Design and Simulation of E-Vehicle Charging Substations with Load Flow and Performance Analysis

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ABSTRACT

The rapid adoption of electric vehicles (EVs) has created a pressing need for efficient, reliable, and scalable charging infrastructure integrated with existing power distribution networks. This paper presents the design and simulation of electric vehicle charging substations with a focus on load flow and performance analysis. A detailed substation model is developed considering typical EV charging loads, transformer ratings, feeder configurations, and protection constraints. Load flow analysis is carried out to evaluate key performance parameters such as voltage profile, power losses, loading conditions, and system stability under different charging scenarios. Simulation results demonstrate the impact of high EV penetration on distribution networks and highlight critical operational challenges, including voltage deviations and increased losses. The proposed design framework aids in optimizing substation capacity planning and operational efficiency, ensuring reliable power delivery to EV charging stations. The findings provide valuable insights for utilities, planners, and researchers involved in the development of sustainable EV charging infrastructure.

Keywords—Electric Vehicles (EV), Charging Substation, Load Flow Analysis, Power Distribution System, Performance Analysis, Smart Grid, Power Losses.

INTRODUCTION

The global transition toward sustainable and low-carbon transportation has significantly accelerated the adoption of electric vehicles (EVs) in recent years. Governments, industries, and research communities are actively promoting EV deployment as an effective solution to reduce greenhouse gas emissions, dependence on fossil fuels, and urban air pollution. However, the large-scale integration of EVs into existing power systems presents new technical and operational challenges, particularly at the distribution level where EV charging infrastructure is directly connected. Among the critical components of this infrastructure are EV charging substations, which play a vital role in ensuring reliable, efficient, and safe power delivery to charging stations. Unlike conventional electrical loads, EV charging loads are highly dynamic, stochastic, and power-intensive. Fast and ultra-fast charging stations demand high power levels within short durations, leading to significant stress on transformers, feeders, and associated protection equipment. Uncoordinated charging can result in voltage fluctuations, increased system losses, transformer overloading, and degradation of overall power quality. These issues necessitate a systematic design and performance evaluation of EV charging substations to ensure compatibility with existing distribution networks while meeting the growing charging demand. Load flow analysis is a fundamental tool used in power system planning and operation to assess the steady-state performance of electrical networks. It provides critical information regarding bus voltages, power flows, line losses, and equipment loading under various operating conditions. In the context of EV charging substations, load flow studies are essential to analyze the impact of different charging scenarios, penetration levels, and substation configurations on the distribution system. Such analysis enables planners to identify potential constraints, optimize component sizing, and implement corrective measures to maintain network stability and reliability.

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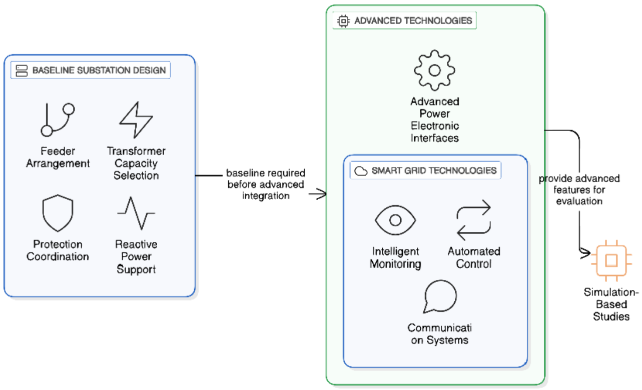

EV Charging Substation Design and Analysis Architecture

The design of EV charging substations requires careful consideration of several technical factors, including transformer capacity selection, feeder arrangement, reactive power support, and protection coordination. Additionally, the integration of advanced power electronic interfaces used in EV chargers introduces harmonics and non-linear characteristics, further complicating substation performance. Simulation-based studies offer an effective approach to model these complexities and evaluate system behavior under realistic operating conditions without disturbing actual grid operations. Recent advancements in smart grid technologies, such as intelligent monitoring, automated control, and communication systems, have further enhanced the potential for efficient EV charging infrastructure. However, before implementing such advanced solutions, it is crucial to establish a robust baseline design supported by detailed load flow and performance analysis shown in Fig. 1. This helps utilities and stakeholders understand the operational limits of the system and develop strategies for future expansion, including the integration of renewable energy sources and energy storage systems. This paper focuses on the design and simulation of EV charging substations with an emphasis on load flow and performance analysis. A comprehensive substation model is developed to represent realistic EV charging loads and distribution network characteristics. Different operating scenarios are simulated to evaluate voltage profiles, power losses, and equipment loading. The analysis aims to identify key performance challenges and propose insights for optimal substation planning and operation. By providing a structured and analytical approach, this study contributes to the development of reliable and sustainable EV charging infrastructure, supporting the broader goals of smart transportation and resilient power systems.

LITERATURE REVIEW

Pawar et al. [1] presented the design of a wireless EV charging station integrated with an automatic billing system, emphasizing user convenience and contactless energy transfer. Their work highlights the growing trend toward wireless charging and automated payment mechanisms, but it primarily focuses on charging technology and billing architecture rather than the impact of charging stations on power distribution networks or substation-level performance. Makuwatsine and Singh [2] investigated the design and simulation of an on-grid solar-powered EV charging station. Their study demonstrated the feasibility of integrating photovoltaic (PV) systems with grid-connected charging infrastructure to reduce dependency on conventional power sources. While the work addresses renewable integration and energy management, detailed load flow and substation performance analysis under varying EV penetration levels remains limited. Nagila et al. [3] focused on ultra-fast EV battery charging using PV sources combined with DC–DC converters. The authors analysed converter performance and charging efficiency, highlighting the technical challenges of fast charging. However, the study does not evaluate the broader distribution system impacts such as voltage variation, feeder congestion, or transformer loading caused by ultra-fast chargers. K. M et al. [4] explored the design and implementation of wireless charging coils for EVs, concentrating on coil geometry, efficiency, and power transfer characteristics. This work contributes to advancements in wireless charging hardware but does not address grid integration challenges or substation-level load flow considerations. Saritha et al. [5] proposed a smart monitoring system for DC power in EVs along with regenerative charging techniques. Their work emphasizes energy recovery and monitoring at the vehicle level, improving overall system efficiency. However, the scope is limited to DC-side monitoring and does not extend to analyzing distribution network performance under aggregated EV charging loads. Kowsalya et al. [6]

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conducted an investigation into batteries and supercapacitors for hybrid EV applications. The study compared energy storage technologies in terms of efficiency, response time, and lifecycle. Although energy storage plays a crucial role in EV charging infrastructure, the work does not examine its influence on charging substations or distribution system load flow. Kavitha et al. [7] presented a retrospective review of solar-powered charging stations and EV technologies. Their survey highlighted the evolution of charging infrastructure and renewable integration trends. While the paper provides valuable insights into technological progress, it lacks quantitative performance analysis of charging stations within power distribution networks. Sivasankar et al. [8] discussed sustainable EV charging infrastructure by integrating solar energy and IoT-based monitoring. Their study focused on smart charging station architecture, real-time monitoring, and energy optimization. However, the impact of such charging stations on voltage stability, losses, and substation loading was not extensively analysed. Sivakumar et al. [9] introduced a UPI-based EV charging station aimed at simplifying payment and improving user accessibility. The work concentrates on digital payment integration and system usability, offering minimal discussion on electrical design, load flow, or performance evaluation of charging substations. Arulmozhi et al. [10] proposed an IoT-enabled EV charging system with battery monitoring and charge scheduling. Their approach improves charging efficiency and battery health through intelligent scheduling. Nevertheless, the study does not include a comprehensive assessment of distribution network constraints under large-scale EV charging scenarios. Senthil et al. [11] investigated solar-based wireless charging using inductive resistance for EVs. The research addressed renewable-powered wireless charging feasibility, but grid interaction, substation design, and system-level performance metrics were not considered. K. V et al. [12] focused on the design and implementation of a common EV charging station suitable for public use. Their work discussed basic electrical design and charging station layout; however, detailed simulation-based load flow analysis and performance evaluation under different EV penetration levels were not included. N. K. K et al. [13] developed a solar-powered EV charging station integrated with IoT for monitoring and control. The study highlighted sustainability and remote monitoring benefits but did not analyze the effects of charging demand variability on distribution substations. Kavin et al. [14] examined dynamic EV charging using wireless power transfer, emphasizing continuous charging while vehicles are in motion. Although innovative, the work remains focused on wireless power transfer mechanisms rather than the supporting power infrastructure and substation performance. Finally, Nair and Sujith [15] presented a comparative path planning analysis for recommending EV charging stations, addressing optimal location and routing strategies. While useful for infrastructure planning from a transportation perspective, the study does not consider electrical network constraints or load flow impacts.

PROPOSED METHODOLOGY

The proposed methodology presents a structured and systematic framework for the design, simulation, and performance evaluation of electric vehicle (EV) charging substations integrated with power distribution networks. The methodology is organized into well-defined phases to ensure accurate system modeling, controlled simulation, comprehensive load flow analysis, and reliable performance assessment under various EV charging scenarios. The following steps outline the complete methodological approach adopted in this study.

1. Selection and Modeling of EV Charging Substation System: The methodology begins with the selection of a representative distribution network integrated with an EV charging substation. A standard test distribution system or a practical radial/meshed distribution feeder is considered to reflect real-world operating conditions. The EV charging substation is modelled by incorporating key components such as distribution transformers, feeders, circuit breakers, protection devices, and EV charging units. Different types of EV chargers (slow, fast, and rapid chargers) are represented using appropriate load models based on their power ratings and charging characteristics. Accurate electrical parameters, including line impedance, transformer ratings, and load demand profiles, are defined to establish a realistic baseline system for analysis.

2. Characterization of EV Charging Load Scenarios: In the next phase, various EV charging scenarios are identified to capture the dynamic nature of EV load demand. These scenarios include normal charging conditions, peak-hour charging, high EV penetration levels, and simultaneous fast-charging events. Time-dependent and aggregated load models are developed to reflect realistic charging behavior. This step enables

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the assessment of the impact of different EV adoption levels on substation performance and distribution network operation.

3. Load Flow Analysis Framework: Load flow analysis is formulated as the core analytical tool to evaluate the steady-state performance of the EV charging substation system. Appropriate load flow algorithms, such as Newton–Raphson or Gauss–Seidel methods, are selected based on system size and convergence requirements. The analysis focuses on determining bus voltage magnitudes, active and reactive power flows, line losses, and transformer loading under each charging scenario. This phase provides insights into voltage regulation issues, feeder congestion, and potential overloading conditions caused by EV charging demand.

4. Simulation Implementation and Parameter Configuration: The complete system model is implemented using simulation tools such as MATLAB/Simulink, ETAP, or other power system analysis software. System parameters, including transformer tap settings, feeder capacities, and load distribution, are configured based on standard practices and utility guidelines. Simulation runs are carried out for each defined EV charging scenario to observe system behavior under varying operating conditions. This controlled simulation environment ensures repeatability and accuracy of results.

5. Performance Evaluation Metrics: System performance is evaluated using key technical metrics such as voltage deviation, total real and reactive power losses, transformer utilization factor, feeder loading percentage, and overall system efficiency. The results obtained from load flow simulations are systematically recorded for each scenario. These metrics enable quantitative assessment of the impact of EV charging substations on distribution network performance and help identify critical operating limits.

6. Comparative and Sensitivity Analysis: A comparative analysis is conducted by evaluating system performance with and without EV charging loads, as well as under different levels of EV penetration. Sensitivity analysis is performed by varying key parameters such as charger ratings, number of charging points, and transformer capacity. This step helps determine the robustness of the substation design and highlights parameters that significantly influence system performance.

7. Validation and Planning Insights: Finally, the results are validated through additional simulation runs and consistency checks to ensure reliability of the findings. The analysed outcomes are used to derive practical insights for optimal EV charging substation planning, capacity sizing, and operational strategies. The proposed methodology provides a comprehensive framework for utilities and researchers to assess EV charging infrastructure impacts and supports the development of efficient, reliable, and scalable EV charging substations for future smart grid applications.

RESULT & ANALYSIS

This section presents the simulation results and detailed analysis of the designed EV charging substation integrated with a distribution network. Load flow studies were carried out under multiple EV charging scenarios to evaluate system performance in terms of voltage profile, power losses, and equipment loading. The simulations were performed using a standard distribution network model with an EV charging substation connected at a designated bus. The base system rating was considered as 11 kV/0.415 kV with a 1 MVA distribution transformer supplying conventional loads along with EV chargers.

1. Description of Simulated Scenarios: To comprehensively analyze the behavior of the proposed EV charging substation and its impact on the distribution network, four distinct operating scenarios were considered in this study. The first scenario represents the base case, where no EV charging load is connected to the system, serving as a reference to evaluate normal network performance. The second scenario corresponds to normal EV charging conditions with approximately 30% EV penetration, reflecting early-stage or moderate adoption of electric vehicles. The third scenario models peak-hour charging conditions with 60% EV penetration, capturing periods of increased demand when many vehicles are charged simultaneously. The fourth and final scenario considers a high EV penetration level of 90% with fast charging facilities, representing a future-intensive charging environment with significant stress on the distribution system. Collectively, these scenarios reflect realistic levels of EV adoption and charging demand typically expected in

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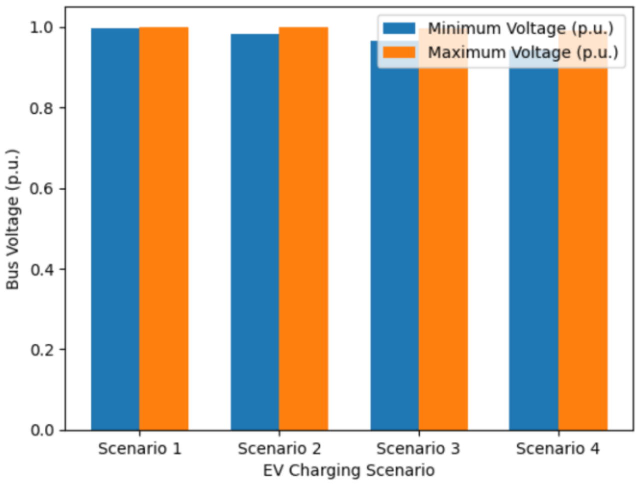
urban distribution networks and enable a thorough assessment of system performance under varying operating conditions.

2. Voltage Profile Analysis: Voltage magnitude at critical buses was analyzed to assess voltage regulation performance. Table I summarizes the minimum and maximum bus voltages obtained from load flow simulations.

Bus Voltage Profile Under Different EV Charging Scenarios

Scenario	Minimum Voltage (p.u.)	Maximum Voltage (p.u.)
Scenario 1	0.997	1.000
Scenario 2	0.982	0.998
Scenario 3	0.964	0.995
Scenario 4	0.942	0.991

In the base case, the voltage profile remains well within acceptable limits. With increasing EV penetration, a noticeable voltage drop is observed, particularly under peak and high fast-changing conditions. Scenario 4 shows the minimum voltage approaching the lower permissible limit (0.95 p.u.), indicating the need for voltage regulation support such as reactive power compensation or on-load tap changers.



Impact of EV Charging Scenarios on Bus Voltage Profile

Fig. 2. showing minimum and maximum bus voltage levels under four different EV charging scenarios. Scenario 1 maintains voltages close to the nominal value of 1.0 p.u., while Scenarios 2, 3, and 4 show progressively lower minimum and maximum voltages. Scenario 4 exhibits the largest voltage drop, indicating increased voltage stress on the distribution network with higher EV charging impact.

3. Power Loss Analysis: Total real and reactive power losses were calculated for each scenario to evaluate the efficiency of the distribution system.

Total System Power Losses

Scenario	Real Power Loss (kW)	Reactive Power Loss (kVAr)
Scenario 1	42.6	31.4
Scenario 2	58.9	44.2

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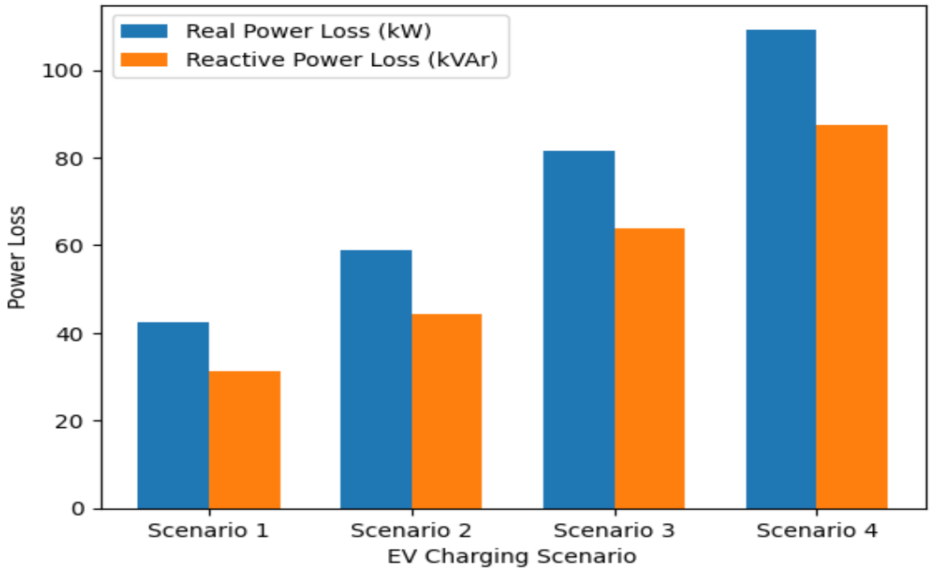
Scenario 3	81.7	63.8
Scenario 4	109.3	87.6

The results indicate a nonlinear increase in power losses with higher EV charging demand. Compared to the base case, real power losses increase by approximately 38% in Scenario 2 and over 150% in Scenario 4. This highlights the significant impact of fast and uncoordinated EV charging on system efficiency and emphasizes the importance of optimized substation and feeder design.



Effect of EV Charging Scenarios on Real and Reactive Power Loss

Fig. 3. showing real and reactive power losses under four different EV charging scenarios. Two bars are displayed for each scenario. The chart indicates that both real and reactive power losses increase significantly from Scenario 1 to Scenario 4, with Scenario 4 experiencing the highest losses, reflecting the increased loading impact of higher EV penetration on the distribution system.

4. Transformer Loading Analysis: Transformer loading is a critical factor affecting reliability and asset lifespan. Table III presents the transformer loading levels under different scenarios.

Distribution Transformer Loading

Scenario	Transformer Loading (%)
Scenario 1	46
Scenario 2	63
Scenario 3	82
Scenario 4	96

Under normal EV charging, the transformer operates within safe limits. However, during peak and high EV penetration scenarios, loading approaches the rated capacity. Scenario 4 indicates near-overloading conditions, which can accelerate transformer aging and increase the risk of thermal failure if sustained over long durations.

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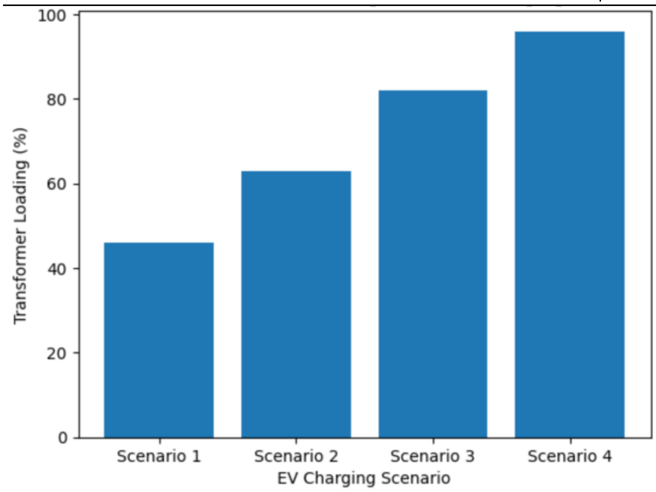


Distribution Transformer Loading under EV Charging Scenarios

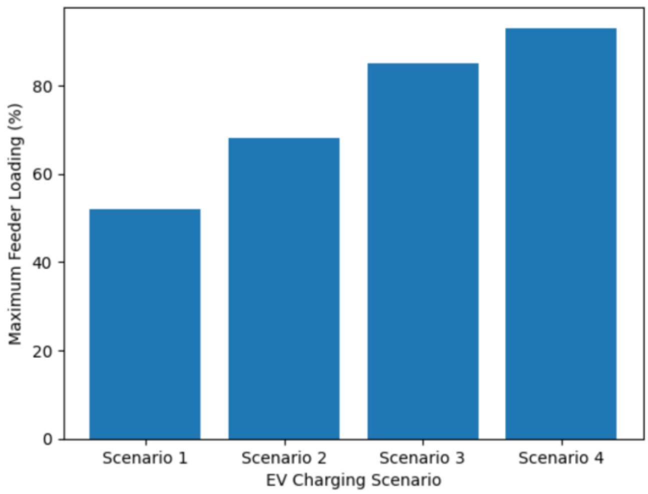
Fig. 4. illustrating distribution transformer loading percentages under four EV charging scenarios. Transformer loading increases steadily from Scenario 1 (46%) to Scenario 4 (96%). Scenario 4 approaches the transformer's rated capacity, indicating a high risk of overloading under heavy EV charging conditions.

5. Feeder Loading and System Performance: Feeder loading levels were also monitored to identify congestion points within the network.

Maximum Feeder Loading

Scenario	Maximum Feeder Loading (%)
Scenario 1	52
Scenario 2	68
Scenario 3	85
Scenario 4	93

The results reveal that feeder congestion becomes critical at high EV penetration levels. While Scenarios 1 and 2 operate comfortably, Scenarios 3 and 4 show feeder utilization nearing thermal limits, potentially leading to protection tripping and reliability concerns.



Impact of EV Charging Scenarios on Feeder Loading

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Fig. 5. showing maximum feeder loading percentages under four EV charging scenarios. Feeder loading increases progressively from Scenario 1 (52%) to Scenario 4 (93%). Scenario 3 and Scenario 4 indicate heavy feeder loading, with Scenario 4 approaching critical operating limits, highlighting the need for feeder capacity enhancement or smart EV charging strategies.

The simulation results clearly demonstrate that EV charging substations significantly influence the operational performance of distribution networks. Increased EV penetration leads to voltage degradation, higher system losses, and increased loading on transformers and feeders. While the system remains stable under moderate EV adoption, high penetration with fast charging necessitates network reinforcement, advanced voltage control, and proper capacity planning. The results validate the effectiveness of load flow analysis as a planning tool for EV charging infrastructure. The datasets and tabulated results provide actionable insights for utilities to determine optimal transformer sizing, feeder upgrades, and the integration of voltage support mechanisms. Overall, the proposed design and simulation framework supports reliable and efficient deployment of EV charging substations in future smart distribution networks.

CONCLUSION

This study presents the design and simulation of an EV charging substation integrated with a distribution network, with emphasis on load flow and performance analysis under varying EV penetration levels. The results demonstrate that while the system operates satisfactorily under low to moderate EV charging demand, high penetration and fast-charging scenarios significantly impact voltage profiles, power losses, and transformer and feeder loading. These findings highlight the necessity of proper substation planning, capacity sizing, and voltage regulation strategies to ensure reliable and efficient operation of EV charging infrastructure. Load flow analysis proved to be an effective tool for identifying critical operating limits and potential network constraints. As a future scope, the proposed work can be extended by incorporating coordinated and smart charging strategies, integration of renewable energy sources and energy storage systems, harmonic and power quality analysis, and real-time control using smart grid technologies to further enhance the resilience, sustainability, and scalability of EV charging substations.

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