hour fluctuations, exemplified by Electric Vehicles (EVs). Using $P_L$ and $Q_L$ vectors with 24 components, variable loads were defined, and the Newton-Raphson method was employed for daily hourly load flow assessments.

This approach facilitated a comprehensive analysis, capturing the dynamic interactions of continuous and discontinuous resources, as well as accommodating the diverse power demand characteristics of low-variable and variable loads over the 24-hour period.

## 4.0 FINDINGS

Hourly load flow analyses were meticulously executed on the well-established IEEE 14-bus test system, recognized for its wide application in simulating energy market problems. This exemplary application involved the strategic integration of electric cars into the test system, as visually represented in Fig. 1. To simulate diverse power consumption scenarios, two distinct dynamic load profiles were formulated. The first profile emulated load demand with relatively low variability, akin to that of industrial settings such as factories or business centers, and was characterized by vectors $P_{L1}$ and $Q_{L1}$, detailed in Fig. 2(a). In contrast, the second load model was designed to represent high variability in power consumption, specifically mirroring the charging status of electric cars. This model was aptly described by vectors $P_{L2}$ and $Q_{L2}$, visually depicted in Fig. 2(b).

Extending the analyses within the same IEEE 14-bus test system, scenarios arising from the integration of renewable distributed resources were explored, as elucidated in Fig. 1. Diverse test scenarios were meticulously crafted, with the first scenario incorporating solar energy (SG scenario), the second involving wind energy (WG scenario), and the third amalgamating both wind and solar energy (HG scenario) in a hybrid system. Fig. 2 presented the production profiles strategically employed in the analysis for both wind and solar energy sources.

This dual-pronged analysis, encompassing electric car integration and renewable energy scenarios within the IEEE 14-bus test system, provided a comprehensive understanding of the system's behavior under varying conditions. The insights garnered from this analysis offer valuable perspectives into the potential challenges and benefits associated with the intricate interplay of these evolving energy dynamics within the power system landscape. In this study, simulation applications were carried out using the MATLAB program.

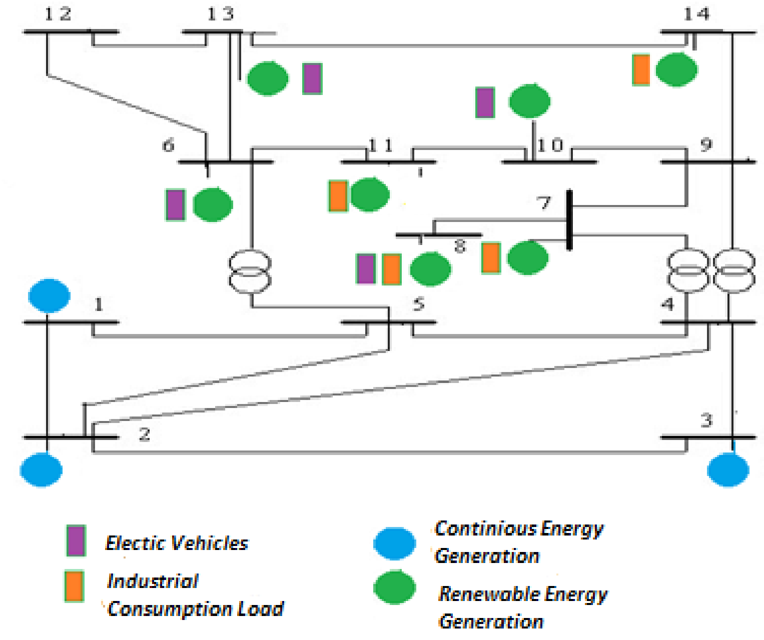

*Figure 1: IEEE 14-Bus Test System for Example Application*

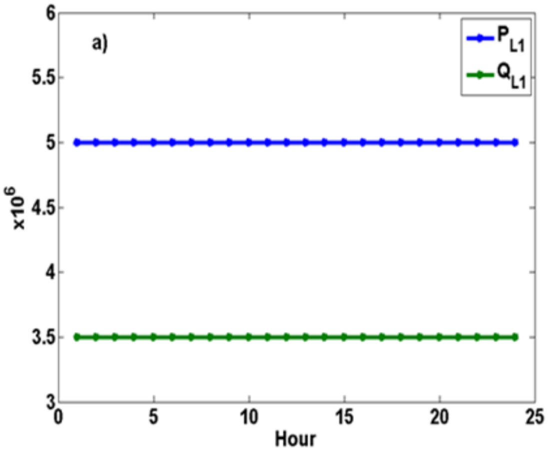

*Figure 2(a): Low-Variation Load Demand Profile ($P_{L1}$, $Q_{L1}$) That Models Low-Variation Load Demand Profile Modeling the Power Consumption of Industrial Zones*

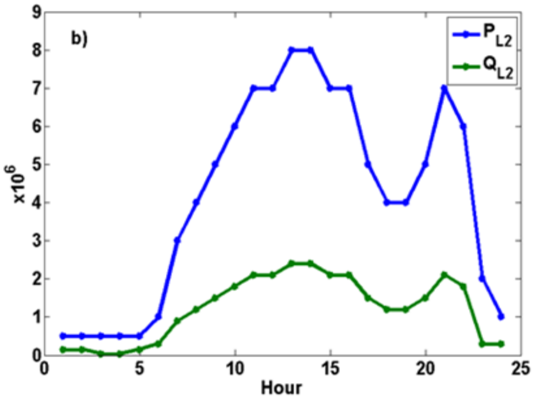

*Figure 2(b): High Variability Load Demand Profile ($P_{L2}$, $Q_{L2}$), Modeling EV Power Consumption*

To conduct a thorough analysis of the impact of Electric Vehicles (EVs) on the power network, two distinct load demand scenarios (LDx3 and LDx7) were systematically compared against the baseline LD scenario. The LDx3 and LDx7 scenarios involved increasing the load power demand by three and seven times, respectively, compared to the standard LD scenario. The results of this comparative assessment are presented in Table 1, providing a detailed overview of the 24-hour line loss outcomes specifically within a test system characterized by a load structure exhibiting relatively low power consumption variability, such as industrial zones.

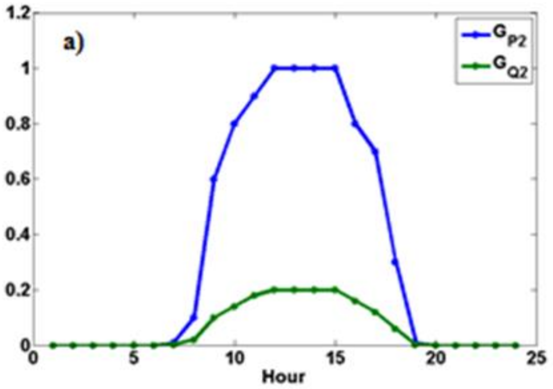

*Figure 3(a): Solar Energy Resources Production Profile*

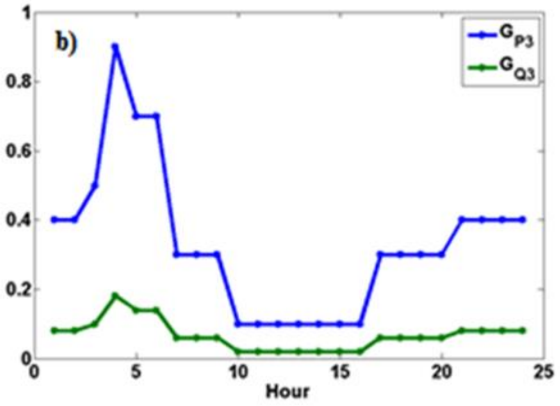

*Figure 3(b): Wind Energy Resources Production Profile*

Furthermore, Table 2 presents the 24-hour line loss results for the LD, LDx3, and LDx7 scenarios in a scenario where the load structure exclusively comprises Electric Vehicles (EVs), showcasing high power consumption variability within the test system. This focused examination enables a nuanced understanding of how varying load demand scenarios, particularly those influenced by EVs, impact line losses in the network.

**Table 1: Line Losses for IEEE 14-Bus Test System Contain Factory's Load**

| Total Loss | P(MW) | Q(MVar) |
|---|---|---|
| LD Scenario | 46.340 | 340.436 |
| LDx3 Scenario | 51.000 | 227.400 |
| LDx7 Scenario | 320.456 | 1.340.340 |

**Table 2: Line Losses for IEEE 14-Bus Test System Contain EVs Load**

| Total Loss | P(MW) | Q(MVar) |
|---|---|---|
| LD Scenario | 44.250 | 316.540 |
| LDx3 Scenario | 47.300 | 186.200 |
| LDx7 Scenario | 240.600 | 760.570 |

Table 1 and Table 2 provide insightful comparisons of line losses within the IEEE 14-Bus Test System under different load demand scenarios, specifically considering the influence of factories (LD scenarios) and Electric Vehicles (EVs) (LD, LDx3, and LDx7 scenarios). In the LD scenarios representing factories' load, the total line loss gradually increases as the demand surges. The LDx3 scenario, with a threefold increase in load demand, shows a moderate rise in line losses, indicating a proportional impact. However, the LDx7 scenario, where the load demand is amplified sevenfold, demonstrates a more pronounced and nonlinear escalation in total line losses. The reactive power also follows a similar trend, proportionally decreasing with higher load demand.

Conversely, the scenarios with EVs as the primary load source exhibit a different trend. The LD scenario, comprising only EVs, displays a considerable reduction in total line losses compared to its factory-loaded counterpart. Even with a threefold increase in EV load demand (LDx3), the rise in line losses is relatively smaller compared to the LDx3 factory load scenario. Similarly, in the LDx7 scenario, despite a substantial increase in EV load demand, the total line losses remain significantly lower than the LDx7 factory load scenario.

These findings suggest that, despite the inherent variability in power consumption associated with EVs, the impact on line losses is comparatively lower than equivalent scenarios with factory load demand. This highlights the potential benefits of EVs in contributing to grid efficiency and reducing overall line losses. However, both scenarios underscore the critical importance of effective load management and strategic planning to address the challenges posed by increased load demand and optimize power system performance.

To comprehensively evaluate the impact of renewable energy resources on the power grid, an extensive comparative analysis was conducted among the existing scenarios (SG, WG, HG and their respective distributed generation variants (SG, WG, HGx5, SG, WG, HGx8) across all three scenarios. In the augmented x5 and x8 scenarios, the energy production levels of renewable distributed resources were intentionally heightened to five and eight times the standard production, respectively. The resulting line losses in the test network for these carefully devised test scenarios within the IEEE 14-bus test system are succinctly presented in Table 3, providing a quantitative insight into the influence of increased renewable energy generation on grid performance which beneficial to understand Microgrid.

**Table 3: Line Losses for IEEE 14-Bus Test System Contain Renewable Energy Sources**

| Total Loss | P(MW) | Q(MVar) |
|---|---|---|
| SG scenario | 49.600 | 246.400 |
| SGx5 scenario | 56.800 | 251.200 |
| SGx8 scenario | 68.800 | 220.200 |
| WG scenario | 49.600 | 239.200 |
| WGx5 scenario | 50.080 | 244.000 |
| WGx8 scenario | 50.560 | 248.800 |
| HG scenario | 50.800 | 253.600 |
| HGx5 scenario | 58.000 | 258.400 |
| HGx8 scenario | 71.200 | 232.000 |

The line loss analysis within the IEEE 14-Bus Test System, focusing on scenarios with different levels of renewable energy generation, reveals noteworthy trends and comparisons. In the solar-generated (SG) scenarios, the total line losses exhibit a gradual increase with higher renewable energy production. The SGx5 and SGx8 scenarios, featuring fivefold and eightfold increases in solar energy generation, respectively, show elevated total line losses. This suggests a positive correlation between solar energy contribution and line losses, emphasizing the importance of careful management to optimize grid efficiency.

Similarly, in the wind-generated (WG) scenarios, there is a consistent but relatively minor increase in total line losses with higher wind energy production. The WGx5 and WGx8 scenarios, representing fivefold and eightfold increases in wind energy generation, demonstrate a moderate impact on total line losses. Wind energy, being intermittent, showcases a more stable influence on line losses compared to solar energy.

The hybrid-generated (HG) scenarios, combining both solar and wind energy sources, portray an interesting pattern. The total line losses increase with higher renewable energy production, with HGx5 and HGx8 scenarios displaying amplified losses. The combination of solar and wind energy introduces a complex dynamic, contributing to the overall impact on line losses.

Comparatively, across all renewable scenarios (SG, WG, HG), the eightfold increase consistently results in higher line losses, indicating a nonlinear relationship between renewable energy contribution and grid losses. This underscores the importance of balanced integration and effective management of renewable resources to optimize grid performance.

In summary, the analysis suggests that while increasing renewable energy production positively contributes to sustainable power generation, there is a need for strategic planning and advanced grid management to mitigate the associated rise in line losses. The findings provide valuable insights for policymakers and system operators in optimizing the integration of renewable energy sources while ensuring grid reliability and efficiency.

## 5.0 CONCLUSION AND RECOMMENDATIONS

The meticulous hourly load flow analyses conducted on the IEEE 14-bus test system, incorporating electric cars and exploring scenarios with renewable energy sources (RES), yield insightful findings with significant implications for the power system landscape.

In the investigation of Electric Vehicles (EVs), the study presents two load demand scenarios, one representing industrial settings (LD scenarios) and the other focused on EVs, showcasing high variability in power consumption. The results indicate that, under varying load conditions, line losses escalate more pronouncedly with traditional industrial load demands compared to EVs. This suggests the potential benefits of EVs in contributing to grid efficiency and reducing overall line losses, emphasizing the need for strategic load management and planning.

The examination of RES integration (SG, WG, HG scenarios) highlights nuanced trends. While the total line losses gradually increase with higher solar energy production, wind energy exhibits a relatively stable influence, attributed to its intermittent nature. The hybrid scenario combining solar and wind energy introduces complexity, resulting in amplified line losses. The findings underscore the nonlinear relationship between renewable energy contribution and grid losses, emphasizing the necessity for balanced integration and advanced grid management.

The results contribute significantly to the existing literature by providing comprehensive insights into the impacts of EVs and RES on line losses within the power system. The study's importance lies in guiding policymakers and system operators toward optimizing the integration of these evolving energy dynamics while ensuring grid reliability and efficiency.

Challenges identified include the nonlinear relationship between renewable energy production and line losses, necessitating careful planning. Additionally, the study recognizes the need for advanced load management strategies to harness the potential benefits of EVs without compromising grid stability.

Future studies in this domain should delve deeper into dynamic load flow analyses considering a broader range of scenarios, including various EV adoption rates and RES penetration levels. Assessing the economic implications and developing robust optimization strategies for grid performance under evolving energy landscapes would further enhance the understanding of sustainable energy integration.

In conclusion, this study provides a holistic perspective on the intricate interplay of EVs and RES within the power system. The results pave the way for informed decision-making in power system planning, offering a foundation for addressing challenges and optimizing the grid for a sustainable and efficient future.

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