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Distributed Control for Large-Scale EV Charging Ecosystems with Coordinated Charging

Abstract
The rapid growth of electric vehicle adoption is turning charging infrastructure into a tightly coupled energy-service network that affects feeder loading, station utilization, and charging service quality. Existing studies have addressed smart charging, coordinated charging, hierarchical control, distributed energy management, and multi-agent scheduling, showing that coordination can improve charging efficiency and reduce congestion. However, these approaches are often fragmented across local optimization or feeder-level mitigation, leaving a gap in scalable frameworks that jointly support local autonomy, regional coordination, and grid-aware supervisory control. To address this gap, this article presents a distributed control and coordination framework for largescale EV charging ecosystems based on station-level intelligence, regional coordination signals, and a supervisory operating layer. The methodology defines the main control variables, coordination logic, and fairness-aware charging strategy, while the results show improved load balancing, reduced grid stress, and controlled charging delay under increasing EV penetration. Overall, the study demonstrates that distributed and hierarchical coordination offers a practical foundation for scalable EV charging management in high-demand environments.
Keywords: electric vehicle charging, distributed control, coordinated charging, load balancing, grid stress, charging delay, hierarchical coordination.

1. Introduction

Electric vehicle charging has evolved into a distributed infrastructure problem because large charging networks now interact directly with feeder loading, local voltage behavior, and temporal peak formation [1]. User movement across charging stations also changes the spatial distribution of charging demand, which means that charging access and charging power cannot be treated as separate operational issues [2]. Station-level operating behavior is further influenced by electricity pricing logic, service competition, and local utilization uncertainty, which pushes charging systems beyond the limits of simple plug-in energy delivery models [3]. These combined technical and service-layer interactions make EV charging ecosystems fundamentally different from conventional fuel networks.

Unmanaged charging creates structural inefficiency because simultaneous charging sessions often accumulate during common residential return periods, workplace departure windows, and fleet turnaround intervals [4]. Under such conditions, charging demand can become highly concentrated within short time horizons, producing feeder stress and lowering the effective hosting capacity of distribution infrastructure. System-wide coordination therefore becomes necessary when large numbers of charging assets share the same electrical environment. The charging problem is no longer defined only by how much energy is delivered, but by when, where, and under which network conditions that energy is delivered.

The need for distributed coordination becomes more pronounced when multiple charging stations are coupled through common distribution limits, shared flexibility resources, or correlated demand migration across neighboring facilities [5]. In such settings, a charging policy that appears locally efficient at one station can still create undesirable peak transfer or queue displacement at the regional level. Coordinated charging frameworks have therefore been examined as a means of balancing user demand with network-aware load shaping, especially when rapid EV growth makes infrastructure reinforcement slower than service demand expansion [6]. A scalable ecosystem must thus manage local autonomy without losing system-wide operating discipline.

A second layer of complexity arises because charging demand now occupies the overlap between mobility systems and power-system flexibility. User-side expectations require low waiting time, predictable access, and acceptable charging completion performance, while grid-side operation requires peak suppression, congestion reduction, and more stable aggregate demand patterns [2]. Station operators must therefore reconcile local commercial and service objectives with broader electrical constraints rather than optimizing one layer independently [3]. These tensions show that a large-scale charging ecosystem needs a framework that is distributed in execution but coordinated in objective.

This article develops a distributed control and coordination framework for large-scale EV charging ecosystems using local station intelligence, regional coordination signals, and a supervisory operating layer. The framework is intended to improve charging load distribution, reduce stress concentration, and preserve service continuity as EV penetration increases. The methodology that follows defines the control architecture, coordination variables, and decision flow used to support this objective.

2. Methodology

The proposed framework is organized as a hierarchical distributed control architecture in which charging stations act as local decision agents, regional coordinators supervise clustered charging behavior, and a supervisory interface translates grid-side conditions into operational bounds for the charging network [7]. This layered structure avoids the communication burden of full centralized scheduling while still allowing system-level control over congestion and charging diversity. The architecture is also designed to support local dynamic correction at the station level, which is important when service conditions deviate from forecast values or when network limits tighten during active operation [8]. Each layer therefore has a distinct role, but coordination is maintained through bounded information exchange rather than unrestricted state sharing.

At the station level, the local controller maintains a state set that includes charger occupancy, queue length, active charging sessions, expected departures, and site-specific electrical limits [8]. For each EV, the scheduler tracks the remaining energy request, the permissible charging rate, the current state of charge, and the available dwell-time window, because these variables directly determine flexibility and service urgency [9]. This local representation allows the station to compute how much charging power can be safely delivered without violating charger ratings or local transformer constraints [9]. The station therefore acts as the primary execution layer where abstract coordination signals are converted into real charging decisions.

A local priority index is then constructed from urgency of departure, remaining energy deficit, waiting duration, and charger feasibility so that not all EV sessions are treated identically under constrained operation. Vehicles with tight departure deadlines and large unfinished energy requirements are assigned different service priority from vehicles with longer dwell time and lower charging urgency. This step is necessary because charging coordination must preserve service quality while still respecting electrical operating limits. The output of this stage is a preferred station-level charging envelope for the upcoming coordination interval.

The methodology also includes a neighborhood-coupled demand perspective because charging stations in mixed-use environments often interact indirectly with nearby homes, flexible buildings, and local energy-management systems [10]. If those surrounding flexible loads respond in similar time windows, rebound peaks may emerge even when each participant appears locally well managed. For this reason, the regional controller is allowed to incorporate coupling intensity and nearby flexibility indicators when deriving station-cluster charging targets. This extends the charging model from an isolated station network to a distribution-aware ecosystem.

Regional coordination is performed through the exchange of aggregate feasible operating regions instead of detailed disclosure of individual EV-level data [11]. Each station transmits a preferred power request, a lower and upper admissible power bound, and its available upward or downward flexibility margin for the next interval. The regional coordinator aggregates these operating envelopes and computes a cluster target that respects feeder capacity, anticipated congestion, and continuity of charging service. This preserves privacy and communication efficiency while keeping the coordination layer aware of network conditions.

Adaptation under uncertainty is handled through a policy-refinement mechanism in which local and regional controllers improve their decision logic through repeated operating cycles [12]. At the station level, the controller updates its behavior using the mismatch between assigned power, realized queue evolution, and charging completion outcomes. At the regional level, coordination signals are refined using observed peak intensity, delay propagation, and flexibility realization across the charging cluster. This adaptive layer improves robustness when EV arrivals and station competition evolve in ways that fixed deterministic rules cannot represent well.

The complete control cycle operates on two time scales. A slower planning layer generates forward-looking charging envelopes from predicted EV arrivals, baseline demand, available charging capacity, and anticipated cluster stress [13]. A faster corrective layer then updates station targets when real-time queues, utilization, or congestion indicators diverge from the planned trajectory [8]. This combination allows the system to remain predictive without becoming rigid during real operation. In this way, planning and adaptation remain tightly coupled inside the same framework.

Performance evaluation is carried out using both grid-facing and service-facing metrics so that the proposed framework can be assessed as a real charging ecosystem rather than only as an abstract scheduling model. The main measures are peak-to-average load ratio, overload occurrence, charging completion rate, average user delay, and allocation fairness across stations, while the principal control variables and coordination parameters used throughout the framework are summarized in Table 1. These metrics together allow the framework to be tested for scalability, stability, and practical coordination quality under increasing EV penetration.

Table 1. Core System Parameters and Coordination Variables Used in the Distributed EV Charging Framework

Symbol	Variable	Description
N_s	Station count	Total charging stations in the coordinated network
$P_i^{\min}, P_i^{\max}$	Station power bounds	Minimum and maximum admissible charging power at station i
P_i^{pref}	Preferred station power	Requested operating power of station i
F_i^{up}, F_i^{down}	Flexibility margins	Upward and downward power adjustment capability
E_k^{rem}, T_k^{dep}	EV service state	Remaining energy demand and departure deadline of EV k

Q_i	Queue state	Waiting intensity or charger occupancy at station i
L_r, C_r	Regional load state	Aggregate regional demand and feeder capacity limit
S_r	Coordination signal	Regional control instruction sent to stations

3. Results and Discussion

The distributed coordination framework produced a clear improvement in charging-load distribution when compared with a non-coordinated baseline and a weakly synchronized station-level control scenario. Under rising EV penetration, the coordinated framework reduced simultaneous charging concentration by spreading power allocation across stations and time intervals rather than allowing uncontrolled local accumulation. This effect is illustrated in Figure 1, where the coordinated strategy maintains a flatter aggregate charging profile and a lower peak loading band than the comparison cases. The most important observation is that the framework did not suppress demand through simple curtailment alone, but instead redistributed charging activity in a way that preserved charging continuity for a larger share of connected vehicles. The result indicates that distributed coordination can improve system-level balance without making the charging process operationally unstable.

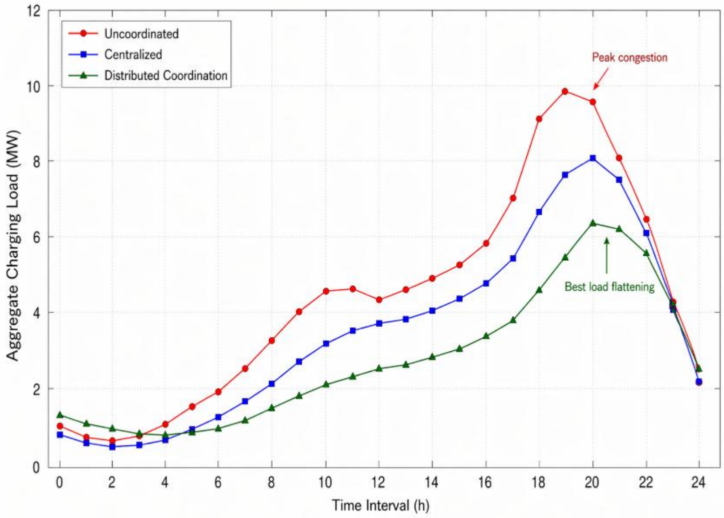

Figure 1. Charging Load Balancing Performance Under Centralized, Uncoordinated, and Distributed Coordination Strategies

A second important result was the reduction in feeder stress during high-demand intervals. When EV arrivals were concentrated within short time windows, the non-coordinated system produced steep loading spikes and short-lived overload conditions, especially at stations located near already stressed network zones. The proposed framework moderated these local surges by continuously updating station power envelopes and reallocating charging effort toward less congested intervals and less burdened stations. As seen in Figure 2, grid stress increased sharply with EV penetration in the baseline case, whereas the distributed framework maintained a slower and more controlled growth trend. This behavior suggests that regional signal exchange was effective in converting dispersed local flexibility into measurable network relief. The coordinated architecture therefore improved electrical resilience under conditions where unmanaged charging would have pushed the system closer to operating limits.

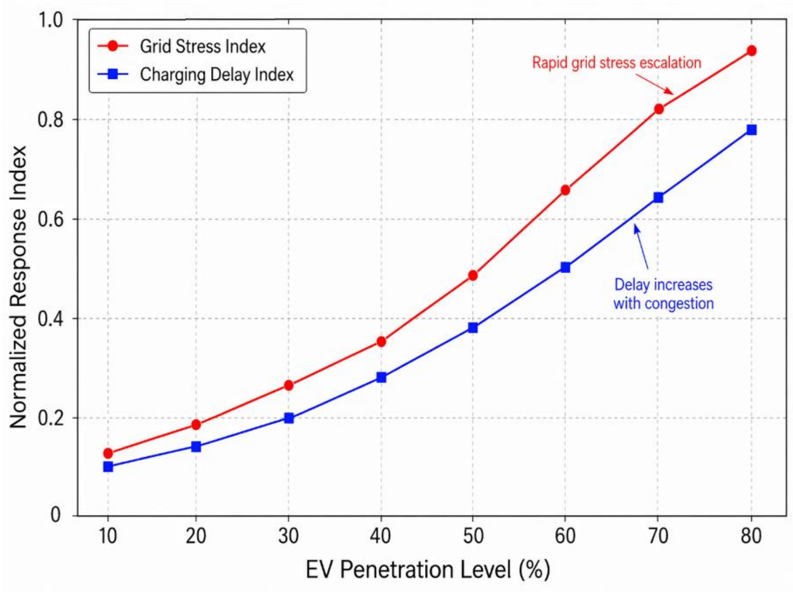

Figure 2. Grid Stress and Charging Delay Response Under Increasing EV Penetration Levels

Charging service quality was also preserved at an acceptable level despite the tighter control over aggregate demand. In many load-management schemes, peak reduction is achieved at the expense of excessive waiting time or incomplete charging sessions, but that pattern was less pronounced in the present framework because the local priority index accounted for both remaining energy demand and departure urgency. Vehicles with constrained dwell-time windows continued to receive preferential access, while lower-urgency sessions absorbed a larger share of the temporal adjustment burden. This resulted in a moderate increase in average delay under stressed conditions, but the increase remained substantially smaller than the reduction in overload severity and peak concentration. The discussion therefore indicates that fairness-aware local scheduling played a key role in preventing coordination from becoming overly restrictive from the user perspective.

The interaction between local autonomy and regional coordination was another notable outcome of the simulation logic. Purely local station control improved charger utilization in lightly stressed conditions, but once demand became spatially clustered, station-level optimization alone could not prevent queue migration and load transfer between neighboring stations. The regional coordination layer corrected this weakness by enforcing cluster-level operating envelopes and by recognizing when local flexibility should be reserved for feeder protection rather than immediate station-level convenience. At the same time, the framework avoided the rigidity of full central dispatch because stations still retained authority over final user-level assignment inside their allocated bounds. This hybrid behavior is important because it demonstrates that large charging ecosystems benefit from coordination across layers rather than dominance by a single control center.

4. Conclusion

This study presented a distributed control and coordination framework for large-scale EV charging ecosystems built around local station intelligence, regional coordination logic, and supervisory operating limits. The framework was designed to address the central problem created by large charging networks, namely that local charging actions increasingly generate system-wide electrical and service consequences. By combining bounded information exchange with layered decision-making, the proposed architecture created a practical balance between local responsiveness and network-level discipline. The resulting control structure provides a useful basis for scalable charging management in high-penetration EV environments.

The results showed that coordinated distributed operation can reduce charging-load concentration, moderate feeder stress, and preserve acceptable charging service performance under increasingly congested conditions. The framework was especially effective because it did not rely on a single centralized scheduler or on isolated station autonomy, but instead used a cooperative structure in which local flexibility was translated into regional operating benefit. This hybrid control logic allowed the system to remain adaptive during short-term disturbances while retaining a predictable planning structure over longer horizons. The study therefore confirms that layered coordination is a strong candidate for future EV charging infrastructure management.

The broader implication of this work is that EV charging ecosystems should be planned as dynamic coordination environments rather than static infrastructure deployments. Future extensions can incorporate renewable coupling, vehicle-to-grid support, market-responsive charging incentives, and stronger uncertainty learning across heterogeneous station clusters. Additional simulation depth may also be added through feeder-level voltage analysis, stochastic travel-demand modeling, and geographically realistic charger placement scenarios. These directions would further strengthen the framework as a deployable control strategy for next-generation electric mobility systems.

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