

Charging Station Dynamic Pricing for Real-Time Congestion Management in Distribution Network: An Adaptive Model-Based Safe Deep Reinforcement Learning Method

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Abstract—This paper studies the pricing strategy for real-time distribution network congestion management, aiming at maximizing the total social welfare while eliminating congestions. The difficulty lies in how to deal with the complex time-varying relationship between price and charging demand in the integrated power system and transportation network, and how to ensure the safety application of the proposed method with limited real historical data. To address the challenges, we first model the EV user charging decision-making process to indirectly reflect the unquantifiable price and demand relationship, and then formulate the pricing problem as a bi-level model with constrained Markov Decision Process (CMDP). After that, we propose the model-based safe DRL framework and develop an adaptive model-based safe deep reinforcement learning (AMSDRL) algorithm to solve the CMDP problem. AMSDRL learns the environment transition model and uses strict and adaptive cost constraint to offset potential modeling errors. Compared to the state-of-the-art safe DRL methods, AMSDRL can be deployed with security guarantees by training limited historical data, which is more practical for applications. The numerical results on the modified IEEE 33-bus and 118-bus systems and the transportation network with real-world EV data demonstrate the effectiveness of the proposed method.

Index Terms—Congestion management, model-based safe deep reinforcement learning, EV charging pricing, power and transportation system, constrained Markov decision process.

NOMENCLATURE

Abbreviations

AMSDRL	Adaptive model-based safe deep reinforcement learning.
CCEM	Constrained cross entropy method
CMDP	Constrained Markov decision process.
CPO	Constrained policy optimization.
CS	Charging Station.
DRL	Deep reinforcement learning.
DSO	Distribution system operator
EV	Electric vehicle.
FOCOPS	First order constrained optimization in policy space.
GMM	Gaussian mixed method
SOC	State of charge.

Sets

B/n	Set/index of buses in network.
E_n/i	Set/index of EVs at bus n .
$\Gamma/\Delta t$	Discrete operating time set/Operating interval of power grid.
$H/H_n/j$	CSs Set/set of CSs at bus n /index of CSs set.
I/E	Set of intersections/roads.

$E_{n,t}^{c/ed/rd}$	EVs set with charging/elastic charging/rigid charging demand.
Parameters	
$t_{n,i}^{a/l/ac}$	Arrival/leaving/maximum acceptable time of EV user.
$SOC_{n,i}^{min/max}$	Minimum/maximum SOC of EV battery.
SOC_{n,i,t_l}	EV SOC at departure.
SOC_{n,i,t_l}^E	EV expected energy state after charging
$v_{i,t}$	Weight coefficient for inclinations.
ω	Conversion factor.
$v_{ab}^0/f_{ab}/q_{ab}$	Free flow speed/current traffic flow/capacity of the road e_{ab} .
$\vartheta_1, \vartheta_2, \vartheta_3$	Road adaptability coefficients.
$L(e_{ab})$	Length of road e_{ab} .
$k_{n,j}$	Number of charging piles of CSs j at bus n .
$L_{n,i}^{u/m/s}(j)$	Length of urban expressway/main road/secondary road from the position of EV i to the target CS j .
$N_{n,j}^C$	Number of available charging piles.
$N_{n,j,t}^{EV,A/L}$	Number of arrival/leaving EVs.
$b_{n,i,t}^{A/L}(j)$	EV binary arrival/leaving status.
$V_{min/max}$	Minimum/maximum voltage magnitude.
I_{max}	Maximum line current.
P_{mn}^L	Capacity of line (m, n).
$\phi_{mn,t}^{max}$	Maximum load percentage of line (m, n).
Variable	
$E_{n,i,t}$	Energy pf EV i at bus n at time stage t .
$P_{n,i,t}^{EV,C/D}$	EV charging/discharging power.
$P_{n,i,max}^{EV,C/D}$	EV maximum charging/discharging power.
$b_{n,i,t}^{EV,C/D}$	EV binary charging/discharging status.
$C_{n,i,t}(j)$	Total cost of charging at target CS j for EV user i of bus n at time stage t .
$T/FC_{n,i,t}(j)$	Time consumption/financial cost.
$T_{n,i,t}^{D/W/C}(j)$	Driving/waiting/charging time of EV user i at bus n who decides to charge at CS j .
$\chi_{n,j,t} / S_{n,j,t}$	Average/average service time of CS j at bus n during time stage t .
$E_{n,i,t}^W(j)$	Energy consumed by EV i at bus n for a one-way trip to the target CS j .
$\Delta E_{u/m,s,t}$	Energy consumption per unit mile in urban, expressway/main roads/secondary roads.
$\lambda_{n,j,t}^{TC/C/S}$	Total charging price/charging price/service fee of CS j at bus n during time stage t .

$\lambda_{n,j}^{S,\min/\max}$	Minimum/maximum service price.
$\lambda_{n,j}^{CS,P}$	CS electricity purchase price.
$\lambda_{n,t}^{DSO,M/D}$	DSO electricity purchase price from the main grid/distributed generators at bus n .
$P_{n,t}/Q_{n,t}$	Active/reactive power of bus n .
$P_{mn,t}/Q_{mn,t}$	Active/reactive power injecting from bus m to n .
$P_{n,j,t}^{CS,M/D}$	Power from the main network/distributed generator to CS j at bus n .
$P_{n,j,t}^{CSS}/P_{n,t}^0$	Power consumed by CSs and non-EV loads.
$P_{n,t}^{DG}$	Output of local distributed generator.
$r_{mn,t}/x_{mn,t}$	Impedance/inductive resistance of line (m, n) .
$V_{n,t}/l_{mn,t}$	Square of node voltage magnitude/line current.

I. INTRODUCTION

THE scale of electric vehicles (EVs) has been growing rapidly in recent years. According to the Global EV outlook of the International Energy Agency, the EV number is expected to reach 1.81 billion in 2030, consuming electricity of 43000 GWh every year. The large amount power drawn by random EV charging would impose great burdens on the distribution network and cause local congestions, which may lead to widespread blackouts associated with serious economic losses and negative social impacts [1].

Although updating the grid facilities can address the above issues directly, which is also essential for the increasing penetration of sustainable energy resource and EVs, it would take a long time due to the policy and high costs involved. To solve the problem, many researchers have worked on the day-ahead market for EV aggregators to alleviate the congestion by scheduling the grid assets wisely. In [2], the price-based EV scheduling method was applied to dispatch distributed energy resources to alleviate the congestion in heavy loaded feeders. In [3], the dynamic tariff was introduced to motivate aggregators to shift their flexible demands while the subsidy-based method in [4] encouraged users to change their planned schedules. Hu, *et. al* [5] proposed a power trading framework to coordinate EV aggregators for congestion management. Although the above works is efficient to relieve the heavy congestion, planning ahead cannot fully avoid congestion caused by the time-varying demand, especially for EVs with high mobility and charging uncertainty. Therefore, the real-time congestion management for EVs is essential for the economical and safe operation of the distribution network.

The real-time congestion management for EVs can be summarized into two types, namely the charging management and pricing incentive. In the field of EV charging management, several methods based on smart charging technology have been proposed. In [6], a rule-based model predictive control method was proposed to regulate the output of PV generators and EV inverters to mitigate the line congestion in the active distribution network. In [7], a coordinated scheme for EV charging and PV operation was proposed to prevent line overload and system energy loss. In [8], a field test validation was conducted in a real Danish distribution grid to verify the

effectiveness of the EV real-time charging strategies for congestion management. However, the above methods have security risks due to the uncertainty of the EV user trip and EV energy level. Besides, the charging management methods are generally needed to remunerate EV users for acquiring EV flexible energy, but how much should be paid for incentives is complex to decide. In view of this, EV charging management is an auxiliary or emergency mean for real-time congestion management, while pricing incentive is more suitable as a long-term treatment.

In terms of pricing incentive approach, Soltani *et al.* [9] used the conditional random field method for real-time optimal price adjustment to prevent the local congestion, and in [10], a real-time pricing and scheduling strategy for EVs was proposed to eliminate the disruptive impact of overloading on the distribution network. However, these two studies did not consider the transportation network in the EV scheduling, which makes the price strategies impossible in reality due to traffic jams, road closures, and other traffic factors. Although the authors of [11]-[13] proposed dynamic pricing strategies for EV charging stations (CSs) under the holistic modeling framework for the transportation network and power distribution network, the user decision models in these studies were crude and could not accurately reflect the different users' decisions regarding price incentives, such as rough classification of user groups into refusing to join and leaving in [11], lack of travel energy constraint in [12]. Besides, the simple portrayal of the traffic system makes the strategies impractical, for example, the lack of distinguish between road types in [13] would give a negative impact on calculating travel time and expected energy consumption, which directly affects the accuracy of user decisions. The studies in [14]-[15] achieve the efficient coordination between EVs and CSs in an integrated electricity-transportation system, however, the proposed methods may not be applicable for the real-time pricing for congestion management due to the long solution time of evolution algorithms. In addition to the above methods, the work of [16] was creative, the authors designed a real-time swap market framework to incentivize flexible demand swap of EVs and heat pumps. But the trading mechanism was not universal due to the harsh operating conditions.

Nevertheless, the aforementioned model-based approaches exhibit two fundamental limitations under a dynamic and stochastic environment. First of all, they highly rely on the complete and accurate information about EVs, CSs and the power grid, which is difficult to obtain in practice, especially information under privacy limitations, such as users trip. Secondly, the fully model-based method may not solve the complex optimization problem effectively due to the EV user's uncertainty behavior and time-varying operating conditions. In fact, most works greatly simplified the proposed models with some impractical assumptions to facilitate the solution.

These shortcomings of model-based methods motivate the appliance of deep reinforcement learning (DRL) method. DRL is a data-driven control method that learns and outputs a near-optimal policy rather than a deterministic optimal solution, which has made DRL methods popular in recent years for

solving real-time optimal control problems with uncertainty. In [17], a DRL-based holistic framework was proposed to stabilize the operation of coordinated power distribution network and transportation network through EV scheduling. In [18], a soft actor critic method was developed to address the continuous charging under the uncertainty of EV user behaviors. In [19], a DRL method with a prioritized experience replay strategy was proposed to solve the examined EV pricing problem. In [20], a graph DRL method was proposed for real-time CS recommendation considering coupled information of power and transportation networks. In [21], an optimal DRL-based EV driving model was proposed for EV charging scheduling in integrated power and transportation systems. Although the aforementioned methods achieve promising results, these methods can only satisfy soft constraints and cannot guarantee the security of the application, which is fatal in practice. In view of this, a few researchers have worked on safe DRL methods to solve the problem of poor applicability. In [22], the authors applied safe DRL approach to solve the constrained EV charging issue for participating in demand response. In [23], a safe DRL method was presented to achieve optimal operation of distribution networks considering the uncertainty of renewable resources. In [24], a multi-agent safe DRL approach was presented for optimal energy management of networked microgrids in distribution systems. However, most of the existing safe DRL methods learn the strategy through a large amount of offline data due to the very low sample efficiency, while the cost of data collection is high or dangerous in real-world applications. Besides, the large difference between policy distribution and data distribution in the offline dataset leads to errors in the estimated values of security constraints, which make the trained policy not really safe.

To address all the problems mentioned above, this paper proposes an adaptive model-based safe DRL (AMSDRL) method for the real-time EV congestion management problem to achieve social welfare maximization while eliminating distribution network congestions. The main contributions of this paper are summarized as follows:

(1) To the author's best knowledge, this paper for the first time proposes a pricing strategy for the real-time congestion management considering EV user's charging decisions in the integrated power and transportation network. We model the EV user charging decision-making process to indirectly obtain the unquantifiable relationship between price and charging demand, and then formulate the pricing problem as a bi-level model with constrained Markov decision process (CMDP).

(2) We propose the model-based safe DRL framework and develop the AMSDRL algorithm, which uses strict and adaptive cost constraint to eliminate potential environment transition modeling errors to ensure the safe training results with limited historical data. Compared to the state-of-the-art safe DRL algorithms in [25] and [26], AMSDRL is more sample efficient, with 51.92% and 40.44% less training time; much safer, with only 0.89% and 0.27% congestion cost during convergence; and more stable, with 82.57% and 80.20% fewer training violations.

(3) We apply the constrained cross entropy method (CCEM)

to solve the pricing problem with continuous action space rather than use the neural networks to output the policy. This makes the AMSDRL has a good performance in scalability, which is verified by the numerical studies on 118-bus distribution systems with the realistic transportation topology and EV data of Shenzhen.

The rest of this paper is organized as follows. The mathematical formulation of congestion management for EVs is set forth in Section II. The AMSDRL algorithm is proposed in Section III. Case studies are presented in Section IV and the conclusion is given in Section V.

II. MATHEMATIC MODELS

A. EV Model

Let $\mathcal{B} = \{0, 1, 2, \dots, n\}$ denote the set of buses and $\mathcal{E}_{n,t}$ denote the set of EVs at bus n at time stage t . Then EV charging and discharging characteristics could be generally modeled as:

$$E_{n,i,t+1} = E_{n,i,t} + (P_{n,i,t}^{EV,C} \eta_{n,i,t}^{EV,C} - P_{n,i,t}^{EV,D} / \eta_{n,i,t}^{EV,D}) \Delta t \quad (1)$$

$$\forall n \in \mathcal{B}, i \in \mathcal{E}_{n,t}, t \in \Gamma_{n,i}^{ev}$$

$$SOC_{n,i,t+1} = SOC_{n,i,t} + (E_{n,i,t+1} - E_{n,i,t}) / B_{n,i} \quad (2)$$

$$\forall n \in \mathcal{B}, i \in \mathcal{E}_{n,t}, t \in \Gamma_{n,i}^{ev}$$

$$0 \leq P_{n,i,t}^{EV,C} \leq b_{n,i,t}^{EV,C} \cdot P_{n,i,\max}^{EV,C} \quad \forall n \in \mathcal{B}, i \in \mathcal{E}_{n,t}, t \in \Gamma_{n,i}^{ev} \quad (3)$$

$$0 \leq P_{n,i,t}^{EV,D} \leq b_{n,i,t}^{EV,D} \cdot P_{n,i,\max}^{EV,D} \quad \forall n \in \mathcal{B}, i \in \mathcal{E}_{n,t}, t \in \Gamma_{n,i}^{ev} \quad (4)$$

$$0 \leq b_{n,i,t}^{EV,D} + b_{n,i,t}^{EV,C} \leq 1 \quad \forall n \in \mathcal{B}, i \in \mathcal{E}_{n,t}, t \in \Gamma_{n,i}^{ev} \quad (5)$$

$$SOC_{n,i}^{\min} \leq SOC_{n,i,t} \leq SOC_{n,i}^{\max} \quad \forall n \in \mathcal{B}, i \in \mathcal{E}_{n,t}, t \in \Gamma_{n,i}^{ev} \quad (6)$$

$$SOC_{n,i,t_f} \geq SOC_{n,i,t_f}^E \quad \forall n \in \mathcal{B}, i \in \mathcal{E}_{n,t} \quad (7)$$

$$\Gamma = \{t_j \mid t_j = j\Delta t, j \in Z^*\} \quad (8)$$

where (1)-(6) describe the EV charging/discharging process and establish the EV energy storage model. (1)-(2) are the update formulations of the EV energy and SOC, respectively. (3)-(5) are the constraints for the EV charging and discharging status. (6) limits the EV energy level and (7) indicates that SOC at departure should meet EV user's energy demand. (8) defines the discrete time stage and the time interval is taken as 15 minutes in this study. The constraints are embedded in the environment and are satisfied through the learning process between the agent and environment.

B. EV User Cost Model

The total cost of charging at target CS j for EV user i with charging demand at bus n at time stage t is formulated as:

$$C_{n,i,t}^{EV}(j) = v_{i,t} \omega TC_{n,i,t}^{EV}(j) + (1 - v_{i,t}) FC_{n,i,t}^{EV}(j) \quad (9)$$

$$\forall n \in \mathcal{B}, i \in \mathcal{E}_{n,t}, j \in \mathcal{H}_n, t \in \Gamma$$

where the CSs set $\mathcal{H} = \mathcal{H}_1 \cup \mathcal{H}_2 \cup \dots \cup \mathcal{H}_n = \{1, 2, \dots, J\}$, J is the total number of CSs in the distribution networks. $v_{i,t}$ is the weight coefficient which reflects the different inclinations of EV users towards the two types of cost and ω is the coefficient that converts the time consumption into cost and its distribution can be obtained by means of questionnaires, etc.

1) Time Consumption

The time consumption is estimated as:

$$T_{n,i,t}^W(j) \approx \frac{\chi_{n,j,t}^{k_{n,j}} E[S_{n,j,t}]^2 (E[S_{n,j,t}])^{k_{n,j}-1}}{2(k_{n,j}-1)! (k_{n,j} - \chi_{n,j,t} E[S_{n,j,t}])^2 \left[\sum_{x=0}^{k_{n,j}-1} \frac{(\chi_{n,j,t} E[S_{n,j,t}])^y}{y!} + \frac{(\chi_{n,j,t} E[S_{n,j,t}])^{k_{n,j}}}{(k_{n,j}-1)! (k - \chi_{n,j,t} E[S_{n,j,t}])} \right]} \quad \forall n \in \mathcal{B}, j \in \mathcal{H}, t \in \Gamma \quad (10)$$

$$TC_{n,i,t}^{EV}(j) = T_{n,i,t}^D(j) + T_{n,i,t}^W(j) + T_{n,i,t}^C(j) \quad (11)$$

$\forall n \in \mathcal{B}, i \in \mathcal{E}_{n,t}^c, j \in \mathcal{H}, t \in \Gamma$

•Driving Time:

The transportation network can be described as an underlying undirected graph $\Gamma = (\mathcal{J}, \mathbf{E})$. We applied the precise speed-flow model in [27] to simulate the EV driving process in dynamic traffic conditions. The driving speed of EV on a directly connected road section e_{ab} is expressed as follows:

$$\begin{cases} v_{ab}(t) = v_{ab}^0 / \left(1 + \left(f_{ab}(t) / q_{ab}\right)^{\xi}\right) & \forall e_{ab} \in \mathbf{E}, t \in \Gamma \\ \xi = \vartheta_1 + \vartheta_2 \left(f_{ab}(t) / q_{ab}\right)^{\vartheta_3} \end{cases} \quad (12)$$

The driving time for EV user i of bus n to charge at CS j is given as:

$$T_{n,i,t}^D(j) = \sum_{e_{ab} \in \mathcal{E}_j^{n,i}} T_{ab}(t) \quad \forall n \in \mathcal{B}, i \in \mathcal{E}_{n,t}^c, j \in \mathcal{H}, t \in \Gamma \quad (13)$$

$$T_{ab}(t) = L(e_{ab}) / v_{ab}(t) \quad \forall e_{ab} \in \mathbf{E}_j^i, t \in \Gamma \quad (14)$$

where $\mathcal{E}_j^{n,i}$ is the set of the transportation paths from EV user i at bus n to CS j . The transportation parameters, including the free flow speed, traffic flow, and the capacity of the road, are calculated by the measured sample data through the fixed-point detector. The path selection for EV is obtained by using the Dijkstra algorithm based on the principle of shortest time.

•Waiting Time:

Here we apply the theory of M/G/k queue in [28] to estimate the waiting process. M/G/k presents an approximation for the mean time a customer waits in queue in a k -server system that assumes Poisson arrivals but allows for a general service distribution. Then the mean waiting time could be calculated as (14), where in this study, $k_{n,j}$ is the number of charging piles of CSs j at bus n . $E[S_{n,j,t}]$ denotes the average service time of CS j at bus n during time stage t .

•Charging Time:

The charging time $T_{n,i,t}^C(j)$ could be estimated as follows:

$$T_{n,i,t}^C(j) = (E_{n,i,t}^C + E_{n,i,t}^W(j)) / P_{n,i,t}^{EV,C} \quad (15)$$

$\forall n \in \mathcal{B}, i \in \mathcal{E}_{n,t}^c, j \in \mathcal{H}, t \in \Gamma$

$$E_{n,i,t}^C = B_{n,i}^{EV} (SOC_{n,i}^E - SOC_{n,i,t}) \quad \forall n \in \mathcal{B}, i \in \mathcal{E}_{n,t}^c, t \in \Gamma \quad (16)$$

$$\begin{cases} \Delta E_{u,t} = 0.247 + 1.52 / v_{ab,t} - 0.004v_{ab,t} \\ \quad + 2.992 \times 10^{-5} v_{ab,t} \\ \Delta E_{m,t} = -0.179 + 0.004v_{ab,t} + 5.492 / v_{ab,t} \\ \Delta E_{s,t} = 0.21 - 0.001v_{ab,t} + 1.531 / v_{ab,t} \end{cases} \quad (17)$$

$\forall e_{ab} \in \mathcal{E}_j^{n,i}, n \in \mathcal{B}, i \in \mathcal{E}_{n,t}^c, j \in \mathcal{H}, t \in \Gamma$

$$E_{n,i,t}^W(j) = \Delta E_{u,t} L_{n,i}^u(j) + \Delta E_{m,t} L_{n,i}^m(j) + \Delta E_{s,t} L_{n,i}^s(j) \quad (18)$$

$\forall n \in \mathcal{B}, i \in \mathcal{E}_{n,t}^c, j \in \mathcal{H}, t \in \Gamma$

where (16) denotes the expected charging energy and (17) is the estimation formulation of energy consumption per unit mile

according to [27]. (18) formulates the energy consumed by EV i at bus n for a one-way trip to the target CS j .

2) Financial Cost

The financial cost of each EV user is calculated as:

$$FC_{n,i,t}^{EV}(j) = E_{n,i,t}^C \lambda_{n,j,t}^{TC} + E_{n,i,t}^W(j) \lambda_{n,j,t}^{WC} \quad (19)$$

$\forall n \in \mathcal{B}, i \in \mathcal{E}_{n,t}^c, j \in \mathcal{H}, t \in \Gamma$

The first item of (19) is the cost for the expected charging energy, while the second item represents the cost for the one-way charging trip.

C. Congestion Management Model

Due to the migration of EV loads influenced by the pricing of each CS and the traffic topology, it is not useful to simply increase or decrease the CSs total charging price, which could result in the loss of profits of CSs due to the excessive load shedding, or even aggravation of congestion.

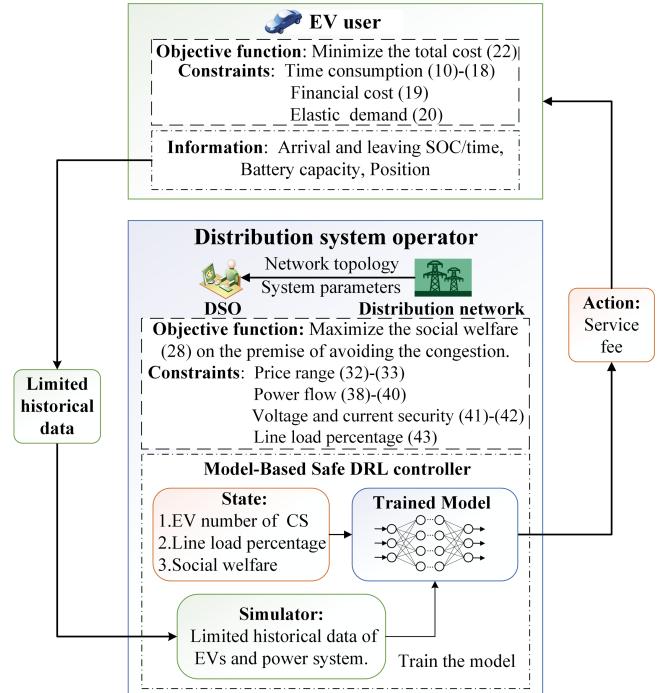


Fig. 1 Structure of the proposed method for congestion management

The structure of the proposed method for distribution network congestion management is shown in Fig. 1. When there is a risk of congestion or a congestion has occurred, the pricing strategy for CSs will be taken over by the distribution system operator (DSO) in order to maximize the social welfare on the premise of eliminating the congestions. The real-time information is first observed by the DSO, only including the CSs EV number, line load percentage and social welfare, which will be explained in detail in the next section. Then the trained policy will be loaded and provide the pricing strategy for the fast response of real-time congestion management. The policy is obtained by the model-based safety DRL controller trained using limited

historical data on EV information as well as power and transportation system parameters. And the policy will be continuously executed and trained until the congestion risk is removed. The EV data only includes the arrival and leaving SOC/time, battery capacity and the departure position without privacy information like the trip chain.

It is essential to establish the price-demand model for congestion pricing strategy, however, it is extremely difficult to model the accurate relationship between price and demand directly by mathematical methods due to the complicated interplay between charging station pricing strategies. But it is intuitive and easy to model the decision-making behaviors of EV users, which means we can solve the problem indirectly.

1) EV User Charging Decision

We classify the EVs with charging demand into the EV set of elastic demand and the EV set of rigid demand, which are shown as follows:

$$\begin{aligned} \mathbf{E}_{n,t}^{ed} = & \{\mathbf{E}_{n,i,t} \mid T_{n,i,t}^D(j) < \Delta t, E_{n,i,t} > E_{n,i,t}^W(j), TC_{n,i,t}^{EV}(j) \leq t_{n,i}^{ac}\} \\ & \forall n \in \mathbf{B}, i \in \mathbf{E}_{n,t}^c, t \in \Gamma \end{aligned} \quad (20)$$

$$\mathbf{E}_{n,t}^{rd} = \{\mathbf{E}_{n,i,t} \mid \mathbf{E}_{n,i,t}^c / \mathbf{E}_{n,i,t}^{ed}\} \quad n \in \mathbf{B}, t \in \Gamma. \quad (21)$$

The first constraint in (20) is set for avoiding risk of violating the real-time pricing timeline, the second one ensures that the EV has enough power to reach the target CS, while the third one indicates that the total charging time consumption should be satisfied within the maximum EV user acceptable time. Price incentive only works for EVs with elastic charging demand and each EV user has only one choice to choose the target CS. EVs with rigid demand chooses the CS nearby (i.e., only time cost is considered).

The objective of EV user decision strategy is to choose the CS j to minimize the total cost, which is formulated as:

$$\begin{aligned} \min_j C_{n,i,t}^{EV} \\ \forall n \in \mathbf{B}, i \in \mathbf{E}_{n,t}^c, j \in \mathbf{H}, t \in \Gamma \\ \text{s.t. (8)-(18)} \end{aligned} \quad (22)$$

Then the update formula for number of EVs of CS j at bus n can be obtained as (23):

$$N_{n,j,t}^{EV} = \begin{cases} N_{n,j,t-1}^{EV} + N_{n,j,t}^{EV,A} - N_{n,j,t}^{EV,L} & N_{n,j,t}^{EV} \leq N_{n,j}^C \\ N_{n,j}^C & N_{n,j,t}^{EV} > N_{n,j}^C \end{cases} \quad (23)$$

$$\forall n \in \mathbf{B}, j \in \mathbf{H}, t \in \Gamma$$

$$N_{n,j,t}^{EV,A} = \sum_n^{|B|} \sum_i^{|E_n|} b_{n,i,t}^A(j) \quad \forall n \in \mathbf{B}, i \in \mathbf{E}_n, j \in \mathbf{H}, t \in \Gamma \quad (24)$$

$$b_{n,i,t}^A(j) = \begin{cases} 1, & \arg \min \{C_{n,i,t}^{EV}\} = j \\ 0, & \text{otherwise} \end{cases} \quad (25)$$

$$\forall n \in \mathbf{B}, i \in \mathbf{E}_n, j \in \mathbf{H}, t \in \Gamma$$

$$N_{n,j,t}^{EV,L} = \sum_n^{|B|} \sum_i^{|E_n|} b_{n,i,t}^L(j) \quad \forall n \in \mathbf{B}, i \in \mathbf{E}_n, j \in \mathbf{H}, t \in \Gamma \quad (26)$$

$$b_{n,i,j,t}^L = \begin{cases} 1, & SOC_{n,i,j,t} \geq SOC_{n,i,j,t}^E \parallel t \geq t_{n,i}^a + t_{n,i}^{ac} \\ 0, & \text{otherwise} \end{cases} \quad (27)$$

$$\forall n \in \mathbf{B}, i \in \mathbf{E}_n, j \in \mathbf{H}, t \in \Gamma$$

where (24)/(26) is the arrival/leaving EV number, and (25)/(27) defines the EV binary arrival/leaving status.

2) Pricing Strategy of DSO for Congestion Management

Our goal is to maximize the social welfare Π^{SW} in the premise of avoiding congestion, i.e., considering the profits of both the generation and demand sides. Let $\mathbf{L} \subset \mathbf{B} \times \mathbf{B}$ denote the set of lines. For each $(m, n) \in \mathbf{L}$, m is the unique parent bus of bus n , then the objective of DSO for congestion management is formulated as follows:

$$\max_{\lambda_{n,j,t}} \Pi^{SW} = \sum_{t \in \Gamma} \left(\sum_{n \in \mathbf{B}} \sum_{j \in \mathbf{H}_n} \Pi_{n,j,t}^{CS} + \Pi_t^{DSO} \right) \quad (28)$$

CS constraints:

$$\Pi_{n,j,t}^{CS} = \Pi_{n,j,t}^{CS,C} - C_{n,j,t}^{CS,P} \quad \forall n \in \mathbf{B}, j \in \mathbf{H}_n, t \in \Gamma \quad (29)$$

$$\Pi_{n,j,t}^{CS,C} = \sum_i^{N_{n,j,t}^{EV}} \lambda_{n,j,t,a}^{TC} P_{n,i,t}^{EV} \Delta t \quad \forall n \in \mathbf{B}, i \in \mathbf{E}_{n,t}, j \in \mathbf{H}_n, t \in \Gamma \quad (30)$$

$$C_{n,j,t}^{CS,P} = \lambda_{n,j,t}^{CS,P} P_{n,j,t}^{CS} \Delta t \quad \forall n \in \mathbf{B}, j \in \mathbf{H}_n, t \in \Gamma \quad (31)$$

$$\lambda_{n,j,t}^{TC} = \lambda_{n,j,t}^C + \lambda_{n,j,t}^S \quad \forall n \in \mathbf{B}, j \in \mathbf{H}_n, t \in \Gamma \quad (32)$$

$$\lambda_{n,j}^{S,\min} \leq \lambda_{n,j,t}^S \leq \lambda_{n,j}^{S,\max} \quad \forall n \in \mathbf{B}, j \in \mathbf{H}_n, t \in \Gamma \quad (33)$$

DSO constraints:

$$\Pi_t^{DSO} = \sum_{n \in \mathbf{B}} \sum_{j \in \mathbf{H}_n} C_{n,j,t}^{DSO,P} - C_{n,j,t}^{DSO,M} - C_{n,j,t}^{DSO,D} \quad \forall t \in \Gamma \quad (34)$$

$$C_{n,j,t}^{DSO,M} = \lambda_{n,t}^{DSO,M} P_{n,j,t}^{CS,M} \Delta t \quad \forall n \in \mathbf{B}, j \in \mathbf{H}_n, t \in \Gamma \quad (35)$$

$$C_{n,j,t}^{DSO,D} = \lambda_{n,t}^{DSO,D} P_{n,j,t}^{CS,D} \Delta t \quad \forall n \in \mathbf{B}, j \in \mathbf{H}_n, t \in \Gamma \quad (36)$$

$$P_{n,j,t}^{CS} = \sum_{i=1}^{N_{n,j,t}^{EV}} P_{n,i,t}^{EV} = P_{n,j,t}^{CS,M} + P_{n,j,t}^{CS,D} \quad \forall n \in \mathbf{B}, i \in \mathbf{E}_{n,t}, j \in \mathbf{H}_n, t \in \Gamma \quad (37)$$

Grid constraints:

$$\begin{cases} \sum_{mn \in \mathbf{L}} (P_{mn,t} - r_{mn} l_{mn,t}) - \sum_{nq \in \mathbf{L}} P_{nq,t} = \sum_{j \in \mathbf{H}_n} P_{n,j,t}^{CS} + P_{n,t}^O - P_{n,t}^{DG} \\ \sum_{mn \in \mathbf{L}} (Q_{mn,t} - r_{mn} x_{mn,t}) - \sum_{nq \in \mathbf{L}} Q_{nq,t} = Q_{n,t} \end{cases} \quad (38)$$

$$v_{n,t} = v_{m,t} + 2(P_{mn,t} r_{mn} + Q_{mn,t} x_{mn}) - l_{mn,t} (r_{mn}^2 + x_{mn}^2) \quad (39)$$

$$\begin{cases} 2P_{mn,t} \\ 2Q_{mn,t} \\ l_{mn,t} - v_{n,t} \end{cases} \leq l_{mn,t} + v_{m,t} \quad (40)$$

$$V_{\min}^2 \leq v_{n,t} \leq V_{\max}^2 \quad (41)$$

$$0 \leq l_{mn,t} \leq l_{\max}^2 \quad (42)$$

$$\phi_{mn,t} = P_{mn,t} / P_{mn}^L \leq \phi_{mn,t}^{\max} \quad \forall (m,n) \in \mathbf{L} \quad (43)$$

for $\forall n, j, t$ in (38)-(43), $n \in \mathbf{B}, j \in \mathbf{H}, t \in \Gamma$

where (29) denotes the CS profits which consists the EV charging profits $\Pi_{n,j,t}^{CS,C}$ defined as (30) and the CS electricity purchase cost $C_{n,j,t}^{CS,P}$ define as (31). The charging price is set in the day-ahead market while the service fee can be adjusted by CS for real-time congestion management.

The energy loss rate and the output of distributed generator are often assumed to be a constant and a predicted power output, which does not increase the difficulty on solving the congestion management problem. Therefore, we can assume that the marginal price of each bus has been set by the day-ahead market

and ignore the energy loss. In this case, maximizing the profits of the DSO is equivalent to maximizing the total profits of DSO from electricity sales to CSs, so the total profits of DSO in (28) can be formulated as (34) ignoring the other components of DSO profits for convenience. (35)/(36) is the cost to DSO of purchasing power from the main grid/distributed generators to sell to CSs.

Finally, the grid constraints for (28) are given as (38)-(43), (38) formulates the linearized power balance. (39) describes the relationship between node voltage and branch current. (38) is the convex relaxation of power flow equality constraints based on second order cone programming. (40)-(43) are the constraints on the node voltage amplitude, line current and line congestion.

Although (22) and (28) constitute a bi-level optimization problem, they are not suitable to be solved by traditional optimization methods for the following reasons. Firstly, the problem contains both discrete and continuous actions, which makes it challenging to solve the algorithm. Secondly, model-based methods require a real-time explicit physical model with accurate parameters to formulate the behavior of EV users which is not possible to obtain. Moreover, as the problem scale grows, the problem will be time-consuming caused by the dramatic increase in the dimensionality of the optimal variable with many complex constraints.

III. METHODOLOGY

DRL is a data-driven method and can be used to solve the dynamic, real-time control problem. However, a suitable DRL method for the congestion management problem should be efficient and safe, and can be deployed in the real world by training only limited historical data. On the one hand, certain exploratory behaviors of trial and error are unacceptable for congestion management, which may cause serious safety issues such as line burning and equipment damage. **Besides, there are usually difference between data distributions in offline and online datasets due to the insufficiency and uncertainty of the sample data (i.e., the offline dataset only contains partial data distributions) which will make the conventional model-based DRL unsafe.** On the other hand, unlike in the field of computer games, we are not able to generate a large number of pricing experiences with low cost. In fact, the datasets for most scenarios are insufficient to support real applications of even off-policy reinforcement learning methods, such as the state-of-the-art soft actor critic (SAC) algorithm. The ideal approach for congestion management is able to train out the safe pricing strategy based on a simulator established by limited historical data collected by CSs aggregations and DSO.

In view of this, inspired by the work in [29]-[30], we propose the AMSDRL algorithm to solve the congestion management problem in the form of CMDP in this section. **The proposed bi-level model acts as a joint environment for the distribution and transportation networks, and the DRL agent can learn the optimal charging strategy through direct interactions with the environment. Specifically, the agent gives actions (service fee) based on the observed information, taking into account the constraints of the distribution network, thus influencing the EV users' decisions. The simulated EV users then choose the optimal charging station with the lowest total cost under the**

transportation constraints, which in turn changes the EV load distribution in the power network.

A. Model-Based Safe DRL Framework

The infinite-horizon CMDP tuple in safe reinforcement learning can be defined as a tuple $(S, A, T, r, c, \gamma, \mu_0)$, where S and A are the space of action and state, $T: S \times A \rightarrow D(S)$ is transition distribution and $P_0 \in D(S)$ is the initial distribution. $r(S, A)$ is the reward function and $c(S, A)$ is the cost function. $\gamma \in (0, 1)$ is the discount factor. A policy π is a mapping from states to distribution over actions. Let $\mathbb{P}_{T,t}^\pi$ denote the probability of being in state s at timestep t when actions are sampled according to policy π and transition T . Then we let $\rho_{s,a}^\pi(s, a) := (1 - \gamma) \pi(a|s) \sum_{t=0}^{\infty} \mathbb{P}_{T,t}^\pi(s)$ be the state-action occupancy distribution of policy π under dynamic transition T , which is a properly normalized probability distribution. The value function in reinforcement learning is formulated as $V^\pi(s) := \mathbb{E}_T^\pi[\sum_{t=0}^{\infty} \gamma^t r(s_t, a_t) | s_0 = s]$ with the expectation which is over $s_0 \sim \mu_0(\cdot)$, $s_t \sim T(s_t | s_{t-1}, a_{t-1})$, $a_t \sim \pi(\cdot | s_t)$, similarly, we define the cost value function as $V_c^\pi(s) := \mathbb{E}_T^\pi[\sum_{t=0}^{\infty} \gamma_c^t c(s_t, a_t) | s_0 = s]$, then the goal of safe reinforcement learning is to find the optimal feasible policy π^* that solves the constrained optimization problem with cumulative constraint threshold as follows:

$$\begin{aligned} \max_{\pi} J(\pi) &:= V^\pi(s) = \mathbb{E} \left[\sum_{t=0}^{\infty} \gamma^t r(s_t, a_t) \right] \\ \text{s.t. } J_c(\pi) &:= V_c^\pi(s) = \mathbb{E} \left[\sum_{t=0}^{\infty} \gamma_c^t c(s_t, a_t) \right] \leq C \end{aligned} \quad (44)$$

However, the transition function T of real environment is typically hard to get, which means π^* cannot be directly solved. The problem can be solved by model-based deep reinforcement learning which learns an estimated transition function \hat{T} from dataset $\mathcal{D} := \{(s, a, r, c, s')\}$ to replace T . Then we can get the surrogate model-based objective function $\hat{J}(\pi)$ and cost constraint $\hat{J}_c(\pi) < C$, respectively.

According to (45), a basic model-based safe DRL framework can be defined, which iterates among the following three steps: (1) solving for optimal policy $\hat{\pi}^*$ approximately, (2) collecting trajectory data (s, a, r, c, s') from $\hat{\pi}^*$, (3) updating estimated transition function \hat{T} using all collected data so far.

B. CMDP Formulation for Model-Based Safe DRL

In this section, the congestion management problem is formulated as a constrained Markov decision process.

1) Definition of State

s_t is the observed status information of CSs and DSO at time stage t , including the line load percentage $\phi_{n,t}$, the number of EVs at each charging station $N_{n,j,t}^{EV}$, the social welfare Π_t^{SW} . The congestion usually occurs only on certain lines, so we just need to get the information of some relevant lines and CSs according to the network topology.

2) Definition of Action

a_t is the control action given by DSO during time stage t , which is the CS service fee $\lambda_{n,j,t}^S$. The values of the action variables should be pre-constrained according to the prior knowledge to reduce the computation time.

3) Definition of Reward and Cost

The reward and cost functions are given as follows:

$$r_t = \tau_1 \Pi_t^{SW} \quad c_t = \tau_2 \phi_t^E \quad \forall t \in \Gamma \quad (45)$$

$$\phi_t^E = \begin{cases} \sum_{n \in B} (\phi_{mn,t} - \phi_{mn,t}^{\max}), & \phi_{mn,t} > \phi_{mn,t}^{\max} \\ 0, & \text{else} \end{cases} \quad \forall (m, n) \in L, t \in \Gamma \quad (46)$$

where ϕ_t^E is the violation errors of congestion. τ_1 and τ_2 are positive weight coefficients. To make it easier for the neuron network to calculate the gradient to improve the algorithm training efficiency, we suggest adjusting τ_1 and τ_2 so that the reward and cost values do not exceed 200. We usually set τ_2 as 100, which means that c_t represents the total percentage of congestion violation while τ_1 is mainly adjusted according to the EV fleet size.

C. Adaptive Model-Based Safe DRL

1) Strict and Adaptive Cost Constraint

The model-based safe DRL framework has a high training efficiency, however, it cannot fully guarantee the safety due to the modeling error, which we will discuss in this section.

The CMDP can be solved by considering its dual problem, the dual formulation of (44) can be written as follows:

$$\begin{aligned} \max_{\rho(s,a) \geq 0} \quad & \frac{1}{1-\gamma} \sum_{s,a} \rho(s,a) r(s,a) \\ \text{s.t.} \quad & \frac{1}{1-\gamma_c} \sum_{s,a} \rho(s,a) c(s,a) \leq C \\ & \sum_{s,a} \rho(s,a) = (1-\gamma_c) \mu_0(s) + \gamma_c \sum_{s',a'} T(s|s',a') \rho(s',a') \end{aligned} \quad (47)$$

where the second constraint defines the space of valid occupancy distributions by ensuring the flow conservation equilibrium between distributions.

The integral probability metric (IPM) associated with the measurable real-valued functions \mathcal{F} on full set χ , i.e., the difference between the true and learned transitions can be defined as follows:

$$\begin{aligned} d_F(T(s,a), T(s,a)) &:= \sup_{f \in \mathcal{F}} \left| \int_{\chi} f dT - \int_{\chi} f dT \right| \\ &= \sup_{f \in \mathcal{F}} \left| E_{s' \sim T(s,a)} [f(s')] - E_{s' \sim T(s,a)} [f(s)] \right| \end{aligned} \quad (48)$$

Telescope Lemma: Let $\hat{J}_c(\pi)$ and $J_c(\pi)$ be two cost constraint functions with the same cost c , but different transitions \hat{T} and T , respectively. Then,

$$J_c(\pi) - J_c(\pi) = \gamma_c \bar{E}_{(s,a) \sim \rho_T^\pi} \left[E_{s' \sim T(s,a)} [V_c^\pi(s')] - E_{s' \sim T(s,a)} [V_c^\pi(s)] \right] \quad (49)$$

The proof of the lemma is given in Appendix. Using the telescope lemma and conclusion of (49), the difference between the expected cost of \hat{T} and T can be bounded as follows:

$$\begin{aligned} & \frac{1}{1-\gamma} \sum_{s,a} (\rho_T^\pi(s,a) - \rho_T^\pi(s,a)) c(s,a) \\ &= \gamma \sum_{s,a} \rho_T^\pi(s,a) \left[E_{s' \sim T(s,a)} [V_c^\pi(s')] - E_{s' \sim T(s,a)} [V_c^\pi(s)] \right] \\ &\leq \gamma \sum_{s,a} \rho_T^\pi(s,a) \sup_{f \in \mathcal{F}} \left| E_{s' \sim T(s,a)} [f(s')] - E_{s' \sim T(s,a)} [f(s)] \right| \\ &= \gamma \sum_{s,a} \rho_T^\pi(s,a) d_F(T(s,a), T(s,a)) \end{aligned} \quad (50)$$

Then we have the following conclusion:

$$\begin{aligned} & \frac{1}{1-\gamma} \sum_{s,a} \rho_T^\pi(s,a) c(s,a) \\ &\leq \frac{1}{1-\gamma} \sum_{s,a} \rho_T^\pi(s,a) c(s,a) + \gamma \sum_{s,a} \rho_T^\pi(s,a) d_F(T(s,a), T(s,a)) \\ &\leq \frac{1}{1-\gamma} \sum_{s,a} \rho_T^\pi(s,a) c(s,a) + d_F(T(s,a), T(s,a)) \end{aligned} \quad (51)$$

(51) shows that satisfying $\frac{1}{1-\gamma} \sum_{s,a} \rho_T^\pi(s,a) c(s,a) \leq C$ does not guarantee that the resulting optimal policy π^* would not violate the safety constraint in the real CMDP (i.e., $\frac{1}{1-\gamma} \sum_{s,a} \rho_T^\pi(s,a) c(s,a) \leq C$) because of the modeling error $d_F(\hat{T}(s,a), T(s,a))$. To guarantee that policy π^* is feasible for T , we rewrite the safety model-based framework (44) with strict and adaptive cost function $J_s(\pi)$ as follows:

$$\begin{aligned} \max_{\pi} J(\pi) &:= E \left[\sum_{t=0} \gamma^t r(s_t, a_t) \right] \\ \text{s.t. } J_s(\pi) &:= E \left[\sum_{t=0} \gamma^t c(s_t, a_t) + \beta u_T(s_t, a_t) \right] \leq C \quad (52) \\ d_F(T(s,a), T(s,a)) &\leq u_T(s_t, a_t) \end{aligned}$$

where u_T is a heuristic cost penalty based on the statistics of the transition model. We use a neural ensemble that outputs a Gaussian distribution $\hat{T}_\theta = \mathcal{N}(\mu_\theta(s_t, a_t), \Sigma_\theta(s_t, a_t))$ to formulate the transition and learn an ensemble of N models $\{\hat{T}_\theta^i = \mathcal{N}(\mu_\theta^i, \Sigma_\theta^i)\}_{i=1}^N$. In other words, we use a neural network with parameter θ to learn and predict the transitions in CMDP. Then we take the maximum Frobenius norm of the standard deviation of the learned models in the ensemble as u_T , which is done for offline reinforcement learning in [25] as follows:

$$u_T(s_t, a_t) = \max_i^N \left\| \sum_{\theta}^i (s_t, a_t) \right\|_{\text{F}}. \quad (53)$$

However, we find that using the cost penalty u_T directly is inflexible, leading to a poor performance in practice, so we set an adaptive scalability factor β to balance safety and exploration, which is shown in (52). We adopt PI control method for updating β as follows:

$$\beta_{t+1} = \beta_t + \alpha (J_C(\pi_t) - C) \quad (54)$$

where α is the learning rate. When $J_C(\pi) > C$, β will be updated bigger to strict the cost constraint, and vice versa.

2) Constrained Cross Entropy Method

The action and state space of pricing strategy of congestion management is continuous, therefore, (50) cannot be solved by formulating into state-action pairs as in discrete environments due to the curse of dimensionality.

To solve (52), we apply the constrained cross entropy method. We use the distributions of natural exponential family (NEF) $F_v = \{f(\cdot; v), v \in \mathcal{V} \subseteq \mathbb{R}^{d_v}\}$ over action space A to cover the distributions on policy space Π . NEF contains many useful distributions, such as Gaussian distribution and Bernoulli distribution. Then the optimal solution of (52) can be reformulated as follows:

$$v^* = \arg \max_{v \in \mathcal{V}} E_{a \sim f_v} [J(a) | a \in A_S] \quad f_v \in F_v \quad (55)$$

where A_S is the set of feasible actions for strict and adaptive constraint $J_s(\pi) < C$. Drawing on the cross entropy methods,

we first need to search for a surrogate function with solvable form to replace (55). The surrogate function is the conditional expectation of $J(a)$ over the sample policies π with sampling distribution f_v .

Here, we introduce the concept of ρ -quantile to express sample policy: the ρ -quantile of random variable X is defined as a scalar σ such that $\mathbb{P}(X \leq \sigma) \geq \rho$ and $\mathbb{P}(X \geq \sigma) \leq 1 - \rho$.

We use $\varphi_G(v, \rho)$ to denote the ρ -quantile of function $G: A \rightarrow \mathbb{R}$ for $a \sim f_v$, $v \in \mathcal{V}$. Generally, ρ represents the proportion of highly ranked actions. If $G(a) \leq \varphi_G(v, \rho)$, that means the G-value of action is smaller than at most $1 - \rho$ of all actions with sampling distribution f_v , vice versa implies that the G-value of action is greater than at least ρ of all actions.

Define the set of operations $\mathcal{O} := \{\geq, >, \leq, <, =\}$, let $\delta: \mathbb{R} \times \mathcal{O} \times \mathbb{R} \rightarrow \{0, 1\}$ be an indicator function for $\circ \in \mathcal{O}$, $a \& b \in \mathbb{R}$, $\delta(a \circ b) = 1$ if and only if $(a \circ b)$ holds. Similarly, we define sample indicator function $H: A \times \mathcal{V} \times (0, 1) \rightarrow \{0, 1\}$ as follows:

$$\begin{aligned} H(a, v, \rho) := & \delta(\varphi_{J_s}(v, \rho) > C) \delta(J_s(a) \leq \varphi_{J_s}(v, \rho)) + \\ & \delta(\varphi_{J_s}(v, \rho) \leq C) \delta(K(a) \geq \varphi_K(v, 1 - \rho)) \end{aligned} \quad (56)$$

$$K(a) := J(a) \delta(J_s(a) \leq C)$$

then, the surrogate function for constrained cross entropy can be expressed as follows:

$$S(v; \rho) = E_{a \sim f_v}[J(a)H(a, v, \rho)] \quad (57)$$

the optimal distribution with minimal variance of the origin objective function (55) can be calculated as follows:

$$v^* = \arg \max_{v \in \mathcal{V}} S(v; \rho) \quad (58)$$

Finally, instead of updating the distribution parameters directly via the solution of (58), we use the following smooth updating rule with weighted factor κ :

$$\hat{v}_t = \kappa v_t^* + (1 - \kappa) \hat{v}_{t-1}. \quad (59)$$

For a more detailed explanation, (56)-(58), i.e., the updated rules for the sampling distribution of actions in constrained case can be expressed as follows: If $\varphi_{J_S}(v, \rho) > C$, which means the proportion of feasible actions is lower than ρ , we select the actions with lowest cost, i.e., action a is preferred if $J_S(a) \leq \varphi_{J_S}(v, \rho)$; If $\varphi_{J_S}(v, \rho) \geq C$, which means the proportion of feasible actions is at least ρ , we select the actions satisfy the constraint with highest reward, i.e., action a is preferred if $J_S(a) \leq C$ and $J(a) \geq \varphi_J(v, 1 - \rho)$. In this study, we use the normal distribution in NEF as f_v , and the full AMSDRL method is described in Algorithm 1.

IV. CASE STUDY

A. Test System and Parameter Settings

All the tests are performed on a computer with 3.40 GHz CPU, 1050Ti GTX graphics card and 16 GB RAM. We apply Pytorch to formulate the neural networks framework of AMSDRL algorithm and Pandapower to establish the modified IEEE 33-bus distribution network.

The topologies of transportation network and modified IEEE 33-bus distribution network are given in Fig. 2 where CS1/2/3 is at node 2/9/10, and the detailed information of the transportation network, CSs and EV users, and EVs technical

specifications is presented in Table I~III. The specifications are based on the GMM (Gaussian mixed method), and the optimal

Algorithm 1: AMSDRL Algorithm

Inputs: Transition model \hat{T}_θ , an empty experience buff \mathcal{D} , cumulative constraint threshold C , initial β value, β learning rate α , smooth learning rate κ , initial sampling distribution $\mathcal{N}(\mu_0, \Sigma_0)$, ρ -quantile, training episode I , CCEM max iteration J , population size N , planning horizon H

Outputs: Optimal action sequence $\{a_1^*, \dots, a_m^*\} := \mu_J$

Process:

- Initial \mathcal{D} with random policy, $k \leftarrow [pN]$
- for** $i = 1, \dots, I$ **do**
- Train \hat{T}_θ using data in \mathcal{D}
- for** $j = 1, \dots, J$ **do**
- Sample N action sequences $A^1 := \{a_t^1\}_{t=1}^H, \dots, A^N := \{a_t^N\}_{t=1}^H$
- Evaluate the actions sequences by simulating trajectories in \hat{T}_θ according to (55).
- Construct feasible set $\Psi := \{\theta_n | J_S(A^n) \leq C, n \in [N]\}$ with (56)-(57)
- if** $|\Psi| < k$ **then**
- Construct elite set $\varsigma := \{\text{The } k \text{ sequences out of all } \{A^n\}_{n=1}^N \text{ with lowest costs}\}$
- else**
- Construct elite set $\varsigma := \{\text{The } k \text{ sequences in } \Psi \text{ with highest rewards}\}$
- end if**
- Compute μ_j, Σ_j according to (58)-(59)
- end for**
- Collect trajectory and store to buff \mathcal{D}
- Calculate $J_C(\pi_t)$ and update β based on (54)
- end for**

cluster number of GMM is obtained by calculating the silhouette coefficient. Power lines $l_{27,28}, l_{9,10}, l_{1,18}$ are prone to congestion with the maximum load percentage limit of 90% and the corresponding line capacities are 15.2, 5.6, 4.9(MW).

The detailed parameters of AMSDRL method are given in Table IV, where we set the learning rate of the adaptive scalability factor higher than the ensemble networks in order to improve the initial training speed. The population size and ρ -quantile determine the stability and speed of convergence. Too large the population size and ρ -quantile can lead to too many elite actions being selected which would reduce the training speed, and vice versa, leading to violent training fluctuations. Based on our test, the appropriate coordinated values of the population size and ρ -quantile are 0.15 and 500 for this study, and the corresponding value of the max iteration for CCEM is better taken as 3~5.

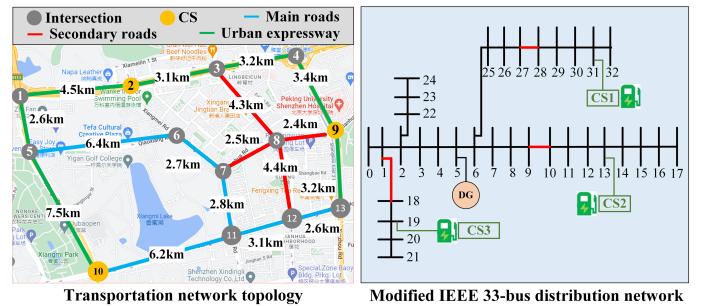


Fig. 2 Illustration of the transportation/distribution network.

TABLE I. PARAMETERS OF TRAFFIC SYSTEM

Parameters	Value		
	Urban expressway	Main roads	Secondary roads
$\vartheta_1/\vartheta_2/\vartheta_3$	1.726/3.15/3		2.076/2.870/3
v^0	70	50	40

Fig. 3 Number of EVs with charging demand at each traffic node

TABLE II. PARAMETERS OF CSs AND EV USERS

Parameters	Value
Number of charging piles of CS1/CS2/CS3	50/30/20
Maximum/Minimum service fee(¥ /kWh)	0.8/0.3
Electricity purchase price of CS(¥ /kWh)	0.7
Electricity cost from the main grid(¥ /kWh)	0.5
Cost of distributed generator(¥ /kWh)	0.3
Distributed generator maximum output(MW)	9
Distribution of the service time(μ, σ^2) (min)	(48.37, 432.50)
Rated charging power(kW)	60
EV user inclination coefficient(μ, σ^2)	(0.5, 0.1)
EV user time cost conversion factor	(15, 3)

TABLE III EV TECHNICAL SPECIFICATIONS GMM MODEL PARAMETERS

Features	Mean value (μ)	Variance (σ^2)
Battery capacity (kWh)	{[53.13], [85.35]}	{[79.01], [200.01]}
Charging time (min)	{[66.65], [36.47]}	{[281.69], [170.88]}
Start-end SOC	{[51.86 → 98.62], [43.3 → 81.69]}	{[[369.62, -0.01], [-0.01, 0.60]], [[390.77, 146.56], [146.56, 258.27]]}

TABLE IV ALGORITHM PARAMETERS

Parameters	Value
Optimizer	Adam
Number of hidden layers	5
Number of hidden units per layer	256
Learning rate of network/ adaptive stability factor	1e-3/1e-2
Discount factor/cumulative constraint threshold	0.99/0
Max iteration for CCEM/ population size/ ρ -quantile/ planning horizon/weighted factor for smooth update	5/500/0.15/12/0.9
Replay buffer size	1e6
Number of samples per mini batch	128
Nonlinearity	Swish

The number of EVs with charging demand is given in Fig. 3. For convenience, we define the ratio of the current traffic flow and capacity of the road as the road condition index $I(t)$. The detailed road condition indexes for urban expressways, main roads and secondary roads during 14:00 to 17:00 are set as Fig. 4 according to the data in [31]. We get the information of arrival/departure SOC, battery, and parking time, as well as the scaled number of EVs with charging demand based on the size of the simulated transportation network from 2098 sets of historical data of CSs during 2:00 pm-5:pm in a certain area, Shenzhen in 2022.

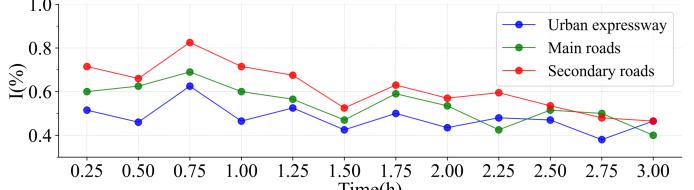
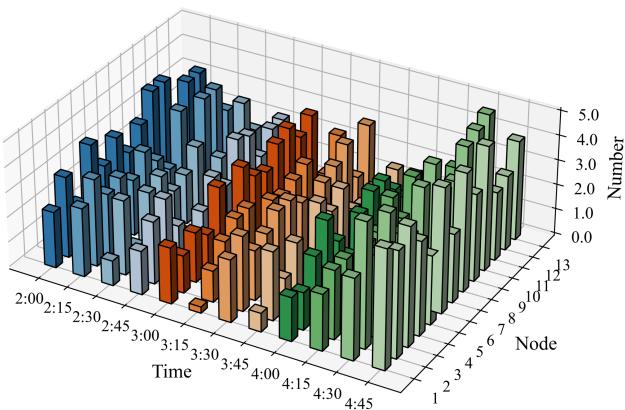


Fig. 4 Road condition index for three types of roads

B. Effectiveness of the AMSDRL Method

Fig. 5 compares the training performance of the proposed AMSDRL and the state-of-the-art safe DRL algorithms with the same learning rate, training samples per step and action preset range. First order constrained optimization in policy space (FOCOPS) [25] and constrained policy optimization (CPO) [26] are the representative algorithms of the two dominant paradigms of policy projection and Lagrangian method in safe DRL. It is worth noting that safe reinforcement learning does not mean that the trained policy would not violate the constraints. The violations are much less frequent than other DRL algorithms, i.e., safe DRL can have a very small number of mild violations [32]. The dark line represents the average reward/cost per 50 steps while the light line represents the actual reward/cost of each training step.

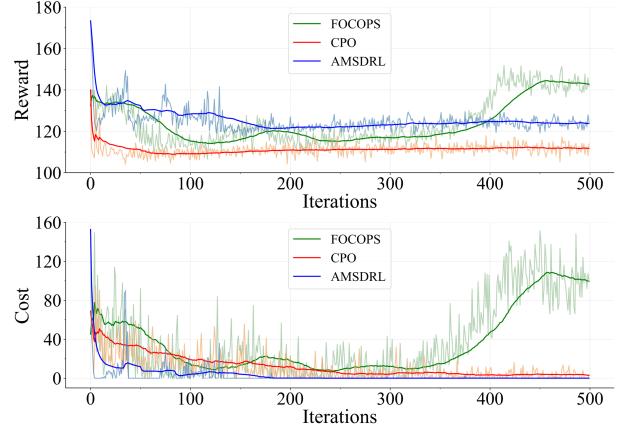


Fig. 5 Comparisons of performance of the state-of-art safe DRL algorithms

TABLE V STATISTICAL RESULTS OF THE TRAINING PERFORMANCE

Items	AMSDRL	CPO	FOCOPS
Average reward during convergence	123.24	121.82	117.69
Average cost during convergence	0.036	4.05	13.52
Number of training violations during the training process	80	404	459
Number of violations of the trained model under the new test set (500 iterations)	11	59	217
Time to convergence (min)	70.87	118.98	147.40
Loading time for the execution (s)	31.14	24.60	46.06

To further compare the performance of three algorithms, the statistical results are presented in Table V. The average reward and cost during convergence reflect the effect of the trained model while the training violations and converged time reveal the stability and efficiency of the algorithms. The load time for the execution of three algorithms is both acceptable, but the proposed AMSDRL exhibits the highest average reward and is

significantly much safer maintaining only 0.89% and 0.27% cost of FOCOPS and CPO, which shows the perfect balance between effectiveness and constraint. Besides, AMSDRL also outperforms the other two algorithms in terms of efficiency and stability, reducing training time by 51.92%/40.44% and training violations by 82.57%/80.20% compared to FOCOPS/CPO.

C. Results and Analysis of the Congestion Management

The control group of Fig. 6-9 is trained by SAC DRL method whose reward function is only CSs profits with the same action preset range of the proposed AMSDRL. And the maximum line load percentage is set to 135%. SAC algorithm is a state-of-the-art stochastic off-policy algorithm, which is usually used as a benchmark algorithm because of its better performance compared to other DRL algorithms.

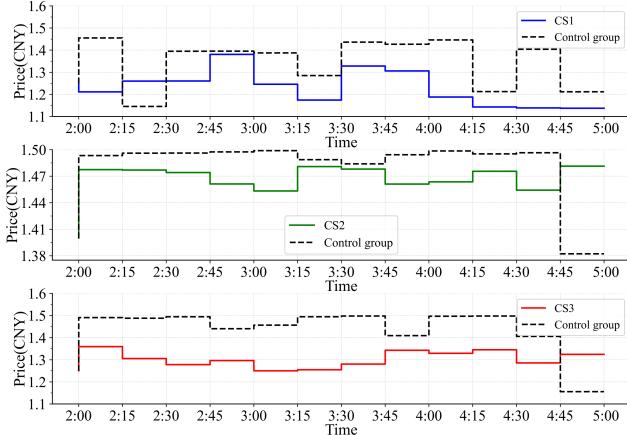


Fig. 6 Real-time price of three CSs.

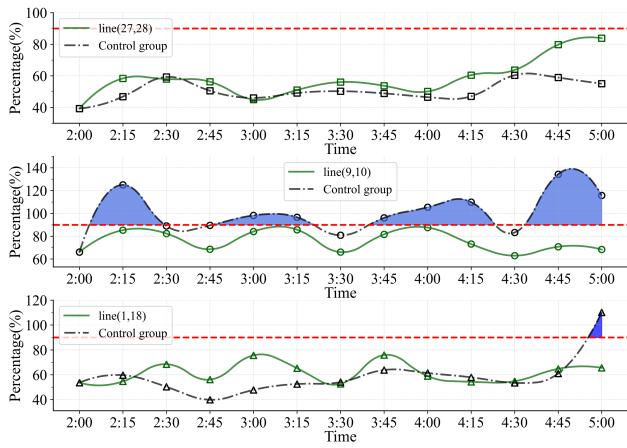


Fig. 7 Load percentage of target lines

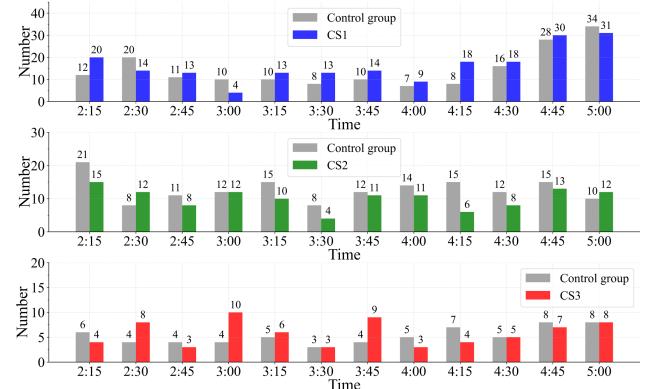


Fig. 8 Number of EVs arriving in each time stage.

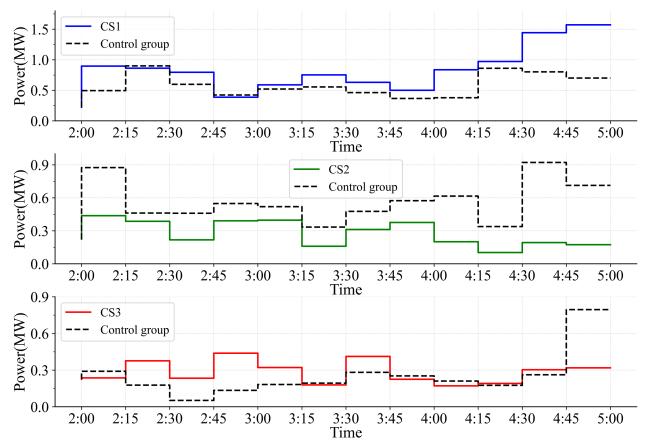


Fig. 9 Active power of three CSs.

Fig. 6 presents the real-time charging price of three CSs. It can be seen that the pricing strategy of the AMSDRL presents significant stratification between three CSs. Fig. 7 shows the load percentage of target lines $l_{27,28}$, $l_{9,10}$, $l_{1,18}$, where the red dashed line represents the line load percentage limit of 90% and the blue fill represents the congestion error. It is observed that the congestions are prone to occur at $l_{9,10}$ in the whole process and $l_{1,18}$ during the end of the congestion management process. Compared to the control group, the proposed method reduces the congestion by up to 66.64% and all the load percentages lie within the range of operating congestion limits with lower fluctuations. Fig. 8 and 9 present the arrival EVs number and active power of three CSs, which give the explanation of the results in Fig. 7. We can find that the price of CS 2 is always relatively higher than CS1 and 3, which makes EVs shifted from CS 2 to CS 1 3 during 2:00-4:45 to avoid congestion at $l_{9,10}$. During 4:45-5:00, with the decrease in price of CS 1 and increase in price of CS 2 and 3, some EVs are encouraged to charge at CS 1 to eliminate the congestion violation at $l_{1,18}$. Note that the CS load includes the charging power of arriving EVs and previously arrived EVs with unsatisfied charging demand, which means that the impact of price is superimposed and the decision process is more complex than the straightforward analysis.

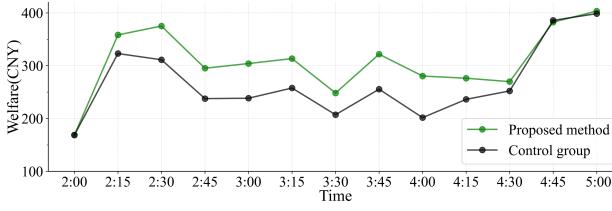


Fig. 10 Social welfare.

The results in terms of the social welfare are shown in Fig 10, whose control group is also trained by the SAC algorithm with the same settings, but the reward function contains social welfare and line load percentage limit of 90%. We originally thought that as a benchmark unconstrained algorithm, the SAC should yield better results in social welfare than AMSDRL, however, the conclusion is the opposite. The total social welfare of the proposed method improves by 15.06% compared with the control group. We believe the reason is that SAC needs a high negative reward to achieve the soft congestion constraint, which would weaken the ability to explore and cause the conservative pricing to prevent the congestion.

D. Scalability Verification

The EV dispatching capacity is mainly limited by the energy and time constraints, which is usually suitable for relatively small region in the transportation network. So we test the method performance for larger systems in terms of nodes and EVs. The simulations were performed on the IEEE 118-bus distribution system to verify the scalability of the proposed method. As shown in Fig 11, there are six CSs at the bus 49, 53, 70, 77, 106, 113. The number of electric vehicles with charging demand quadrupled. Power lines $l_{35,47}$, $l_{66,67}$, $l_{102,103}$ are prone to congestion with corresponding line capacities of 30, 26, 60(MW). The detailed results are presented in Table VI.

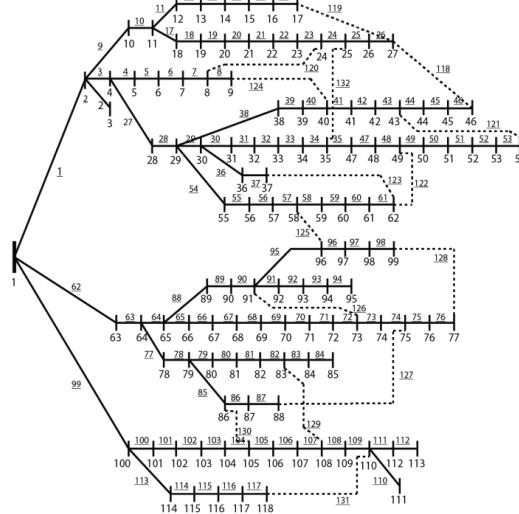


Fig. 11 Illusion of the transportation network and IEEE 118-bus distribution system for scalability verification.

Compared with the simulation results on IEEE 33-bus system, similar conclusions can also be concluded on the IEEE 118-bus system with only 13.12%/7.93% increase in training/loading time. This is because the AMSDRL uses the constrained cross entropy method to directly calculate the distributions of actions rather than using a policy network to output the sample policy. The computational time mainly depends on the factor of

population size. The growth in EVs and traffic nodes will not significantly increase the training time or loading time in theory.

TABLE VI RESULTS OF SIMULATIONS ON IEEE 118-BUS DISTRIBUTION NETWORK

Items	Value
Average/ Maximum congestion reduction of the three lines(kW)	15.25/34.32
Maximum reduction of line load percentage (%)	57.17
Social welfare increase (%)	17.61
Time to convergence (min)	80.17
Loading time for the execution (s)	33.61

V. CONCLUSION

A model-based safe DRL method is proposed to solve the real-time EV congestion management problem with coupled power and transportation networks. The congestion management problem is formulated as a CMDP and solved by the AMSDRL algorithm. Numerical studies conducted on the modified IEEE 33-bus and 118-bus distribution systems with real historical data demonstrate the effectiveness of the proposed method. The following conclusions can be drawn:

1) The proposed method significantly prevents all the line congestions with lower fluctuations and reduces the maximum line load percentage by 66.64%, while improving the total social welfare by 15.06% compared with the control group.

2) Compared with FOCOPS/CPO, the proposed AMSDRL algorithm achieves better convergence reward, safer constraint satisfaction with only 0.89% /0.27% cost during the convergence, higher training efficiency with 51.92%/40.44% reduction in training time and greater training stability with 82.57%/80.20% reduction in violations.

3) The method is good for scalability. The training/loading time of the proposed method on the IEEE 118-bus large distribution network increases only 13.12%/7.93% compared to the training results of the IEEE 33-bus system.

APPENDIX

Proof of the *Telescope Lemma*:

Let C_j^E be the expected cost from executing the first j steps of π and then switching to T for the remainder, as follows:

$$C_j^E = \underset{a_i \sim \pi(s_i)}{\mathbb{E}} \left[\sum_{t=0}^{\infty} \gamma^t c(s_t, a_t) \right]_{\substack{t < j: s_{t+1} \sim T(s_t, a_t) \\ t \geq j: s_{t+1} \sim \pi(s_t, a_t)}}$$

Note that $\hat{J}_c(\pi) = C_\infty^E$ and $J_c(\pi) = C_0^E$, then

$$J_c(\pi) - J_c(\pi) = \sum_{j=0}^{\infty} (C_{j+1}^E - C_j^E).$$

C_{j+1}^E can C_j^E can be expanded as

$$\begin{aligned} C_{j+1}^E &= C_j + \underset{s_j, a_j \sim \pi, T}{\mathbb{E}} \left[\underset{s' \sim T(s_j, a_j)}{\mathbb{E}} \gamma^{j+1} [V_c^\pi(s')] \right] \\ C_j^E &= C_j + \underset{s_j, a_j \sim \pi, T}{\mathbb{E}} \left[\underset{s' \sim T(s_j, a_j)}{\mathbb{E}} \gamma^{j+1} [V_c^\pi(s')] \right]. \end{aligned}$$

After substitution, we have

$$\begin{aligned}
& J_c(\pi) - J_c(\bar{\pi}) \\
&= \sum_{j=0}^{\infty} \gamma^{j+1} \mathbb{E}_{s_j, a_j \sim \pi, T} \left[\mathbb{E}_{s' \sim T(s_j, a_j)} \gamma^{j+1} [V_c^\pi(s')] - \mathbb{E}_{s' \sim T(s_j, a_j)} \gamma^{j+1} [V_c^{\bar{\pi}}(s')] \right] \\
&= \gamma \overline{\mathbb{E}}_{(s, a) \sim \rho_T^\pi} \left[\mathbb{E}_{s' \sim T(s, a)} [V_c^\pi(s')] - \mathbb{E}_{s' \sim T(s, a)} [V_c^{\bar{\pi}}(s')] \right].
\end{aligned}$$

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