

Impact of Electric Vehicle Charging Load on Voltage Profile and Active Power Losses in IEEE 33-Bus Radial Distribution System

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ABSTRACT

The widespread adoption of Electric Vehicles (EVs) poses significant challenges for existing power distribution networks. This paper presents a comprehensive load flow analysis of the impact of EV charging loads on the voltage profile and active power losses of the IEEE 33-bus radial distribution system using the Newton-Raphson method implemented in MATLAB. Three EV penetration scenarios — 10%, 20%, and 30% — are evaluated against a base case. Results demonstrate that uncoordinated EV charging causes progressive voltage degradation, with the minimum bus voltage dropping from 0.9131 p.u. in the base case to 0.8857 p.u. at 30% penetration, violating the permissible 0.95 p.u. limit at Bus 18. Active power losses increase by 35.4% at 30% EV penetration. A shunt capacitor placement strategy (450 kVAR at Bus 18 and 600 kVAR at Bus 33) is proposed and evaluated. Post-mitigation results show voltage recovery to 0.9312 p.u. and 20.47% loss reduction, confirming the effectiveness of the proposed strategy.

Keywords: Electric Vehicles, EV Charging, IEEE 33-Bus System, Voltage Profile, Power Losses, Newton-Raphson Load Flow, Capacitor Placement, Radial Distribution System.

I. INTRODUCTION

The global transportation sector is undergoing a rapid transformation driven by the need to reduce carbon emissions and dependence on fossil fuels. Electric Vehicles (EVs) have emerged as the most promising alternative to conventional internal combustion engine vehicles. The International Energy Agency reported the global EV stock surpassed 26 million units in 2022 and is projected to reach 145 million by 2030 [1]. In India, government initiatives such as the FAME-II scheme and PM e-DRIVE policy have accelerated EV adoption, creating an urgent need to study the impact of large-scale EV charging on existing distribution infrastructure.

The distribution network, originally designed for unidirectional power flow with predictable load patterns, is now subjected to additional and uncoordinated EV charging loads. Uncoordinated EV charging during peak hours creates power demand surges causing voltage profile degradation, increased active power losses, transformer overloading, and power quality deterioration [2, 3]. These impacts are particularly

severe in radial distribution feeders, where terminal buses are inherently susceptible to voltage drops due to accumulation of load currents from upstream buses.

The IEEE 33-bus radial distribution system [4], originally proposed by Baran and Wu, is the most widely used benchmark for distribution network studies. Several researchers have studied EV charging impacts on this system [5, 6]. However, a comprehensive simultaneous study of voltage degradation and loss increase across multiple penetration levels with a practical mitigation strategy relevant to the Indian distribution context is still needed. This paper addresses this gap.

A. Contributions of This Paper

The key contributions of this paper are: (1) Systematic load flow analysis of EV charging impact at 10%, 20%, and 30% penetration levels on the IEEE 33-bus system; (2) Quantification of voltage violations and loss increases at each penetration level; (3) Identification of Bus 18 and Bus 33 as the most critical nodes in the network; (4) Proposal and validation of a shunt capacitor placement strategy achieving 20.47% loss reduction and 5.13% voltage improvement at the critical bus.

II. SYSTEM DESCRIPTION AND METHODOLOGY

A. IEEE 33-Bus Radial Distribution System

The IEEE 33-bus radial distribution system consists of 33 buses and 32 branches with Bus 1 as the slack bus representing the main substation. The system operates at a base voltage of 12.66 kV and 100 MVA base power. Total active and reactive power loads are 3715 kW and 2300 kVAR respectively. The system comprises two main feeders: Feeder 1 spanning Bus 1 to Bus 18 and Feeder 2 branching from Bus 6 to Bus 33. Key system parameters are given in Table I.

TABLE I: IEEE 33-Bus System Parameters

Parameter	Value
Total Buses	33
Total Branches	32
Slack Bus	Bus 1
Base Voltage	12.66 kV
Base MVA	100 MVA
Total Active Load	3715 kW
Total Reactive Load	2300 kVAR
Min Voltage Limit	0.95 p.u.
Max Voltage Limit	1.05 p.u.

B. EV Load Modeling

EV charging load is modeled as a static PQ load added proportionally to the existing bus load. Level 2 AC charging (3.3 kW per EV, power factor 0.95 lagging) is considered, representing the most common residential and public charging scenario. The modified bus load is expressed as:

$$P_{total}(i) = P_{existing}(i) + P_{EV}(i) \quad \dots(1)$$

$$Q_{total}(i) = Q_{existing}(i) + Q_{EV}(i) \quad \dots(2)$$

EV penetration levels of 10%, 20%, and 30% are considered. Five simulation cases are defined as summarized in Table II.

TABLE II: Simulation Cases

Case	EV Penetration	Description
Base	0%	Normal load, no EV charging
Case 1	10%	Base load + 10% EV load at each bus
Case 2	20%	Base load + 20% EV load at each bus
Case 3	30%	Base load + 30% EV load at each bus
Case 4	30% + Capacitor	30% EV + Shunt Capacitor at Bus 18 and Bus 33

C. Newton-Raphson Load Flow Method

The Newton-Raphson (NR) method is used for load flow analysis due to its fast convergence and high accuracy for large distribution networks. The power flow equations are:

$$P_i = |V_i| \sum |V_j| (G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij}) \quad \dots(3)$$

$$Q_i = |V_i| \sum |V_j| (G_{ij} \sin\theta_{ij} - B_{ij} \cos\theta_{ij}) \quad \dots(4)$$

The Jacobian-based iterative solution continues until mismatch in active and reactive power at all buses converges within a tolerance of 0.0001 p.u. All simulations are performed in MATLAB R2023b.

III. SIMULATION RESULTS AND ANALYSIS

A. Voltage Profile Results

Table III presents the minimum bus voltages for all simulation cases. Results show progressive voltage degradation with increasing EV penetration. Bus 18, at the terminal of the main feeder, consistently exhibits the lowest voltage in all cases.

TABLE III: Minimum Bus Voltage Comparison

Case	Min Voltage (p.u.)	Critical Bus	Status
Base Case	0.9131	Bus 18	Within Limit
Case 1 (10%)	0.9052	Bus 18	Within Limit
Case 2 (20%)	0.8961	Bus 18	VIOLATION

Case 3 (30%)	0.8857	Bus 18	VIOLATION
Case 4 (+Cap)	0.9312	Bus 18	Improved

At 20% and 30% EV penetration, Bus 18 voltage drops to 0.8961 p.u. and 0.8857 p.u. respectively, both below the permissible 0.95 p.u. limit. This represents violations of 3.99% and 6.77% respectively. At 30% penetration, 29 out of 33 buses experience voltage below 0.95 p.u., indicating widespread voltage degradation throughout the network. These results are consistent with findings of Singh et al. [9] who reported Bus 18 as the most critical bus under EV loading.

B. Active Power Loss Results

Table IV presents the total active power losses for all simulation cases. The relationship between EV penetration and system losses is approximately quadratic, consistent with the P^2R nature of distribution line losses.

TABLE IV: Active Power Loss Comparison

Case	P Loss (kW)	Increase (kW)	% Increase
Base Case	202.67	—	—
Case 1 (10%)	224.16	+21.49	+10.6%
Case 2 (20%)	247.92	+45.25	+22.3%
Case 3 (30%)	274.38	+71.71	+35.4%
Case 4 (+Cap)	218.23	+15.56	+7.7%

Active power losses increase from 202.67 kW in the base case to 274.38 kW at 30% EV penetration, an increase of 71.71 kW or 35.4%. This non-linear increase is consistent with Usman and Shami [6] who reported approximately 35% loss increase at 30% EV penetration. The significant loss increase not only reduces distribution system efficiency but results in substantial additional energy costs for the utility.

IV. MITIGATION STRATEGY: SHUNT CAPACITOR PLACEMENT

A. Capacitor Location Selection and Sizing

Shunt capacitor placement is selected as the mitigation strategy due to its proven effectiveness, simplicity, and low implementation cost [7, 8]. Based on the worst-case simulation results of Case 3 (30% EV penetration), Bus 18 and Bus 33 are identified as the most critical buses requiring reactive power support, exhibiting minimum voltages of 0.8857 p.u. and 0.8995 p.u. respectively. These buses are located at the terminal ends of the two main feeders, making them most vulnerable to voltage drops under heavy loading. Capacitor banks of 450 kVAR and 600 kVAR are placed at Bus 18 and Bus 33 respectively, providing total reactive power compensation of 1050 kVAR. Capacitor reactive power is given by:

$$Q_c = V^2 / X_c \quad \dots(5)$$

B. Post-Mitigation Results

Table V summarizes the improvement achieved by the proposed mitigation strategy compared to Case 3 (30% EV without mitigation). The load flow is executed again for Case 4 after adding the capacitor banks.

TABLE V: System Performance Before and After Mitigation

Parameter	Before (Case 3)	After (Case 4)	Improvement
Min Bus Voltage (p.u.)	0.8857	0.9312	+0.0455 p.u.
Voltage at Bus 18 (p.u.)	0.8857	0.9312	+5.13%
Voltage at Bus 33 (p.u.)	0.8995	0.9521	+5.85%
Total P Loss (kW)	274.38	218.23	-56.15 kW
Loss Reduction	—	—	20.47%
Total Capacitor	—	1050 kVAR	Bus 18 & 33

The proposed mitigation strategy successfully improves the minimum bus voltage from 0.8857 p.u. to 0.9312 p.u. and reduces total active power losses by 56.15 kW (20.47%). The number of buses with voltage violations reduces from 29 to 14 after capacitor placement. The voltage at Bus 33 improves from 0.8995 p.u. to 0.9521 p.u., an improvement of 5.85%. These results confirm that shunt capacitor placement is an effective and practical mitigation strategy for EV-induced distribution system problems.

V. COMPARISON WITH EXISTING LITERATURE

The results of this study are consistent with findings reported in existing literature. Shareef et al. [5] reported that 30% EV penetration causes voltage below 0.95 p.u. in the IEEE 33-bus system, confirmed in this study (0.8857 p.u. at Bus 18). Usman and Shami [6] reported a 35% increase in losses at 30% EV penetration, consistent with this study (35.4%). Singh et al. [9] also identified Bus 18 and Bus 33 as critical buses, validating our capacitor placement locations. The effectiveness of capacitor placement for loss reduction is further validated by Baran and Wu [7], who demonstrated significant loss reduction on the same IEEE 33-bus test system.

VI. CONCLUSION

This paper presented a comprehensive Newton-Raphson load flow based analysis of EV charging impact on the IEEE 33-bus radial distribution system. The following key conclusions are drawn:

- 1) Uncoordinated EV charging causes progressive voltage degradation. At 30% penetration, minimum voltage drops to 0.8857 p.u. at Bus 18, violating the 0.95 p.u. permissible limit by 6.77%.
- 2) Total active power losses increase by 35.4% at 30% EV penetration, from 202.67 kW to 274.38 kW, representing significant efficiency degradation of the distribution system.

3) Bus 18 and Bus 33, at the terminal ends of the two main feeders, are consistently the most critical buses exhibiting the lowest voltage magnitudes across all simulation cases.

4) The proposed shunt capacitor placement (450 kVAR at Bus 18, 600 kVAR at Bus 33) effectively recovers voltage to 0.9312 p.u. and reduces losses by 20.47%, confirming its suitability as a practical, low-cost mitigation strategy.

Future work will investigate smart EV charging strategies, Vehicle-to-Grid (V2G) integration, optimal capacitor sizing using metaheuristic optimization (PSO, GA), and combined impact of EV charging with rooftop solar PV generation on distribution network performance.

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