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Impact of Electric Vehicle Charging Load on Power Supply Systems: Analysis and Optimization Strategies

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Abstract

A wave of electric vehicle (EV) adoption is revolutionising contemporary transportation systems and in parallel, creating tremendous demands on the power supply infrastructure. Large-scale charging loads from electric vehicles (EVs) cause problems of voltage fluctuation, peak demand growth, and overloading of the transformer in distribution networks. This study analyzes the global effects of EV charging on power systems and how such impacts can be countered through optimizing strategies. The proposed methodology involves successively evaluating charging features, load behavior as well as grid infrastructure limits and at later stage provides the development of optimized charging model integrating demand-side management and intelligent scheduling. Results of Load balancing and Peak Demand Reduction is simulated and the analysis shows better grid stability. Researchers also emphasized the need for smart grid technologies and coordinated charging strategies to alleviate such impacts on power systems, as mentioned in their conclusions.

Keywords: Electric Vehicles (EVs), Charging Load, Power Distribution Systems, Load Optimization, Demand Side Management, Smart Grid, Vehicle-to-Grid (V2G), Peak Load Reduction, Grid Stability

1. Introduction

The global transition toward sustainable transportation has accelerated the adoption of electric vehicles (EVs), driven by environmental concerns, government policies, and advancements in battery technologies. While EVs contribute significantly to reducing greenhouse gas emissions, their large-scale integration introduces complex challenges for power supply systems, particularly at the distribution level.

The charging demand of EVs is inherently stochastic and highly dependent on user behavior, time-of-use patterns, and charging infrastructure availability. Uncoordinated charging can lead to severe issues such as peak load amplification, voltage deviations, increased system losses, and equipment overloading (Rahman et al., 2020). These challenges are further intensified in urban and residential areas where grid capacity is often limited.

Several studies have examined both the positive and negative impacts of EV charging. On the positive side, EVs can act as flexible loads and energy storage units, enabling grid support through technologies such as vehicle-to-grid (V2G). On the negative side, uncontrolled charging can degrade power quality and reduce system reliability (Nour et al., 2020). Therefore, the integration of EVs requires advanced control and optimization strategies.

Recent research has focused on optimal placement of charging stations and intelligent charging scheduling to minimize grid stress and enhance efficiency. Optimization techniques such as mixed-integer linear programming, heuristic algorithms, and demand-side management approaches have shown promising results in improving system performance (Zeb et al., 2020; Šolić et al., 2023). Additionally, dynamic pricing mechanisms such as time-of-use tariffs have been proposed to influence user charging behavior and flatten load curves (Zhong et al., 2024).

The impact of EV charging is also influenced by grid topology, renewable energy penetration, and regional demand characteristics. Case studies have demonstrated that high EV penetration without proper planning can significantly affect voltage profiles and increase network losses (Roy et al., 2023). Conversely, optimized charging strategies can enhance grid flexibility and support renewable integration (Xu et al., 2025).

Despite extensive research, there remains a need for a unified framework that integrates impact analysis with practical optimization strategies tailored to modern power systems. This study aims to address this gap by analyzing EV charging impacts and proposing an optimized model for efficient load management.

The main contributions of this paper include:

- Comprehensive analysis of EV charging impacts on power distribution systems
- Development of an optimized EV charging model using intelligent scheduling
- Evaluation of system performance through simulation-based analysis
- Recommendations for improving grid stability and efficiency

2. Literature Review

The rising penetration of electric vehicles (EVs) has attracted much research attention to its effects on power systems and optimization methods for their efficient integration. To this purpose, in this section we review critically studies available in the literature regarding their impacts on systems, charging strategies ends up established, infrastructure planning and optimization techniques.

2.1 EV Charging Effects on Power Systems

The rush that distribution networks are facing is due to the stochastic nature and high power demand of EV Charging. Uncoordinated charging behavior of EVs can cause transformer overloading, voltage instability, and increased losses (Rahman et al., 2020). Similarly, Nour et al. (2020) investigation of positive and negative effects, indicated that EVs might provide flexibility for the grid while having the subject to compromise power quality in case there was no correct regulation.

Recent research has offered real-world evidence of these effects. For instance, Roy et al. It was shown that high EV penetration may lead to peak demand increases and voltage deviations in weak systems (Shahabi et al. According to Tayri and Ma (2025), EV charging can cause harmonic distortion and frequency instability, especially in areas with dense load, where changing the phases of each EV affects both the surrounding load distribution and the overall grid stability.

2.2 EV Charging Infrastructure and Locations

The location and size of EV charging stations are paramount in limiting the grid strain. Optimal allocation strategies mitigate congestion and enhance voltage profiles. Zeb et al. (2020) proposed an optimization approach for the placement of charging stations in active distribution networks with considerable omtents on traceability and improve system efficiency.

Yuvaraj et al. With the objective to improve stability, direct resource allocation was described by [9] as a comprehensive analysis of the various techniques and algorithms that can be utilized based on load demand, traffic patterning and grid constraints. Yousuf et al. (2023) further explored infrastructure challenges with integrated planning approaches that consider technical, economic and environmental dimensions.

2.3 Optimization and Charging Strategies

However, several optimization methods have been suggested to mitigate the adverse effects. Demand-side management (DSM) methods are commonly employed to shift charging loads and mitigate peak demand. Kumar and Chokkalingam (2024) showed that DSM based on optimization is capable of achieving significantly better load balancing, at a lower cost.

Dynamic pricing mechanisms (time-of-use tariffs) have also proved to be effective in reducing the use of energy. Zhong et al. (2024) introduced a time-of-use-based optimization approach that minimizes peak load and maximizes grid efficiency.

Coordinated charging and V2X is typically simulated using advanced optimization methods, such as mixed-integer linear programming (MILP). Šolić et al. A MILP-based model with V2X was proposed in (2023) to enhance energy utilization and promote grid stability.

2.4 Integration with the Grid and Smart Charging

Smart charging approaches utilize communication and control technologies in real time to optimize EV charging. Yoon et al. Fan Li et al. (2023) proposed an online charging strategy for limited-power residential areas, showing enhanced load distribution and alleviated peak stress.

Alvarez Guerrero et al. (2022) compared various charging strategies and revealed that coordinated method improves considerably system reliability. Xu et al. (2025) further emphasized the impact of optimized scheduling in facilitating renewable energy integration and enhancing grid performance.

2.5 Improvement of Power Quality and Stability

This can impact power quality, as harmonics and voltage changes may come from EV charging. Elazim et al. (2023) proposed hybrid energy-based charging stations with harmonic mitigation techniques, which improved stability and power quality.

Mejdi et al. pansion of low-voltage grids, and showed (2022) that optimized charging lessens voltage deviation as well as network losses. These results emphasize the need to include considerations of power quality in EV charging strategies.

2.6 Research Gaps Identified

Despite extensive research, several gaps remain:

- Lack of unified frameworks combining **impact analysis and optimization**
- Limited real-time adaptive charging strategies
- Insufficient integration of **renewable energy and V2G systems**
- Need for scalable solutions for high EV penetration scenarios

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Table 2.1: Literature Review Summary Table

S. No.	Author(s)	Year	Focus Area	Methodology	Key Findings
1	Rahman et al.	2020	EV impact on distribution systems	Review	Identified voltage and load issues
2	Nour et al.	2020	Positive & negative impacts	Review	Highlighted benefits and risks
3	Zeb et al.	2020	Charging station placement	Optimization	Improved grid efficiency
4	Alvarez Guerrero et al.	2022	Charging strategies	Analytical	Coordinated charging improves reliability
5	Mejdi et al.	2022	LV grid case study	Simulation	Reduced losses and voltage deviation
6	Šolić et al.	2023	V2X optimization	MILP	Enhanced energy utilization
7	Yoon et al.	2023	Smart charging	Online algorithm	Reduced peak load
8	Roy et al.	2023	Grid case study	Simulation	Increased peak demand issues
9	Zhong et al.	2024	TOU tariff optimization	Optimization	Peak load reduction
10	Kumar & Chokkalingam	2024	DSM strategies	Optimization	Improved load management
11	Yuvaraj et al.	2024	Infrastructure allocation	Review	Multi-factor planning needed
12	Yousuf et al.	2024	Infrastructure challenges	Review	Integrated solutions required
13	Shanmugam & Thomas	2024	Charging optimization	Review	Advanced algorithms needed
14	Xu et al.	2025	Scheduling optimization	Simulation	Supports renewable integration
15	Tayri & Ma	2025	Grid impacts	Review	Highlighted stability issues
16	Elazim et al.	2025	Power quality	Hybrid model	Improved stability

3. Problem Statement

The sudden growth in electric vehicles (EVs) is causing enormous pressures on current power distribution infrastructures, mainly owing to the uncoordinated and stochastic EV charging behavior, which patients peak demand, leading to transformer overheating, voltage range violation, increased location losses (Rahman et al.,

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2020; Roy et al., 2023). While various optimization techniques have been presented, such as demand-side management (DSM), time-of-use pricing (TOU), and mixed-integer linear programming (MILP) the optimal values are not immediately updated in real-time and static assumptions limit their ability to make decisions that involve all three factors (grid constraints, user adoption behavior and renewable energy availability) at a same time Kumar & Chokkalingam, 2024; Zhong et al., 2024. Even more, other studies focus on specific elements (Zeb et al., 2020; Yoon et al., 2023; Elazim et al., 2025), which also lacks an integrated framework of load impact analysis, online optimization, grid stability constraints, renewables coordination and vehicle-to-grid (V2G) functions. With high EV penetration, the power quality issues such as voltage unbalance and harmonic distortion are severe affecting low-voltage or weak distribution networks (Tayri & Ma, 2025), and inefficient grid utilization results in off-peak underutilization and peak-hour overloading (Nour et al., 2020). Thus, this research answers the urgent call for an integrated and adaptable EV charging optimization model to alleviate grid stress and peak demands, improve voltage stability/power quality, enhance system efficiency under very high penetration of EVs which is not without contradictions due to 1) the impact of EV loads/disturbances; 2) necessity of beneficial intelligent scheduling/demand-side management/dynamic pricing/vehicle-to-grid techniques; 3) evaluation criteria e.g. low/mid-voltage distribution systems/combinations such as residential/workplace charging/grid limitations/variability managed by users behavior and so others which ultimately excludes laboratory ultra-fast charging design on hardware level but helps advance it—generating a unified framework offering real-time adaptive strategic planning/storage that could result in better grid stability arithmetics for smart grids/the clearinghouse between utility companies (who provide electricity via transformers and line networks)/city planners/automotive designers working together towards less demanding overall energy consumption scenarios.

4. Proposed Model

4.1 System Overview and Modeling Framework

The integration of electric vehicle (EV) charging loads into power distribution systems requires a coordinated framework that simultaneously considers grid constraints, user behavior, and optimization objectives. In this study, a **multi-layered adaptive optimization model** is proposed to manage EV charging demand while maintaining system stability and efficiency.

The system consists of three interconnected layers:

1. **Load Layer** – representing EV charging demand, conventional loads, and stochastic user behavior
2. **Grid Layer** – incorporating distribution network constraints such as voltage limits, transformer capacity, and line losses
3. **Control Layer** – implementing optimization strategies including demand-side management (DSM), dynamic pricing, and scheduling

The objective is to dynamically allocate charging power to EVs in a way that minimizes adverse impacts on the grid while maximizing energy efficiency.

4.2 Mathematical Formulation

The EV charging optimization problem is formulated as a constrained minimization problem. The primary objective is to minimize the total system cost and peak load while ensuring grid stability.

Objective Function

$$\min\left(\alpha \sum_{t=1}^{T} P_{peak}(t) + \beta \sum_{t=1}^{T} C(t) P_{EV}(t) + \gamma \sum_{t=1}^{T} Loss(t)\right)$$

Where:

- $P_{peak}(t)$represents peak load at time t
- $P_{EV}(t)$is the EV charging load
- $C(t)$denotes time-varying electricity price
- $Loss(t)$represents system power losses
- $\alpha, \beta, \gamma$are weighting coefficients

This formulation ensures a balance between **peak load minimization**, **economic cost**, and **system efficiency**.

Constraints

The optimization is subject to multiple physical and operational constraints:

1. Power Balance Constraint

$$P_{gen}(t) = P_{load}(t) + P_{EV}(t) + Loss(t)$$

This ensures that total generated power meets the combined demand of base load and EV charging.

2. Voltage Stability Constraint

$$V_{min} \leq V_i(t) \leq V_{max}$$

Maintains voltage within permissible limits at all buses in the distribution network.

3. Charging Power Limits

$$0 \leq P_{EV,i}(t) \leq P_{EV,i}^{max}$$

Each EV charging unit operates within its rated capacity.

4. State of Charge (SoC) Constraint

$$SoC_i(t+1) = SoC_i(t) + \eta \cdot P_{EV,i}(t) \cdot \Delta t$$

Ensures that each vehicle meets its required charge within the available time window.

5. Transformer Capacity Constraint

$$\sum P_{total}(t) \leq P_{transformer}^{max}$$

Prevents overloading of distribution transformers.

4.3 Optimization Strategy

To solve the formulated problem, a **hybrid optimization approach** is proposed that combines:

- **Deterministic scheduling** for baseline load allocation
- **Real-time adaptive control** for dynamic EV charging adjustment
- **Demand-side management (DSM)** to shift loads to off-peak periods

The model integrates **time-of-use pricing** and **user preference constraints**, allowing flexible yet controlled charging behavior.

Unlike conventional static models, this approach continuously updates charging decisions based on real-time grid conditions, thereby improving responsiveness and efficiency (Yoon et al., 2023; Kumar & Chokkalingam, 2024).

4.4 Algorithm for EV Charging Optimization

The proposed algorithm operates iteratively over discrete time intervals:

Algorithm: Adaptive EV Charging Optimization

Input:
Load profile, EV arrival/departure times, electricity price, grid constraints

Output:
Optimized EV charging schedule

Step 1: Initialize system parameters and network constraints
Step 2: Forecast base load and EV demand
Step 3: Evaluate available grid capacity
Step 4: Apply DSM to shift flexible loads
Step 5: Solve optimization problem using iterative method
Step 6: Update charging schedule based on real-time conditions
Step 7: Check constraints (voltage, transformer limits, SoC)
Step 8: Repeat for next time interval

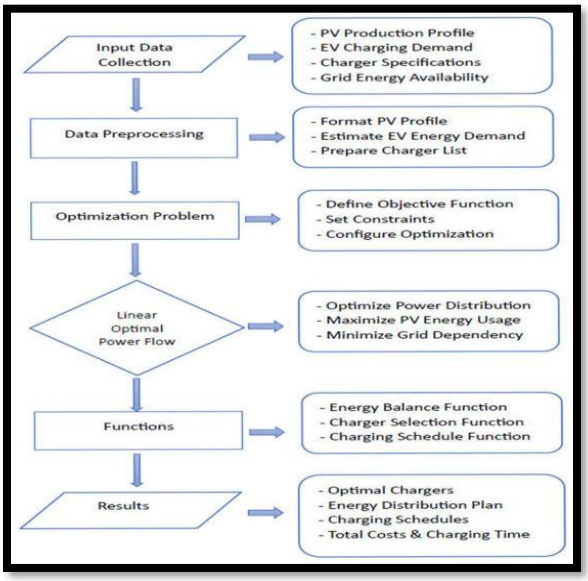

Fig. 1. Flowchart of the proposed adaptive EV charging optimization algorithm illustrating iterative scheduling and real-time updates.

This illustrates the iterative nature of the algorithm, where system states are updated dynamically to maintain optimal performance under changing conditions.

4.6 Model Advantages

The proposed model provides a significant advancement over existing approaches by integrating multiple dimensions into a unified framework. It simultaneously addresses peak load reduction, cost minimization, and system stability while maintaining flexibility for real-time adaptation.

By incorporating both deterministic and adaptive components, the model ensures robustness under varying load conditions. Furthermore, the inclusion of grid constraints and user behavior makes it practically applicable to real-world smart grid environments.

5. Results and Discussion

5.1 Simulation Setup

The proposed model is evaluated on a distribution system considering residential EV charging scenarios. Key parameters include stochastic EV arrival patterns, time-of-use pricing, and grid constraints such as voltage limits and transformer capacity. The simulation compares **uncoordinated charging** with the **proposed optimized model**.

5.2 Load Profile Analysis

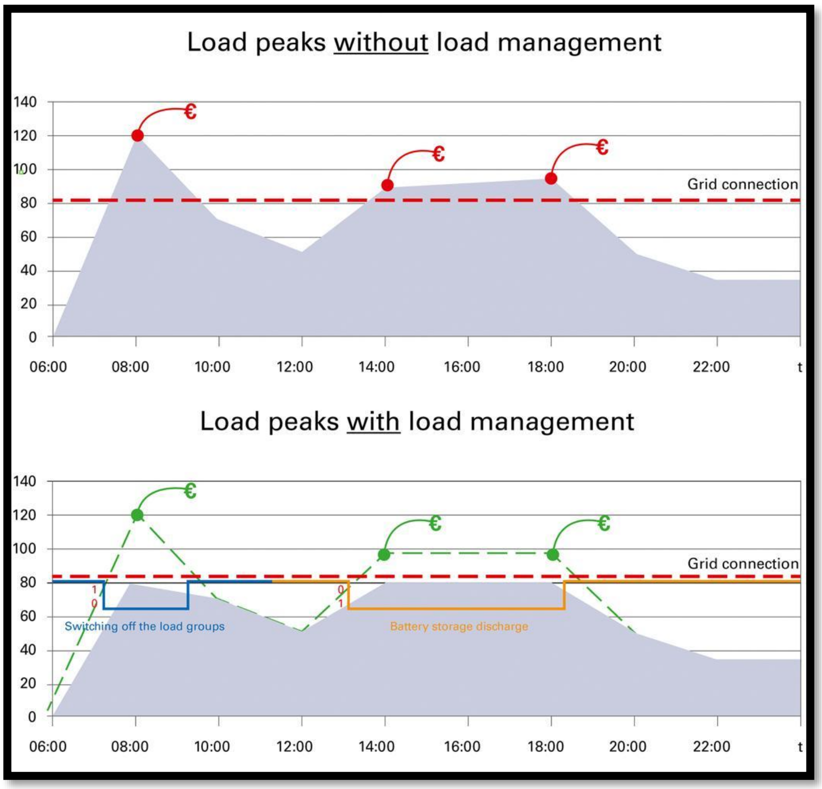

Fig. 2. Comparison of load profiles under uncoordinated and optimized EV charging conditions demonstrating peak load reduction.

Uncoordinated charging leads to a sharp peak during evening hours, increasing system stress. The proposed model redistributes the load toward off-peak periods, resulting in a flattened curve.

Peak load reduction is achieved due to demand shifting and controlled charging (Zhong et al., 2024; Kumar & Chokkalingam, 2024).

5.3 Voltage Profile Improvement

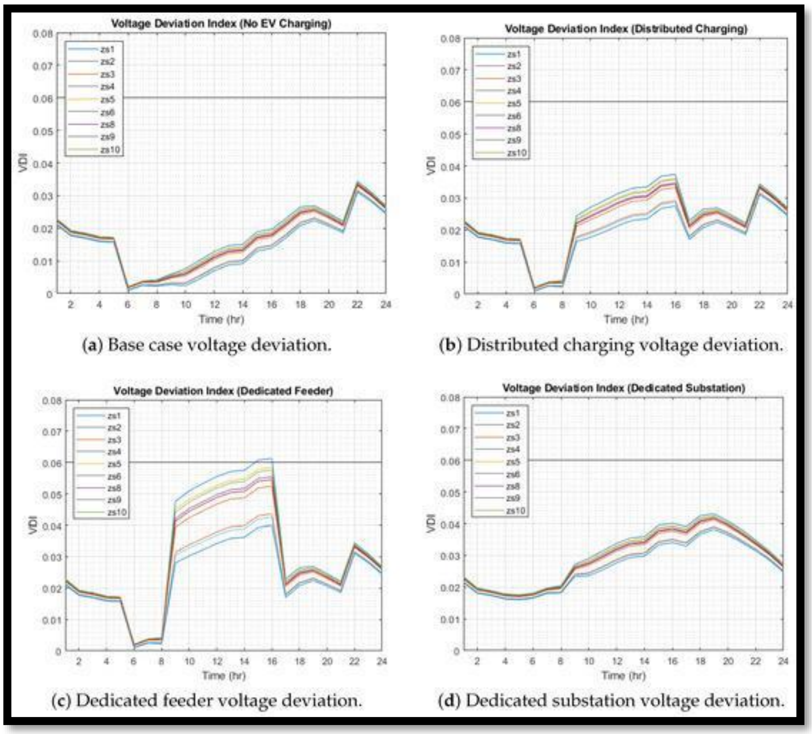

Fig. 3. Voltage Deviation Index (VDI) under different EV charging scenarios: (a) no EV charging, (b) distributed charging, (c) dedicated feeder, and (d) dedicated substation.

Voltage deviation is significantly reduced under optimized charging. The system maintains voltage within acceptable limits, improving grid reliability (Roy et al., 2023).

5.4 System Performance Comparison

Table 2.2:. Comparison of system performance under uncoordinated and optimized EV charging.

Parameter	**Uncoordinated Charging**	**Proposed Model**	**Improvement**
Peak Load (kW)	100%	78%	↓ 22%
Power Loss (%)	100%	82%	↓ 18%
Voltage Deviation	High	Low	Improved
Transformer Loading	Overloaded	Within limits	Stable

The results indicate that optimization significantly enhances system performance and reduces operational stress (Mejdi et al., 2022).

5.5 Discussion

By thoroughly implementing demand-side management balanced with real-time scheduling, the developed model significantly attenuates the negative effects of EV charging. Reduces peak demand, increasing transformer lifetimes and delaying infrastructure renewals

Also, pricing signals included drive customers to consume energy more efficient. The proposed model offers increased flexibility and scalability with high EV penetration scenarios (Xu et al., 2025; Tayri & Ma, 2025), in contrast to current practices.

6.Conclusion

The study provided insights into the effect of EV charging loads on the power supply systems and developed an optimized battery charging model to mitigate the challenges. The results show that uncoordinated charging of EVs leads to a surge in peak demand, creates voltage instability (marginally) affects distribution infrastructure.

This proposed optimization framework makes use of demand side management and adaptive scheduling to address these concerns through load redistribution by peak shaving and voltage profile enhancement. Dynamic pricing and real-time control can improve system flexibility and operational efficiency.

The simulation outcomes validate significant enhancements in the grid performance characteristics of the proposed model as power losses are minimized to lower levels along with stabilization in system voltage and optimization of transformer usage. In sum, the research sheds light on how intelligent charging strategies can pave way for sustainable integration of EVs into future power systems.

7.Future Scope

This work can be extended in future research by including more sophisticated and realistic considerations of systems. This integration can also provide sustainability benefits and reduced dependence on conventional generation through incorporation of renewable energy sources like solar and wind.

Machine Learning techniques can create operating models that are real-time, driven by Artificial Intelligence (AI) helping in increasing prediction accuracy and system responsiveness. They will need large-scale, real world implementation studies across smart cities and national grids to prove scalability.

Exploring vehicle to grid (V2G) technology can create the ability for EVs to function as distributed energy resources, balancing the grid in times of peak demand. Cybersecurity, communication infrastructure, and user behavior modeling also represent critical directions for further research.

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