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Research Article

The Strategy of Managing the Influence of Electric Vehicles along with Demand Response Loads in the Electricity Distribution Network with the Aim of Reducing Operating Costs and Improving Network Losses and Voltage Drop

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Extended Abstract

The rapid global deployment of electric vehicles (EVs) represents a pivotal shift toward sustainable urban mobility, driven by advancements in battery technology, tightening emissions regulations, and the urgent need to mitigate fossil fuel dependency. However, the uncoordinated integration of EVs into existing low-voltage distribution networks—originally designed without anticipating such dynamic, high-power, and spatially concentrated loads—poses significant operational challenges. These include increased peak demand coinciding with typical grid stress hours, elevated energy losses, voltage violations (particularly at feeder extremities), and phase unbalance due to single-phase residential EV connections. Left unmanaged, high EV penetration can compromise network reliability, necessitate costly infrastructure upgrades, and undermine the economic and environmental benefits of electrified transportation.

This paper addresses this critical challenge by proposing an integrated optimal management strategy that synergistically combines Demand Response (DR) programs and bidirectional EV charging/discharging (G2V/V2G) to transform EV integration from a threat into a grid asset. The core innovation lies not merely in adopting known tools, but in their co-optimized, multi-objective coordination within a unified framework that simultaneously targets both economic efficiency and technical performance of the distribution system.

The proposed approach is formulated as a multi-objective optimization problem with four key objectives:
(1) Minimization of the total energy procurement cost for end-users;
(2) Minimization of the cost associated with EV energy supply (which can become negative during V2G);
(3) Minimization of network energy losses; and
(4) Minimization of voltage deviation from nominal values across all three phases to mitigate unbalance.

The economic objective function (EOF) encapsulates the net cost of supplying base residential loads, EV charging/discharging transactions, network losses, and incentive payments to DR participants. Crucially, the model explicitly differentiates between Grid-to-Vehicle (G2V) and Vehicle-to-Grid (V2G) modes, allowing EVs to act as distributed energy storage resources that can inject power back into the grid during peak hours, thereby generating revenue for their owners and providing ancillary services to the operator.

The technical objective function (VOF) focuses on maintaining voltage stability and balance. It penalizes the deviation of the voltage magnitude at each phase of every bus from its nominal value (1.0 p.u.), directly targeting the root causes of voltage drop and phase unbalance exacerbated by unevenly distributed, single-phase EV loads.

The optimization model is subject to a comprehensive set of constraints that ensure physical and operational feasibility:

- Power flow equations for unbalanced three-phase radial distribution networks (IEEE 37-bus standard);
- EV-specific constraints, including state-of-charge (SoC) dynamics, battery capacity limits, bidirectional power flow limits governed by charger/inverter ratings, and binary variables to enforce exclusive G2V or V2G operation;
- DR program constraints, modeling two types of responsive loads: (i) price-sensitive loads that can shift consumption across time blocks based on elasticity, and (ii) voltage-sensitive loads that can be curtailed during low-voltage events; participation is bounded at both individual and system-wide levels;
- Network operational constraints, including bus voltage limits (0.9–1.05 p.u.), feeder thermal limits, and substation capacity (800 kVA).

To solve this complex mixed-integer nonlinear problem, a two-stage solution methodology is employed. In the first stage, the ε-constraint method is used to generate a set of Pareto-optimal solutions by treating one objective as primary while converting the others into constraints with varying thresholds. This effectively explores the trade-off frontier between economic and technical goals. In the second stage, a fuzzy max-min decision-making approach is applied to select the most balanced compromise solution from the Pareto set, ensuring equitable satisfaction of all objectives.

The strategy is rigorously validated on the IEEE 37-bus unbalanced distribution test system, populated with 150 residential EVs (two per load bus). Realistic behavioral models are used to simulate stochastic EV arrival/departure times and daily energy consumption (20–30 miles/day), based on normal probability distributions. The evaluation is conducted across three key scenarios:

1. Unmanaged EV Integration: At 50% penetration (75 EVs), the substation hits its 8.0 p.u. capacity limit, voltage at the terminal bus (Bus 36) drops below 0.85 p.u. (violating the 0.9 p.u. limit), and daily energy losses increase by 33.3% (from 39.1 to 58.0 kWh). The total energy procurement cost rises to $230.61.
2. DR-Only Management: Implementing DR alone allows penetration to increase to 75% (112 EVs) and provides modest improvements—peak load is reduced by 14.1%, losses by 13%, and voltage unbalance by 21.2%. However, it remains insufficient to support full (100%) EV penetration without violating operational constraints.
3. Proposed Co-Optimized Strategy (DR + EV G2V/V2G): This integrated approach enables 100% EV penetration (all 150 vehicles) while significantly enhancing grid performance. The peak load is reduced by 18.5% (to 5.049 p.u.), freeing up 22% of substation capacity for future loads. Remarkably, despite the added load, total daily energy losses increase by only 1 kWh (to 40.1 kWh) compared to the no-EV base case. Voltage at Bus 36 is maintained at a stable 0.92 p.u., and phase unbalance is reduced by over 50%. The total operating cost is lowered to $184, an 8.15% reduction compared to the unmanaged 50% penetration scenario and a striking achievement given the doubled EV fleet.

In conclusion, this work demonstrates that the challenges of high EV penetration can be effectively converted into opportunities through intelligent, co-optimized resource management. The proposed strategy not only defers costly network upgrades but also actively improves grid resilience, efficiency, and power quality. Its robustness to behavioral uncertainties and its balanced treatment of economic and technical priorities make it a practical and scalable solution for modern distribution system operators. Future work

will extend this framework to incorporate distributed renewable generation and more sophisticated uncertainty modeling for load and EV behavior.

Keywords: electric vehicle management, power distribution network, energy loss, optimization, voltage drop, responsive loads

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