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A Multi-Objective Optimization Approach for Load Smoothing and Rapid PEV Charging in Low-Voltage Networks

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***Abstract*—The widespread adoption of Plug-in Electric Vehicles (PEVs) creates significant challenges for existing low-voltage (LV) distribution networks, including voltage deviations, load imbalance, and increased stress on grid assets. This paper proposes a multi-objective optimization framework for coordinated PEV charging that jointly considers grid load smoothing and rapid charging. An energy management system (EMS) dynamically allocates charging power according to network conditions and user charging requirements. A Pareto-front analysis is used to characterize the trade-off between charging speed and grid performance, while Jain's Fairness Index and the Gini coefficient assess the equity of charging among users. Simulation results show that the proposed strategy smooths the power profile and maintains fair charging progress across all vehicles. The voltage evaluation further identifies operating points that may lead to voltage violations at the most critical bus under high PEV penetration, highlighting the need for voltage-aware charging coordination in future LV networks.**

Keywords—Fairness metrics, Load smoothing, Distribution networks, Multi-objective optimization, Plug-in electric vehicles

I. INTRODUCTION

The number of Plug-in Electric Vehicles (PEVs) has increased rapidly in recent years, driven by advances in battery technology, cost reductions, and global decarbonization policies [1]. This growth is expected to continue, with electric vehicles projected to represent a major share of future road transport [2]. However, large-scale PEV integration can create significant challenges for low-voltage (LV) distribution networks, including demand peaks, voltage deviations, and overloading of transformers and feeders [3]. Since many LV networks were not originally designed for high charging demand, coordinated and optimized charging strategies are required to maintain reliable and stable network operation with limited power system investment.

In response to these challenges, extensive research has focused on developing energy management systems (EMSs) that treat PEVs as flexible and controllable loads [4]. Coordinated charging strategies have been proposed for different application scales, including commercial fleets [5], residential condominiums [6], microgrids [7], and capacity-constrained distribution networks [8]. Other studies have investigated dynamic pricing and demand-side management mechanisms to shift charging demand away from peak-load periods and improve grid operation [9], [10]. Stochastic and predictive approaches have also been introduced to account for renewable generation, electricity prices, user preferences, and demand uncertainty [11], [12]. In parallel, multi-objective PEV charging methods have been proposed to balance operational cost, charging convenience, peak reduction, and power system efficiency [13]. However, fewer studies jointly analyze load smoothing, rapid charging, fairness among users, and voltage behavior in LV networks within the same coordinated charging framework.

Despite these efforts, existing optimization models often emphasize different objectives separately. Some studies focus on cost minimization, others prioritize fast charging and user convenience, while others aim to smooth the load profile to improve grid performance. However, these objectives are conflicting, since improving charging speed may increase demand peaks and worsen network operating conditions. Moreover, fairness among users and voltage impacts in LV feeders are not always evaluated together with the charging schedule. Therefore, a coordinated multi-objective framework is needed to balance grid stability, charging efficiency, and user equity in a practical charging strategy [13].

To address these conflicting objectives, this paper proposes a multi-objective optimization framework for coordinated PEV charging in LV distribution networks. The framework jointly minimizes upward grid-power peaks and the remaining SOC deficits at vehicle departure, thereby balancing load smoothing and rapid charging requirements. Unlike approaches that mainly focus on cost reduction or charging completion, the proposed method explicitly evaluates the trade-off between grid-oriented and user-oriented objectives through a Pareto-front analysis. In addition, fairness among PEV users is assessed using the Gini

coefficient and Jain's Fairness Index, while voltage profiles are evaluated in MATLAB/Simulink to identify operating points that may become critical for LV network operation.

The remainder of this paper is organized as follows: Section II presents the constraints, objective functions, and voltage evaluation method; Section III describes the case study setup; Section IV discusses the simulation results and analysis; and Section V concludes the paper with key findings and suggestions for future work.

II. Constraints and Objective Functions

This section presents the proposed multi-objective optimization framework for coordinated PEV charging, including the main operational constraints, objective functions, and voltage evaluation method.

A. LV Distribution Network Configuration

A representative LV distribution network is illustrated in Fig. 1, showing an EMS connected to the utility grid, residential demand, and several PEV charging units. The EMS monitors total demand and grid power exchange while scheduling PEV charging according to network capacity and user requirements. Each PEV communicates its state of charge (SOC) and charging requirements to the EMS, which allocates charging power accordingly. This configuration represents residential or community-scale applications, such as neighborhoods, office complexes, or public parking areas. The objective is to coordinate charging so that vehicles reach, or come as close to, their target SOCs before departure, depending on available grid capacity and system constraints. This strategy supports efficient use of the distribution network while maintaining reliability and user satisfaction.

B. Power Balance and Operational Constraints

At each time interval, the total power imported from the upstream grid must equal the sum of the residential load demand and the charging demand of all connected PEVs. This balance is expressed as

$$P_{Grid}(t) = \sum_{b=1}^{B} P_{load,b}(t) + \sum_{v=1}^{V} P_{PEV,v}(t)\,,\ \forall t. \tag{1}$$

Here, $P_{load,b}(t)$ denotes the demand at bus b, and $P_{PEV,v}(t)$ is the charging power assigned to vehicle v. The terms B and V represent the total number of buses and PEVs, respectively. $P_{Grid}(t)$ indicates the total power imported from the upstream grid.

To prevent grid congestion, the total imported power must remain below the maximum allowable capacity P_{Grid}^{max}:

$$P_{Grid}(t) \le P_{Grid}^{max},\ \forall t. \tag{2}$$

By dynamically adjusting charging power within this limit, the EMS maintains operational feasibility while supporting efficient energy use and user satisfaction.

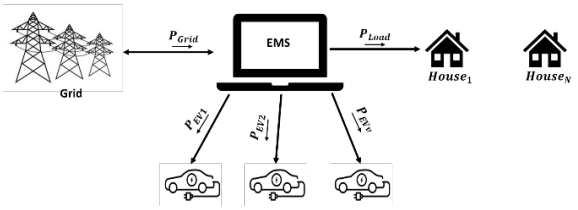


Fig. 1. Configuration of a LV distribution network

To penalize upward demand peaks, a non-negative auxiliary variable $P_{pen}(t)$ is introduced as:

$$P_{Grid}(t) - P_{avg} \le P_{pen}(t),\ \forall t, \tag{3}$$

where $P_{pen}(t) \ge 0$. This variable quantifies the amount by which the total grid power exceeds the average base demand level.

The average grid demand, computed from the residential load without PEV charging is given by

$$P_{avg} = \frac{1}{T}\sum_{t=1}^{T}\Big(\sum_{b=1}^{B} P_{load,b}(t)\Big). \tag{4}$$

Let $SOC_v(t)$ denote the state of charge of vehicle v at time t. Each PEV arrives at $t_{arr,v}$ and remains connected until its departure time $t_{dep,v}$, which is defined by the user's availability. The SOC evolution is modeled in discrete time as

$$SOC_v(t+1) = SOC_v(t) + \frac{\eta P_{PEV,v}(t)\Delta t}{E_v^{nom}}, \qquad t_{arr,v} \le t < t_{dep,v}. \tag{5}$$

Where η is the charging efficiency, Δt is the time-step duration, and E_v^{nom} is the nominal battery energy capacity.

The SOC must remain within feasible bounds:

$$0 \le SOC_v(t) \le 1, \quad \forall v, t. \tag{6}$$

The charging power for each vehicle is constrained by the charger and battery limits:

$$0 \le P_{PEV,v}(t) \le P_{PEV,v}^{max} \quad \forall v, t. \tag{7}$$

To represent the remaining SOC deficit at departure, a non-negative auxiliary variable $z_{PEV,v}$ is defined as

$$z_{PEV,v} \ge SOC_v^{target} - SOC_v\big(t_{dep,v}\big),\ \forall v. \tag{8}$$

If the target SOC is reached, $z_{PEV,v} = 0$. This formulation reflects practical situations where the departure time is fixed by the user's schedule, and the EMS aims to minimize the unmet charging requirement within the available connection window.

C. Objective Functions

The optimization problem is formulated from the perspective of the distribution system operator (DSO), aiming to maintain network operation and stability while satisfying user charging requirements. Two complementary objectives are considered within the multi-objective framework: grid load smoothing and minimization of user dissatisfaction.

The load smoothing objective reduces peaks in grid power demand by penalizing exceedances above the average base demand level:

$$J_1 = \sum_{t=1}^{T}\big(P_{pen}(t)\big)^2. \tag{9}$$

Minimizing J_1 reduces upward grid-power peaks and helps limit transformer and feeder loading, thereby improving operational stability. This formulation focuses the smoothing effort on demand spikes above the average base demand, which are typically critical for congestion and equipment stress in LV networks.

In parallel, the second objective minimizes user dissatisfaction, represented by the aggregated SOC deficit across all vehicles at their respective departure times:

$$J_2 = \sum_{v=1}^{V} z_{PEV,v}. \quad (10)$$

Minimizing J_2 encourages the EMS to reduce the remaining SOC deficit at departure and therefore improve user charging satisfaction within the available connection window.

To combine the two objectives, a weighted-sum approach is adopted. Since J_1 and J_2 have different numerical scales, each objective is normalized before applying the weighting factors. Specifically, J_1 and J_2 are divided by their respective maximum values, J_1^{max} and J_2^{max}, obtained from preliminary runs that identify the highest value reached by each objective. The final multi-objective function is therefore written as

$$Minimize: OF = \alpha \frac{J_1}{J_1^{max}} + \beta \frac{J_2}{J_2^{max}} \quad (11)$$

where α and β determine the relative importance of load smoothing and user satisfaction, respectively. Normalizing both objectives places them on a comparable scale and enables a fairer evaluation of the Pareto front.

D. Voltage Evaluation Method

To assess the voltage behavior of the LV distribution network under the optimized charging schedules, the feeder is modeled in MATLAB/Simulink. The power profiles obtained from the multi-objective optimization, including residential load demand and PEV charging power, are applied to the corresponding buses of the network model. The simulation is performed over the full scheduling horizon, and the nodal voltages are computed at each time step. In this work, voltage limits at each bus are checked after the optimization stage to identify Pareto solutions that may cause voltage-critical operating conditions. This post-optimization analysis shows the impact of coordinated PEV charging on the weakest feeder buses and supports the selection of voltage-compliant operating points.

III. Case Study and System Description

The proposed optimization framework is tested on a seven-bus radial LV distribution feeder supplying both residential loads and PEV charging stations, as illustrated in Fig. 2. The feeder has a total length of $450\,m$ and is connected to the upstream medium-voltage grid through a $20\,kV/230\,V$, $200\,kVA$ distribution transformer. Residential loads are located at buses 1 to 6, with peak apparent power ranging from 6 to $12\,kVA$. These loads represent aggregated residential demand at each bus, corresponding approximately to ten to twelve households. In addition, one PEV charging station is installed at each bus from 1 to 6, with a maximum charging power of $6.6\,kW$ per charger.

The maximum allowable grid import P_{Grid}^{max} from Eq. (2) is set according to the transformer rating and LV feeder capacity. The charging efficiency η is fixed at 0.97 to represent typical AC charging conditions. Each PEV is equipped with a battery of nominal capacity $E_v^{nom} = 40\,kWh$, representing a common mid-range passenger electric vehicle.

The overall network demand follows a typical residential daily pattern, with higher consumption during morning and evening periods. Load profiles are drawn from the GECAD laboratory dataset [14], which provides measured residential consumption data. A distinct aggregated household profile is assigned at each connection bus, allowing the case study to represent realistic LV operating conditions while keeping the feeder model compact for evaluating the proposed charging optimization framework.

IV. Results

This section presents the results obtained from the multi-objective framework. It outlines the procedure for selecting weighting coefficients, analyzes the resulting Pareto front and fairness indices, and evaluates the impact of optimized charging on the voltage profiles of the weakest bus.

A. Weighting Coefficient Selection and Simulation Setup

To evaluate the trade-off between load smoothing and rapid charging, a series of simulations were conducted by varying the weighting coefficients α and β in (11). A total of 100 combinations were tested under the constraint $\alpha + \beta = 1$, where α represents the importance of grid-power smoothing (J_1) and β corresponds to the priority given to reducing user dissatisfaction (J_2). This parameter sweep enables a comprehensive exploration of the Pareto front, illustrating how different weighting preferences influence system performance and charging outcomes.

The study considers multiple PEVs connected to different buses within the distribution feeder. For all PEVs, the arrival time ($t_{arr_{PEV_v}}$) is set to 7:30 am, the departure time

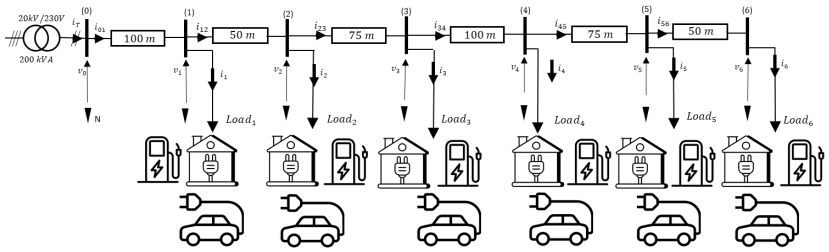


Fig. 2. Studied LV distributed network

($t_{dep_{PEV_v}}$) is set to 2: 30 pm, and the target SOC ($SOC_{\mathrm{PEV_v}}^{final}$) is set to 100%. The SOC values at arrival are summarized in Table 1. The selected time window represents a controlled daytime charging scenario, such as workplace or community parking, where vehicles arrive in the morning and remain connected for a limited period. These parameters define each vehicle's feasible charging interval within the optimization horizon. Since the available time window does not allow any vehicle to reach full charge, the analysis focuses on assessing the efficiency and fairness of the proposed multi-objective approach rather than achieving complete charge saturation.

Table 1. PEV location and initial SOC values

PEV location [P_{PEV_v}]	SOC at arrival [$SOC_{\mathrm{PEV_v}}^{initial}$]
PEV 1 at bus 1	37%
PEV 2 at bus 2	35%
PEV 3 at bus 3	40%
PEV 4 at bus 4	35%
PEV 5 at bus 5	50%
PEV 6 at bus 6	45%

This setup allows the optimization process to analyze how varying the emphasis between J_1 and J_2 affects charging performance, network loading, and user satisfaction. The resulting solutions form the basis for the Pareto-front analysis presented in the following subsection.

B. Pareto-Front Analysis and Performance Evaluation

The Pareto front represents the set of non-dominated solutions that define the optimal trade-off between the two conflicting objectives: load smoothing (J_1) and user dissatisfaction (J_2). Each point on the Pareto front corresponds to a specific selection of weighting coefficients (α, β) with $\alpha + \beta = 1$. This representation shows how emphasizing one objective, such as rapid charging, can negatively affect the other by increasing grid-power peaks. The optimization sweep generates a series of Pareto-optimal solutions, as shown Fig. 3, with each point representing a different balance between load smoothing and user satisfaction. As α increases, the grid power profile becomes smoother, leading to a lower J_1, but user dissatisfaction increases due to a higher J_2. Conversely, lower values of α prioritize rapid charging, which may lead to larger demand fluctuations. The Pareto front therefore supports the selection of an operating point according to the desired compromise between grid-oriented and user-oriented objectives.

To further evaluate the fairness and charging balance of the Pareto-optimal solutions, two performance indicators are computed: the Gini coefficient index and Jain's Fairness Index (JFI) [15]. In this study, both metrics are applied to the SOC deficits of the PEVs at departure, allowing an assessment of how equitably the remaining charging deficit is distributed across vehicles. The Gini coefficient measures the inequality among the SOC deficits and is expressed as

$$G = \frac{\sum_{v=1}^{V}\sum_{w=1}^{v}|z_{PEV,v} - z_{PEV,w}|}{2V^2\bar{z}}, \qquad (12)$$

where $z_{PEV,v}$ and $z_{PEV,w}$ represent the SOC deficit of PEV,v and PEV,w, and $\bar{z}$ is the average SOC deficit across the fleet. A lower Gini value indicates that the SOC deficits are more evenly distributed, meaning that the charging outcome is fairer among the vehicles.

The JFI also evaluates the equity of SOC deficits among the PEVs and is given by

$$J = \frac{\left(\sum_{v=1}^{V} z_{PEV,v}\right)^2}{V\sum_{v=1}^{V} z_{PEV,v}^2}, \qquad (13)$$

where $z_{PEV,v}$ again corresponds to the SOC deficit of each PEV. The index ranges from 0 to 1, with higher values indicating a more balanced charging process in which no vehicle is disproportionately delayed or disadvantaged.

Table 2 summarizes the Gini and JFI values for a representative set of Pareto-optimal solutions. The JFI ranges from 0.87 to 0.92, indicating high uniformity in SOC deficit distribution, while the Gini coefficient remains between 0.16 and 0.22, reflecting low inequality among vehicles. These metrics confirm that the optimized charging schedules provide fair and balanced charging across the PEV fleet, while the voltage evaluation in the next subsection identifies which Pareto solutions are suitable from the network-operation perspective.

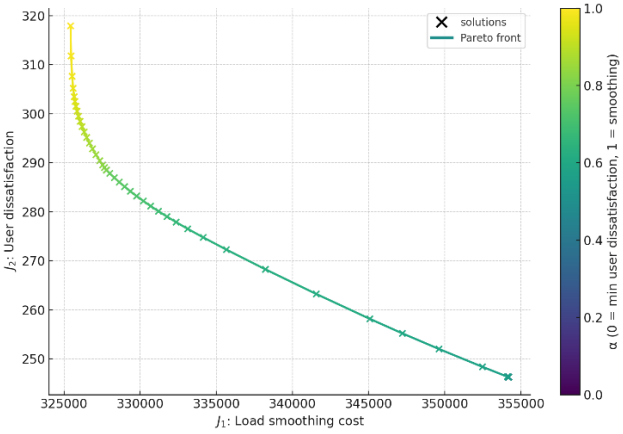


Fig. 3. Pareto front of the multi-objective

Table 2. GINI and JFI values for Pareto-optimal solutions

α (J_1)	β (J_2))	GINI	JFI
0.000	1.000	0.199	0.876
0.590	0.410	0.215	0.871
0.700	0.300	0.189	0.887
0.750	0.250	0.186	0.890
0.820	0.180	0.183	0.893
0.870	0.130	0.179	0.897
0.900	0.100	0.177	0.899
0.920	0.080	0.176	0.900
0.940	0.060	0.175	0.902
1.000	0.000	0.159	0.916

C. Simulation Results

After analyzing the Pareto-optimal solutions, the feeder voltage performance was evaluated to identify the operating points that violate the minimum acceptable limit [16]. As shown in Fig. 4, weighting configurations with α values between 0 and 0.64 lead to voltage drops at bus 6 below 207 V, while higher α values keep the voltage within the

required range. This indicates that voltage violations mainly occur for the lowest values of α, where rapid charging is prioritized over load smoothing. The result highlights the sensitivity of the weakest bus to charging schedules that place less emphasis on smoothing grid-power peaks.

The following results correspond to the operating point with $\alpha = 0.59$ and $\beta = 0.41$. This point is not selected as the final recommended solution, since it belongs to the voltage-critical region, but is analyzed to illustrate the impact of rapid-charging-oriented schedules on grid power, SOC progression, and feeder voltage.

Fig. 5 shows the total grid power demand with and without PEV charging. As expected, PEV charging increases the demand between 07:30 and 14:30. However, the optimized schedule distributes the charging activity over time, reducing sharp peaks and maintaining a smoother demand profile.

Fig. 6 and Fig. 7 show the charging power profiles of PEVs $1-3$ and PEVs $4-6$, respectively. The charging power is allocated fairly among all vehicles, without excessive priority given to any single PEV. The allocation adapts to both network capacity and the remaining connection time of each vehicle.

Fig. 8 and Fig. 9 illustrate the SOC evolution. Although none of the vehicles reach full charge due to limited connection duration, the SOC trajectories remain smooth and closely aligned, indicating a balanced charging progression.

Fig. 10 displays the voltage at bus 6, the weakest node of the feeder. During several charging intervals, the voltage falls below 207 V threshold as a result of simultaneous charging by multiple PEVs. This under-voltage issue confirms that some Pareto-optimal solutions may not be suitable from a network-operation perspective, highlighting the need to select voltage-compliant operating points or include voltage limits directly in future optimization models.

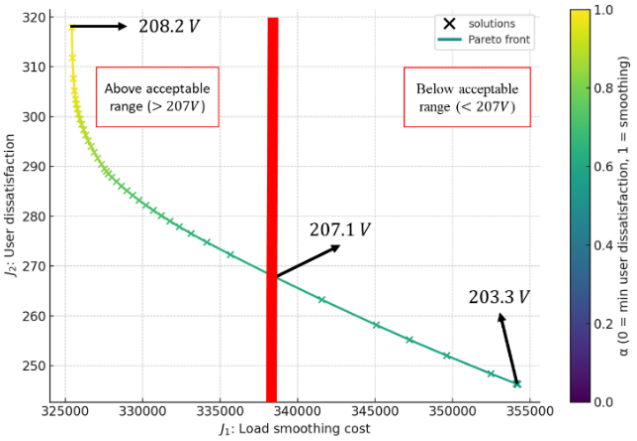


Fig. 4. Pareto front with indication of voltage violations at bus 6

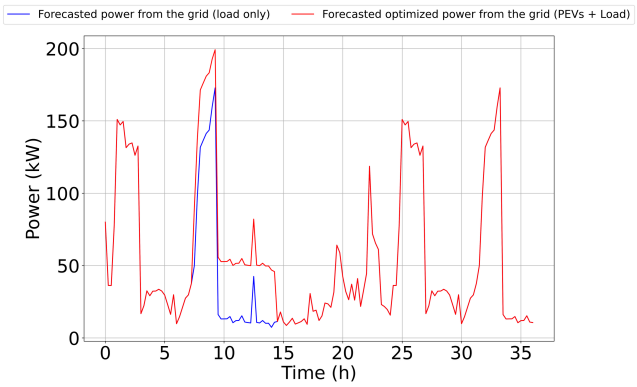


Fig. 5. Total network power under two operating scenarios

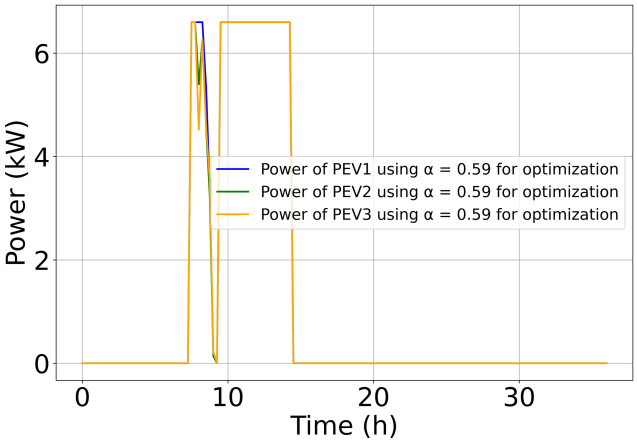


Fig. 6. Power delivered for PEV 1, 2, and 3

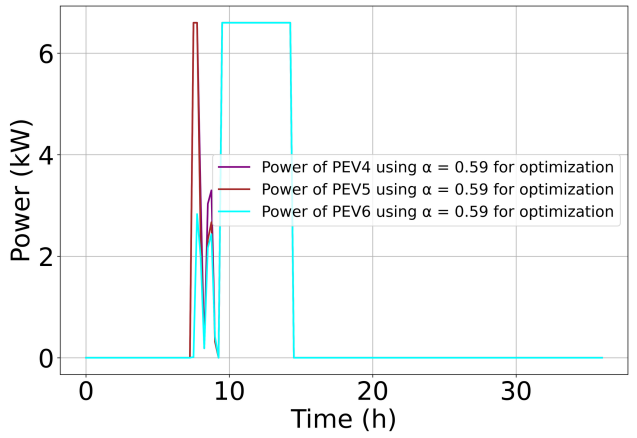


Fig. 7. Power delivered for PEV 4, 5, and 6

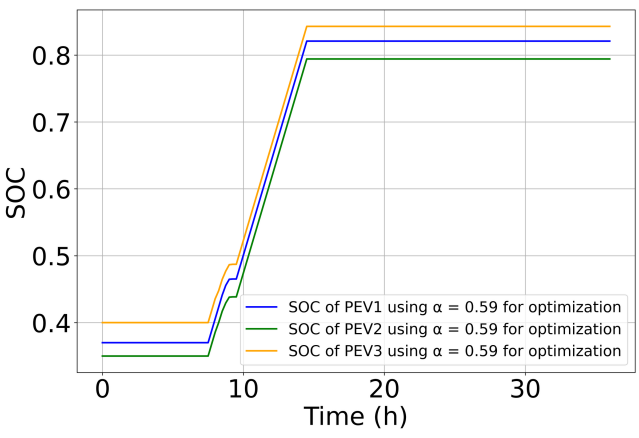


Fig. 8. SOC of PEV 1, 2, and 3

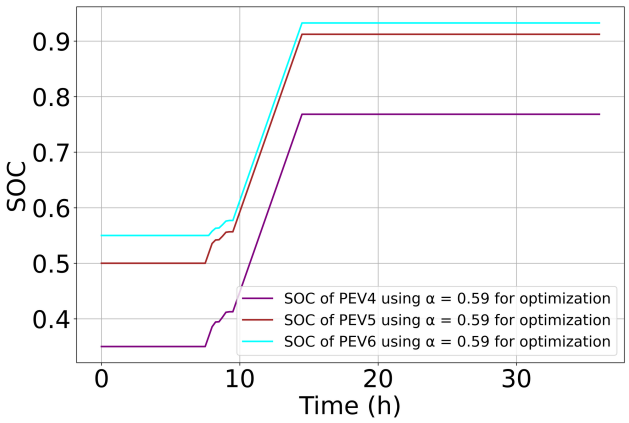


Fig. 9. SOC of PEV 4, 5, and 6

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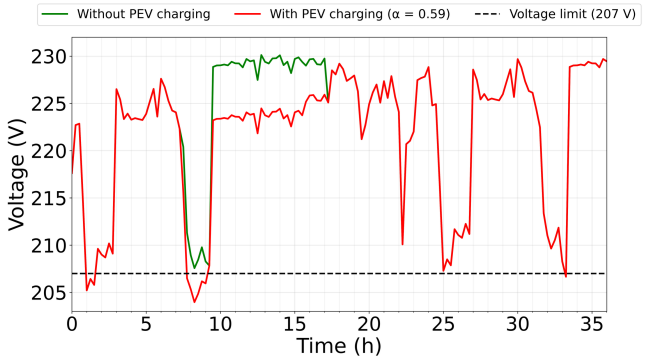


Fig. 10. Voltage profile at the critical bus under two operating scenarios

V. Conclusion

This work developed a multi-objective optimization framework for coordinated PEV charging in an LV distribution network, balancing load smoothing and rapid charging requirements. The proposed framework generates flexible charging schedules that reduce upward grid-power peaks while keeping SOC deficits fairly distributed among vehicles, as confirmed by the Gini coefficient and Jain's Fairness Index. The Pareto-front analysis showed how different weighting factors affect the compromise between grid-oriented and user-oriented objectives. MATLAB/Simulink simulations showed that the optimized charging profiles smooth the power demand and distribute charging power fairly among PEVs. However, the voltage evaluation also showed that some Pareto-optimal solutions may cause under-voltage at the weakest bus under high PEV penetration. These results highlight the need to select voltage-compliant operating points and to include voltage limits more directly in the optimization model. Future work will extend the framework with voltage-aware objectives or constraints and larger charging scenarios to improve robustness while maintaining efficient and fair charging for all users.

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