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Design and Planning of a Multiple-charger Multiple-port Charging System for PEV Charging Station

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***Abstract*—Investment of charging facilities is facing deficit problems in many countries at the initial development stage of plug-in electric vehicles (PEVs). In this paper, we study the charging facility planning problem faced by a PEV charging station investor who aims to serve PEV customers with random behaviors and demands (but follow a series of predicted distributions) with lower economic costs of both charging facilities and practical operation. Firstly, we design a multiple-charger multiple-port charging (MCMP) system which provides the capability of scheduling a limited quantity of chargers to serve more PEVs. Secondly, we further develop a general two-stage stochastic programming model to plan the MCMP system inside a PEV parking lot with consideration of coordinated charging. Thirdly, we classify MCMP stations according to three different connecting patterns between chargers and parking spaces. Fourthly, the general planning model is simplified (as a reference) based on the classification. Finally, we complement our analysis through case studies.**

***Index Terms*—Plug-in electric vehicle, charging facility planning, multiple-charger multiple-port charging system, stochastic programming, coordinated charging.**

NOMENCLATURE

1) Indices and Sets

i	Index of chargers
j	Index of parking spaces
t,τ	Index of time intervals
ω / Ω	Index/set of scenarios

2) Parameters and Variables

J	Number of parking spaces
T	Number of time intervals in a day
Δt	Duration of a time interval (h)
α	Annual discount rate
γ	Life cycle of PEV charging facilities (year)
$cost^{\text{ch}}$	Investment costs of a charger ($)
$cost^{\text{co}}$	Investment costs of a connection between a charger and a parking space ($)
π_t^{tou}	Time-of-use (TOU) electricity price at time interval t ($/kWh)
$\pi^{\text{pe}}(.)$	Penalty for uncompleted charging demands ($/kW)
π^{ca}	Capacity price for the charging stations ($/kVA·month)
P^{ra}	Rated power of a charger (kW)
η	Charging efficiency of a charger
L_t	Load excluding charging loads at time interval t (kW)
$B_{t,j}$	Battery capacity of the PEV at parking space j at time interval t (kWh)
$SoC_{t,j}^{\text{a}}$	Arrival state of charge (SOC) of the PEV that arrives at time interval t and parks at parking space j
$SoC_{t,j}^{\text{d}}$	Expected departure SOC of the PEV that departs at time interval t and parks at parking space j
$SoC_{t,j}^{\text{p}}$	Present SOC of the PEV at parking space j at time interval t
$E_{t,j}^{\text{un}}$	Uncompleted charging demands that occur at parking space j at time interval t (kWh)
$S_{t,j}^{\text{pa}}$	Parking state of parking space j at time interval t, $S_{t,j}^{\text{pa}}=1$, if a PEV parks at parking space j at time interval t; $S_{t,j}^{\text{pa}}=0$, otherwise

3) Decision Variables

I	Number of chargers
$S_{i,j}^{\text{co}}$	Connecting state between charger i and parking space j, $S_{i,j}^{\text{co}}=1$, if charger i and parking space j are connected by cables and switches; $S_{i,j}^{\text{co}}=0$, otherwise
$P_{t,i}$	Charging power of charger i at time interval t (kWh)
$P_{t,j}$	Charging power of the PEV at parking space j at time interval t (kWh)
$S_{t,i,j}^{\text{ch}}$	Charging state between charger i and parking space j at time interval t, $S_{t,i,j}^{\text{ch}}=1$, if charger i is charging the PEV at parking space j at time interval t; $S_{t,i,j}^{\text{ch}}=0$, otherwise
$S_{t,j}^{\text{ch}}$	Charging state of PEV at parking space j at

This work was supported in part by the National Key Research and Development Program of China (2016YFB0900103) and the National Natural Science Foundation of China (51477082).

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time interval t, $S^{\mathrm{ch}}_{t,j}=1$, if a charger is charging the PEV at parking space j at time interval t; $S^{\mathrm{ch}}_{t,j}=0$, otherwise

I. Introduction

As a cleaner mode of transport, plug-in electric vehicles (PEVs) have aroused worldwide attention and been regarded as an effective solution to meet energy and environmental challenges [1]. A number of countries around the world have released incentive policies, such as tax reductions, to encourage the PEV development, accelerate the transformation of the transportation energy and cultivate new auto markets [2], [3]. In China, strategic plans have been made to increase investment in clean energy vehicles area [3], [4]. Additionally, the government of China is aiming at an overall ownership of five million PEVs by 2020 [5].

In spite of the above motivations and actions, barriers to large-scale penetration and commercialization of PEVs exist in various aspects. Among others, the inconvenience for a PEV to get recharged is one of the most critical factors. It is widely believed that sufficiently pervasive charging facilities are the premise and foundation of the extensive PEV market acceptance [6]. But at the initial development stage of PEVs, the construction of charging facilities is facing high expenditure and low revenue so that governments need to afford massive subsidies. The heavy investment has resulted in present charging infrastructures still far from enough for the convenient charging service [5], [7].

As a consequence, a lot of efforts have been devoted to the planning problem of PEV charging facilities so as to bring the investment cost down and facilitate the wide adoption of PEVs. Reference [8] provides a mathematical model of EV charging demand for a rapid charging station on a highway. Reference [9] presents an optimal deployment model for a given number of public charging stations to maximize the social welfare associated with the coupled transportation and power networks. Also from the traffic system and power system perspectives, reference [4] proposes a multi-objective PEV charging station planning method to ensure charging service while reducing power losses and voltage deviations of distribution systems. In [10], the optimal sites of PEV charging stations are first identified by considering environmental factors and charging station service radius, then a mathematical model is utilized to decide the optimal sizing of PEV charging stations. Reference [11] puts forward a multi-objective collaborative planning model for planning the integrated power distribution and PEV charging systems to minimize the overall annual cost of investment and energy losses and maximize the annual captured traffic flow simultaneously. In [3] and [12], the planning problems of PEV charging stations are studied based on weighted Voronoi diagram and particle swarm optimization, respectively. Authors of [13] firstly formulate the planning problem of PEV charging stations based on the charging station coverage and the convenience of drivers, secondly prove the complexity of the problem and finally propose four solution methods, which are respectively suitable for different situations.

However, almost all the published papers on PEV charging facility planning are from the perspective of a city planner but not a station operator. For a PEV charging station, the operator trends to adopt coordinated charging strategies and make more profits in practice [2], [14]-[16]. By responding to the time-of-use (TOU) or real-time electricity prices, coordinated charging strategies help to spread the electricity use throughout the day. As a result, the charging loads are flattened and less chargers work simultaneously at the peak loads in a charging station under coordinated charging. It implies the possibility of reducing the charger investment costs in PEV charging stations. However, to the best of our knowledge, there is few published work on charging facility planning inside PEV charging stations, which incorporates the coordinated charging of PEVs at the planning stage and enhances the utilization rates of charging resources. Reference [7] designs a new charging spot model to share one charger to several PEVs, but the design cannot solve the problem thoroughly. Another charging resource sharing method is supported by PEVs, i.e., foldable and stackable electric vehicles, which can be stacked and charged in a train [17], but the idea cannot be implemented at present.

Based on the above considerations, we focus on studying the charging facility design inside PEV charging stations by incorporating coordinated charging while planning so as to reduce the investment costs. The major contributions of this paper include: 1) designing a multiple-charger multiple-port charging (MCMP) system for PEV charging stations which provides the capability of sharing limited chargers to more PEVs (a comparison of the existing charging schemes and this paper's design is shown in Table I, and more detailed descriptions analysis are presented in Section II); 2) developing a general two-stage stochastic programming model to plan the MCMP system in a PEV charging station; 3) defining three connecting patterns between chargers and parking spaces, classifying MCMP stations based on the definitions and analyzing them; 4) simplified planning models are presented (as a reference) based on the classification.

The remainder of this paper is organized as follows. Section II summarizes different types of charging facilities and introduces the MCMP system. Section III describes charging facility planning method using the MCMP system. Section IV shows case studies and Section V concludes.

II. Different Types of Charging Facilities for PEV Charging Stations

In this section, we firstly summarize and analyze two types of charging facilities inside PEV charging stations, i.e., SCSP piles (traditional type) and SCMP piles (proposed in [7]) and then present the new charging facility design, i.e., the MCMP system. Note that: 1) a charger is a PEV charging machine including rectifier devices, which converts the AC source to the DC output; 2) a charging port is the interface used to connect PEV batteries and is considered not a part of a charger here; 3) a charging pile is composed of chargers, charging ports and cables between them.

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TABLE I
COMPARISON OF DIFFERENT CHARGING SCHEMES

Design	Objective	Characteristics
Single-charger single-port charging (SCSP) piles (traditional design).	Guaranteeing that all the PEVs can get recharged immediately when they come.	Each parking spaces are equipped with one charger, which brings high charging service quality but high charging facility investment.
Foldable and stackable PEVs [17].	Sharing charging resources and reducing charging facility investment.	PEVs stack in a train and share one charger, but specialized PEVs are needed, which are not suitable for private PEVs.
Single-charger multiple-port charging (SCMP) piles [7].		Several PEVs share one charger, which are equipped with multiple charging ports.
MCMP charging system (this paper).		Chargers are integrated and provide charging service through shared charging ports to achieve a high utilization rate of chargers.

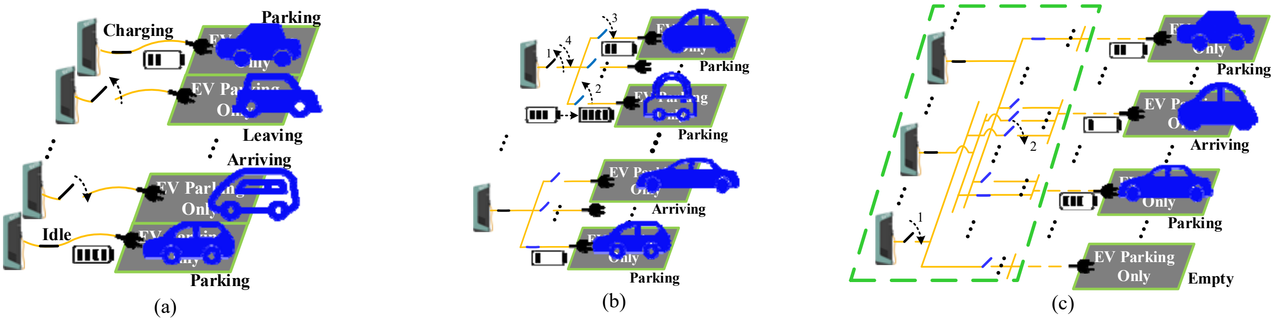

Fig. 1. The schematic diagram of (a) an SCSP station, (b) an SCMP station, and (c) an MCMP station.

A. SCSP Station

The SCSP pile is the most common one among the aforementioned charging facilities. In an SCSP station, each charging pile is equipped with one charging port and serves a certain parking space (see Fig. 1 (a)). Thus, a PEV owner is allowed to charge his or her car as soon as he or she arrives at the parking space. However, it is easily observed in Fig. 1 (a) that a charging pile will be occupied and idle if the PEV does not leave in time when charged completely, i.e., an SCSP pile is only available when the corresponding parking space is empty. A large number of idle chargers will result in huge economic loss and charging resource waste, especially when coordinated charging is executed [14], [15]. It is worthy to note that multiple SCSP piles can be integrated into a single-spot multiple-port charging (SSMP) pile, which extends multiple charging ports and can charge multiple PEVs simultaneously. Similar to that in the SCSP station, the idle charger issue is also probable to occur at an SSMP station.

The fundamental cause of the idle charger problem of SCSP and SSMP stations lies in their connecting patterns between chargers and parking spaces. Each charger in these two stations can only serve one parking space (an SSMP pile can be regarded as a combination of multiple chargers, and the quantity of chargers is equal to the quantity of charging ports). Owing to this, huge charging resource waste is possible if a PEV occupies a parking space for a long time. The following type of charging station, i.e., SCMP station, shows its advantage to some extent at this point.

B. SCMP Station

In an SCMP station, each charging pile also owns multiple ports (see Fig. 1 (b)). The difference between an SCMP pile and an SSMP charging pile is that the former only deployed one charger but the latter are designed with multiple outputs, i.e., an SCMP pile can only charge one PEV at a time, while this number for an SSMP pile can reach up to its number of charging ports. The design of SCMP pile is for the sake of enhancing the utilization rate of charging resources [7].

Note that a load switch (the black switch in Fig. 1 (b)), which can be operated when the power (electricity) is on, and multiple disconnectors (the blue switches in Fig. 1 (b)), which can only be operated when the power (electricity) is off, are equipped for an SCMP pile. While the switches for the SCSP and SSMP piles can only be load switches. The disconnectors can only be operated when the corresponding load switch is off in SCMP stations. In Fig. 1 (b), the marked numbers present the order of switch operations when the charging pile needs to change its service object.

Although, the SCMP station can mitigate the idle charger issue, it cannot solve the problem thoroughly. Because the charging service quality will be affected by PEVs' parking behaviors. The detailed discussions are given in the following pages.

C. MCMP Station

Different from the above designs, MCMP system integrates all the chargers inside the charging station to provide the capability that all the PEVs share chargers fairly. The concept of *power sharing* can be used here to well illustrate our design idea [17]. *Power sharing* inside a PEV charging station denotes the capability of sharing charging resources to PEVs. It inspires us to design a flexible and proper connecting pattern between chargers and parking spaces to achieve a good quality of *power sharing*. In MCMP system, we firstly aggregate the cables of chargers which can serve a certain parking space, then connect them to the corresponding charging port through an underground cable (orange dash lines in Fig. 1 (c)). As a result, each charger is allowed to serve multiple parking spaces and each PEV is allowed to be charged by multiple chargers (see Fig. 1 (c)), but one charger can only charge one PEV at a time. For example, in Fig. 1 (c), an arriving PEV can get recharged

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immediately if there is an available charger among those connected to the parking space.

We note the following features of MCMP system. 1) MCMP system is designed for charging stations where PEV users come not only for charging but also for parking. These charging stations are in sharp contrast to urgent charging station where PEVs leave as soon as charging is completed. Almost all destination charging station, such as residential and company PEV parking lots, and some midway charging station, such as mall PEV parking lots, are appropriate to apply this design. 2) A split installing method, i.e., deploying chargers and cables inside the green dash line in Fig. 1 (c) in a large cabinet away from parking spaces, is more appropriate for proposed MCMP system. Because it is convenient to adjust the connecting relations between chargers and parking spaces. 3) Similar to SCSP pile, there are also load switches (the black switch in Fig. 1 (c)) and disconnectors (the blue switch in Fig. 1 (c)) in MCMP system, and all the disconnectors can only be operated when the corresponding load is off (marked numbers in Fig. 1 (c) is the switch operation order); 4) the SCSP and SCMP piles are two special cases of the MCMP system.

The MCMP system can theoretically realize arbitrary connecting relations for chargers and parking spaces. In practical charging station design, it is critical to implement a suitable connection pattern that trades off the cable and switch costs with charging system efficiency. Thus, based on this design, we formulate mathematical models to plan the charging facilities in an MCMP station in the next section.

III. Charging Facility Planning Method for MCMP Stations

A. General Optimization Model for the Planning of an MCMP Station

For the purpose of taking coordinated charging into account while planning, the objective includes both investment costs (investment stage) and operation costs (operation stage). Also, since the PEV parking behaviors and charging demands are uncertain, a series of scenarios with corresponding occurrence probabilities is considered for the optimal planning of an MCMP station[1], where there are I chargers and J parking spaces ($I \le J$, I is a variable and J is given and fixed).

Mathematically, a two-stage stochastic programming model is formulated to describe the planning problem, shown as follows:

$$\min_x C(x) = \min_x \left\{ \underbrace{C^{\mathrm{I}}(x)}_{\text{investment stage}} + \underbrace{\mathbb{E}_\omega \min_y \left[C^{\mathrm{O}}(x, y(\omega), \omega) \right]}_{\text{operation stage}} \right\} \tag{1}$$

where

$$C^{\mathrm{I}}(x) = \Gamma \left(cost^{\mathrm{ch}} \cdot I + cost^{\mathrm{co}} \cdot \sum_{i=1}^{I} \sum_{j=1}^{J} S_{i,j}^{\mathrm{co}} \right) \tag{2}$$

$$\begin{aligned} C^{\mathrm{O}}(x, y(\omega), \omega) = 365 \cdot & \sum_{t=1}^{T} \sum_{i=1}^{I} \left(P_{t,i}(\omega) \cdot \Delta t \cdot \pi_t^{\mathrm{tou}} \right) \\ & + 365 \cdot \sum_{t=1}^{T} \sum_{j=1}^{J} \pi^{\mathrm{pe}} \left(E_{t,j}^{\mathrm{un}}(\omega) \right) \\ & + 12 \cdot P^{\mathrm{ra}} \cdot \pi^{\mathrm{ca}} \cdot I. \end{aligned} \tag{3}$$

The above problem includes two stages: the investment stage and the operation stage. The former is the first stage (the master problem) and the latter is the second stage (the subproblem). In (1), the first term is investment costs, which are in the form of equivalent annual value and calculated by (2), and the second term is the operation costs, which are in form of expected annual value and calculated by (3). In (2), multiplied by the capital recovery factor $\Gamma = \frac{\alpha(1+\alpha)^\gamma}{(1+\alpha)^\gamma - 1}$ (α is the discount rate and γ is the life cycle of PEV charging facilities), the initial investment costs, including the charger costs and the connection costs, are allocated equally to each year. In (3), the operation costs include three parts: the first term is electricity purchase costs; the second term is the non-completion penalty of charging demands; the third term is the capacity charge for the charging station. The penalty $\pi^{\mathrm{pe}}(\cdot)$ in the second term is set as a convex function [18].

In the two-stage problem, the master problem seeks to obtain an optimal solution $x = \{I, \boldsymbol{S}^{\mathrm{co}}\}$, where $\boldsymbol{S}^{\mathrm{co}}$ is the connecting state matrix with components $S_{i,j}^{\mathrm{co}}, \forall i, j$, and minimize the total equivalent annual costs. For a given x, the subproblem then solves the optimal expected annual operation costs under a number of scenarios $\omega \in \Omega$ with decision variables $y = \{\boldsymbol{P}^{\mathrm{ch}}, \boldsymbol{S}^{\mathrm{ch}}\}$, where $\boldsymbol{P}^{\mathrm{ch}}$ is the charging power matrix of chargers with components $P_{t,i}, \forall t, i$ and $\boldsymbol{S}^{\mathrm{ch}}$ is the charging state matrix with components $S_{t,i,j}^{\mathrm{ch}}, \forall t, i, j$.

In the subproblem, i.e., (4)-(10), we adopt the coordinated charging to optimize the variable operation costs, i.e., the first two terms in (3), and obtain the solution y. For given scenario $\omega \in \Omega$ and x, the rolling horizon optimization simulation [7], [16] from $\tau = 1$ to $\tau = T$ are implemented to simulate the operation of real-time coordinated charging strategy and then calculate the variable operation costs. If a new PEV is connected to the MCMP system at time interval t, the mathematical model for the coordinated charging strategy, which is utilized to update the charging powers of all the chargers, is formulated as follows.

$$\min_y f = \sum_{\tau=t+1}^{t+T} \sum_{i=1}^{I} P_{\tau,i}(\omega) \cdot \Delta t \cdot \pi_\tau^{\mathrm{tou}} + \sum_{\tau=t+1}^{t+T} \sum_{j=1}^{J} \pi^{\mathrm{pe}} \left(E_{\tau,j}^{\mathrm{un}}(\omega) \right) \tag{4}$$

subject to:

$$S_{\tau,i,j}^{\mathrm{ch}} \le S_{i,j}^{\mathrm{co}}, \forall \tau \in \{t+1, \cdots, t+T\}, i, j \tag{5}$$

$$\sum_{i=1}^{I} S_{\tau,i,j}^{\mathrm{ch}} \le S_{\tau,j}^{\mathrm{pa}}, \forall \tau \in \{t+1, \cdots, t+T\}, j \tag{6}$$

$$\sum_{j=1}^{J} S_{\tau,i,j}^{\mathrm{ch}} \le 1, \forall \tau \in \{t+1, \cdots, t+T\}, i \tag{7}$$

$$0 \le P_{\tau,i} \le P^{\mathrm{ra}} \sum_{j=1}^{J} S_{\tau,i,j}^{\mathrm{ch}}, \forall \tau \in \{t+1, \cdots, t+T\}, i \tag{8}$$

[1] We assume that each charger is connected to at least one parking space and each parking space is connected to at least one charger.

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$$\begin{cases} SoC^{\mathrm{p}}_{\tau,j} = 0, \text{if } S^{\mathrm{pa}}_{\tau,j} = 0 \text{ and } S^{\mathrm{pa}}_{\tau+1,j} = 0 \\ SoC^{\mathrm{p}}_{\tau,j} = SoC^{\mathrm{a}}_{\tau,j}, \text{if } S^{\mathrm{pa}}_{\tau,j} = 0 \text{ and } S^{\mathrm{pa}}_{\tau+1,j} = 1 \\ SoC^{\mathrm{p}}_{\tau,j} = SoC^{\mathrm{p}}_{\tau-1,j} + \sum_{i=1}^{I} P_{\tau,i} \cdot S^{\mathrm{ch}}_{\tau,i,j} \cdot \eta \cdot \Delta t / B_{\tau,j}, \text{if } S^{\mathrm{pa}}_{\tau,j} = 1 \end{cases}, \quad \forall \tau \in \{t+1, \cdots, t+T\}, j \tag{9}$$

$$\begin{cases} E^{\mathrm{un}}_{\tau,j} = B_{\tau-1,j}\left(SoC^{\mathrm{d}}_{\tau,j} - SoC^{\mathrm{p}}_{\tau-1,j}\right), \text{if } S^{\mathrm{pa}}_{\tau,j} = 0 \text{ and } S^{\mathrm{pa}}_{\tau-1,j} = 1 \\ E^{\mathrm{un}}_{\tau,j} = 0, \text{if } S^{\mathrm{pa}}_{\tau,j} = 1 \text{ or } \left(S^{\mathrm{pa}}_{\tau,j} = 0 \text{ and } S^{\mathrm{pa}}_{\tau-1,j} = 0\right) \end{cases}, \quad \forall \tau \in \{t+1, \cdots, t+T\}, j. \tag{10}$$

The optimization time horizon in the above model is from current time interval $t+1$ to time interval $t+T$. And for a PEV arriving at time interval u and leaving at time interval v, we suppose its available charging time is from time interval $u+1$ to time interval $v-1$. $SoC^{\mathrm{a}}_{\tau,j}$ and $SoC^{\mathrm{d}}_{\tau,j}$ are respectively the arrival and expected departure states of charge (SOCs) of PEV parking at parking space j at time interval τ, and $SoC^{\mathrm{p}}_{\tau,j}$ is the present SOC of PEV ($SoC^{\mathrm{a}}_{\tau,j}=0$, if no PEV comes to parking space j at the time interval τ, and $SoC^{\mathrm{d}}_{\tau,j}$, $SoC^{\mathrm{p}}_{\tau,j}$ similarly). For $\tau > t$, $SoC^{\mathrm{a}}_{\tau,j}$, $SoC^{\mathrm{d}}_{\tau,j}$ and $B_{\tau,j}$ follow the corresponding derived distributions based on historical data. $\sum_{j=1}^{J} S^{\mathrm{pa}}_{\tau,j}$ are estimated through the arrival number temporal distribution and $S^{\mathrm{pa}}_{\tau,j}$ are determined randomly, or by human intervention if there are parking instructions (cf. the next subsection). When $S^{\mathrm{pa}}_{\tau,j}$ is determined by parking instructions, which should be given in advance, $S^{\mathrm{pa}}_{\tau,j}$ is also a parameter for the subproblem. Note that the model can still be effective without forecasting, i.e., the predicted values can be replaced with zeros [7], but a decision-making misplay probably occurs, for example, delaying a large quantity of loads to a low price period with arrival peak.

Note that 1) for given scenario ω and given x, the model (4)-(10) is used to solve the coordinated charging strategy at any time interval when a new PEV arrives, so the model needs to be calculated many times to update the charging strategy through the day and then the final charging profile, i.e., y, can be obtained and substituted into the first stage model to calculate the operation costs; 2) In (1), the second term is the expected annual operation costs of different scenarios, so the model (4)-(10) should be calculated for the results of all the scenarios $\omega \in \Omega$; 3) in model (4)-(10), the uncertainties lie in PEV parking behaviors and charging demands, and for different $\omega \in \Omega$, the PEV parking behavior parameters ,i.e., $S^{\mathrm{pa}}_{\tau,j}$, and charging demand parameters, i.e., $SoC^{\mathrm{a}}_{\tau,j}$, $SoC^{\mathrm{d}}_{\tau,j}$ and $B_{\tau,j}$, are probably different.

The objective of the model (4)-(10) is composed of electricity purchase costs and the non-completion penalty of charging demands. Different from (3), electricity purchase costs and non-completion penalty here are for the following optimization time horizon, i.e., the duration from time interval $t+1$ to time interval $t+T$. For constraints (5)-(10), (5)-(7) restrict charging states due to the physical connections, parking states and chargers, respectively; (8) ensure the real-time charging power between 0 and the rated power; (9) and (10) describe limitations on the present SOCs and uncompleted charging demands, respectively.

However, in the above two-stage stochastic programming model, the master problem and the subproblem are highly coupled with variables $x = \{I, \boldsymbol{S}^{\mathrm{co}}\}$, of which the dimension, $1 + I \times J$, is large and varies with I . Hence, solving the model is computationally intractable. In the following subsections, we classify MCMP stations and seek to relax the high-degree coupling according to the categories.

B. Different Types of MCMP Stations

In this subsection, for further analysis, we define three types of connections between chargers and parking spaces for an MCMP station. As the premise, we first introduce the parking instruction here. For a given charging facility design, the parking instruction is an auxiliary heuristic method to realize *power sharing*. The main idea of parking instructions is informing the PEV customer where to park when he or she arrives. In general, the parking signal needs to instruct the incoming PEV to park at the parking space with the top charging priority in all the available parking spaces.

For an MCMP station with I chargers and J parking spaces, we use Φ to denote the set of scenarios that there are I PEVs with charging requests in the MCMP station. For scenario $\varphi \in \Phi$, the maximum number of chargers that can work simultaneously is denoted by m_φ ($m_\varphi \le I$).

Definition 3.1 (Defective Connections): In an MCMP station with *defective connections* (MCMP-DC station), $m_\varphi < I$, $\forall \varphi \in \Phi$.

Definition 3.2 (Instruction-needed Connections): In an MCMP station with *instruction-needed connections* (MCMP-IC station), Φ can be divided into two sets Φ_1 and Φ_2 ($\Phi_1 \cap \Phi_2 = \varnothing$ and $\Phi_1 \cup \Phi_2 = \Phi$), which meet: 1) $\Phi_1, \Phi_2 \ne \varnothing$; 2) $m_\varphi < I$, $\forall \varphi \in \Phi_1$; 3) $m_\varphi = I$, $\forall \varphi \in \Phi_2$.

Definition 3.3 (Reliable Connections): In an MCMP station with *reliable connections* (MCMP-RC station), $m_\varphi = I$, $\forall \varphi \in \Phi$.

Remark 3.1: The intersection of any two of the above three kinds of connections is empty and the union of them is the universal set of all kinds of connections. *Defective connections* are unreasonable due to its inherent limitation of chargers' utilization rate. In an MCMP-IC station, the chargers normally cannot work simultaneously even when there are exactly I PEVs with charging requests. So parking instructions are used as an auxiliary method to realize better *power sharing*. *Reliable connections* completely realize *power sharing* and no parking instruction is needed.

Remark 3.2: Connections of an MCMP system can be equivalent to a bipartite graph $G = \langle V_1, V_2, E\rangle$ ($|V_1| = I$, $|V_2| = J$), where V_1 , V_2 and E represent chargers, parking spaces and connections, respectively. Examples of a simple MCMP system with three chargers and four parking spaces are shown in Fig. 2. It can be observed from Fig. 2 that 1) for *defective connections*, there is no one-to-one connections between chargers and any three parking spaces; 2) for *instruction-needed connections*, there exist one-to-one connections between chargers and some

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three parking spaces, but not any three parking spaces; 3) for *reliable connections*, there exist one-to-one connections between chargers and any three parking spaces.

It is trivial to prove that we can always delete at least one charger without any efficiency (*power sharing* ability and customer charging experience) loss in an MCMP-DC station, i.e., an MCMP-DC station can be converted to an MCMP-IC station or an MCMP-RC station with the economic benefits improved and no efficiency loss. Thus, in following discussion, we only focus on MCMP-IC stations and MCMP-RC stations.

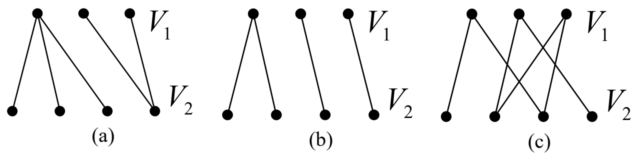

Fig. 2. Equivalent bipartite graphs of (a) *defective connections*, (b) *instruction-needed connections* and (c) *reliable connections*.

Suppose no PEV arrives or leaves from t_1 to $t_1+\Delta t_1$,and in order to achieve the minimum uncompleted charging demands, the lowest total charging requests for the MCMP station from t_1 to $t_1+\Delta t_1$ is $R^{\text{st}}_{t_1,\Delta t_1}$ ($R^{\text{st}}_{t_1,\Delta t_1} \le I\cdot P^{\text{ra}}\cdot\Delta t_1$). Then the theoretical maximum remaining output of the station without increasing new charging request loss can be calculated by: $O^{\max,\text{st}}_{t_1,\Delta t_1} = I\cdot P^{\text{ra}}\cdot\Delta t_1 - R^{\text{st}}_{t_1,\Delta t_1}$. The theoretical maximum remaining output for arbitrary available parking space from t_1 to $t_1+\Delta t_1$, denoted by $O^{\max,\text{ch}}_{t_1,\Delta t_1}$, cannot exceed $O^{\max,\text{st}}_{t_1,\Delta t_1}$ and the upper bound output of a charger in a duration of Δt_1, i.e., $P^{\text{ra}}\cdot\Delta t_1$, so we have $O^{\max,\text{ch}}_{t_1,\Delta t_1} = \min(O^{\max,\text{st}}_{t_1,\Delta t_1}, P^{\text{ra}}\cdot\Delta t_1)$. Use $O^{\max,\text{ch}}_{j,t_1,\Delta t_1}$ to denote the actual maximum remaining output for an available parking space j from t_1 to $t_1+\Delta t_1$ without increasing charging request loss. It can be easily proved that $O^{\max,\text{ch}}_{j,t_1,\Delta t_1} \le O^{\max,\text{ch}}_{t_1,\Delta t_1}$ and $\sum_{j=1}^{\tilde{J}} O^{\max,\text{ch}}_{j,t_1,\Delta t_1} \ge O^{\max,\text{st}}_{t_1,\Delta t_1}$ (suppose there are $\tilde{J}$ available parking spaces, and they are parking spaces $1,2,\cdots,\tilde{J}$).

Proposition 3.1: In an MCMP-RC station, $O^{\max,\text{ch}}_{j,t_1,\Delta t_1}$ equals $O^{\max,\text{ch}}_{t_1,\Delta t_1}$, $\forall j=1,\cdots,\tilde{J}$, if no PEV arrives or leaves from t_1 to $t_1+\Delta t_1$.

Proposition 3.2: In an MCMP-IC station, using arbitrary parking instruction method, the probability that $O^{\max,\text{ch}}_{j,t_1,\Delta t_1} < O^{\max,\text{ch}}_{t_1,\Delta t_1}, j\in\{1,\cdots,\tilde{J}\}$ occurs is positive.

The proofs of Propositions 3.1 and 3.2 are given in Appendixes A and B, respectively. Note that for any time period, we can divide it into multiple time periods when no PEVs arrives and leaves, then the above conclusions hold during each small time period.

According to Proposition 3.2, in an MCMP-IC station, charging request losses probably occur, i.e., there are some idle chargers but some PEVs' requests cannot be satisfied, although the charging request is within $O^{\max,\text{ch}}_{t_1,\Delta t_1}$. The fundamental cause is that *instruction-needed connections* cannot completely realize *power sharing* and parking instructions cannot fully make up for it. Note that this kind of charging request losses differ from ones that occur only due to the limitation of charger number and rated charging power.

Generally, using *instruction-needed connections* needs less connection costs than using *reliable connections*, but needs additional parking instruction costs, probably more non-completion penalty of charging demands and more charger investment costs. Therefore, the station investor is facing a trade-off, which also depends on the parking instruction method. However, various charging priority rules bring diverse parking instructions. For example, the station operator can regard the parking space connected with more chargers as the one with higher charging priority, and for the parking spaces with same number of connected chargers, their charging priority differences are decided by the remaining charging requests of respective connected chargers (Rule 1); another rule is ranking the parking order spaces adaptively according to the actual maximum remaining output for parking spaces from t_1 to $t_1+\Delta t_1$, i.e., $O^{\max,\text{ch}}_{j,t_1,\Delta t_1}$ (here t_1 is the current time interval and Δt_1 is the parking duration of the incoming PEV) (Rule 2). Note that: Rule 2 seems to be better than Rule 1, but it requires the PEV users to provide their charging demands and departure time before getting charged and the station control center can only calculate the charging priorities when the PEV comes, which makes Rule 2 more difficult to implement than Rule 1. To make some further prospect, we leverage Rules 1 and 2 to illustrate the characteristics of MCMP-IC stations through examples. Fig. 3 shows an equivalent bipartite graph of an MCMP-IC station with three chargers and five parking spaces and we suppose the current states of the stations are: 1) two PEVs both with charging demands $0.8\cdot P^{\text{ra}}\cdot\Delta t$ from t_1 (current time interval) to $t_1+\Delta t_1$ park at parking spaces 1 and 3, respectively; 2) parking spaces 2, 4 and 5 are empty. Two cases are constructed here to state that neither Rule 1 or Rule 2 is superior to the other one.

Case 1: Suppose a PEV comes with charging demands $0.5\cdot P^{\text{ra}}\cdot\Delta t$ from t_1 to $t_1+\Delta t_1$, and immediately a PEV comes with charging demands $0.4\cdot P^{\text{ra}}\cdot\Delta t$ from t_1 to $t_1+\Delta t_1$.

Case 2: Suppose a PEV comes with charging demands $0.5\cdot P^{\text{ra}}\cdot\Delta t$ from t_1 to $t_1+\Delta t_1$, and immediately a PEV comes with charging demands $0.9\cdot P^{\text{ra}}\cdot\Delta t$ from t_1 to $t_1+\Delta t_1$.

Both in *Cases 1* and *2*, the first PEV will park at parking space 2 and the second PEV will park at parking space 4 or 5 if using Rule 1, and two PEVs will both park at parking spaces 4 and 5 if using Rule 2. The differences are that in *Case 1*, the uncompleted charging demands using Rule 1 and Rule 2 are $0.1\cdot P^{\text{ra}}\cdot\Delta t$ and 0, respectively, while in *Case 2*, the dissatisfied charging demands using Rule 1 and Rule 2 are $0.1\cdot P^{\text{ra}}\cdot\Delta t$ and $0.4\cdot P^{\text{ra}}\cdot\Delta t$, respectively. In *Case 1*, Rule 2 show its advantage in make full exploitation of the PEV information. But in *Case 2*, Rule 2 fails since an earlier arriving PEV with relatively small charging demands occupies a parking space with the top charging priority (according to Rule 2) and the latter arriving PEV with larger charging demands can only park at a parking space with lower charging priority (according to Rule 2), which result in charging request losses for the latter arriving PEV. Also in *Case 2*, Rule 1 fortunately avoids this accident and achieves lower charging request losses. From the examples and Proposition 3.2, we can see that any charging priority rule for parking instructions cannot guarantee the absolute superiority

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than others. It is because that the uncompleted charging requests of an MCMP-IC station depend heavily on PEVs' arrival behaviors and their charging demands, which are both exogenous factors. Regarding the MCMP-IC stations, it is also worthy to note that 1) another reason of the nontriviality of getting the optimal parking instruction is due to the difficulty of describing different charging priority mathematically; 2) for a given parking instruction method, some new constraints should be added to the general model, i.e., problem (1), to describe the parking behaviors (see Subsection III.D for the example).

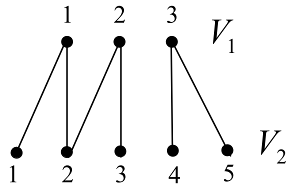

Fig. 3. Equivalent bipartite graph of an MCMP-IC station with three chargers and five parking spaces.

Different from an MCMP-IC station, for a given duration, the charging request losses of an MCMP-RC station are not affected by exogenous factors unless the total charging requests exceed the maximum output of the station. Thus, for an MCMP-RC station, it can be easily derived that all the charging demands in both *Cases 1* and *2* can be satisfied because the total demands are no more than $3 \cdot P^{\mathrm{ra}} \cdot \Delta t_1$ (the maximum output of the station in the duration).

On the basis of the above analysis and the consideration that practical planning asks for the reliability of charging service, in this paper, we mainly focus on the planning of an MCMP-RC station, and provide a reference planning method of an MCMP-IC station based on Rule 1 for comparison.

C. Optimization Model for the Planning of an MCMP-RC Station

For an MCMP-RC station, no parking instruction is needed. Given I, we hope to design *reliable connections* with the least connections.

Theorem 3.1 (The Least Connections for Reliable Connections): For an MCMP-RC station, the number of the least connections is $I \times (J - I + 1)$ and each charger are connected to $J - I + 1$ parking spaces.

The proof of Theorem 3.1 and the detailed examples of reliable connections with the least connections are deferred to Appendix C. For given connections, we can utilize Hall's marriage theorem in graph theory to evaluate whether they are *reliable connections* or not. In the equivalent bipartite graph $G = \langle V_1, V_2, E \rangle$, the corresponding connections are *reliable connections* if $|N(S)| \geq |S|$, $\forall S \subseteq V_1$ and $|S| \leq I$ ($N(S)$ means the set of adjacent vertices of S). But finding all kinds of the *reliable connections* with least connections is NP-hard, because each kind of *reliable connections* includes $\mathbf{C}_J^I$ perfect matchings respectively for bipartite graphs composed of all the chargers and arbitrary I parking spaces, and finding all the perfect matchings for one bipartite graph is NP-hard.

Based on Theorem 3.1, the number of connections only depends on I, so the decision variables of the master problem are reduced to I. The general model, i.e., problem (1), can be simplified:

$$\min_{I} C(I) = \min_{I} \left\{ C^{\mathrm{I}}(I) + \mathbb{E}_{\omega} \min_{y} \left[C^{\mathrm{O}}(I, y(\omega), \omega) \right] \right\} \tag{11}$$

where

$$C^{\mathrm{I}}(I) = \Gamma \left[cost^{\mathrm{ch}} \cdot I + cost^{\mathrm{co}} \cdot (J - I + 1) \cdot I \right] \tag{12}$$

$$\begin{aligned} C^{\mathrm{O}}(I, y(\omega), \omega) = 365 \cdot \sum_{t=1}^{T} \sum_{j=1}^{J} \left(P_{t,j}(\omega) \cdot \Delta t \cdot \pi_t^{\mathrm{tou}} \right) \\ + 365 \cdot \sum_{t=1}^{T} \sum_{j=1}^{J} \pi^{\mathrm{pe}} \left(E_{t,j}^{\mathrm{un}}(\omega) \right) \\ + 12 \cdot P^{\mathrm{ra}} \cdot \pi^{\mathrm{ca}} \cdot I. \end{aligned} \tag{13}$$

In the above model, the master problem and the subproblem are only coupled with variable I. Hence, comparing to the general model, the computational efficiency is improved exponentially. In (13), we use $P_{t,j}(\omega)$ instead of $P_{t,i}(\omega)$, because arbitrary I PEVs can be charged simultaneously at an MCMP-RC station so that we only need restrict the amount of $P_{t,j}(\omega) > 0$ at each time interval, i.e., it is negligible that which charger serves which parking space. So, after the adoption of MCMP-RC stations, $\boldsymbol{S}^{\mathrm{ch}}$ can be removed from y, then we have $y = \{\boldsymbol{P}^{\mathrm{pa}}\}$ where $\boldsymbol{P}^{\mathrm{pa}}$ is the charging power matrix for parking spaces with components $P_{t,j}, \forall t, j$.

In the subproblem, the mathematical model for the coordinated charging, which will be calculated if a new PEV arrives at time interval t, is instead formulated as follows.

$$\min_{y} f = \sum_{\tau=t+1}^{t+T} \sum_{j=1}^{J} P_{\tau,j}(\omega) \cdot \Delta t \cdot \pi_{\tau}^{\mathrm{tou}} + \sum_{\tau=t+1}^{t+T} \sum_{j=1}^{J} \pi^{\mathrm{pe}} \left(E_{\tau,j}^{\mathrm{un}}(\omega) \right) \tag{14}$$

subject to:

$$0 \leq P_{\tau,j} \leq P^{\mathrm{ra}} S_{t,j}^{\mathrm{ch}}, \forall \tau \in \{t+1, \cdots, t+T\}, j \tag{15}$$

$$\sum_{j=1}^{J} S_{\tau,j}^{\mathrm{ch}} \leq I, \forall \tau \in \{t+1, \cdots, t+T\}, j \tag{16}$$

$$0 \leq P_{\tau,j} \leq P^{\mathrm{ra}}, \forall \tau \in \{t+1, \cdots, t+T\}, j \tag{17}$$

$$\begin{cases} SoC_{\tau,j}^{\mathrm{p}} = 0, \text{ if } S_{\tau,j}^{\mathrm{pa}} = 0 \text{ and } S_{\tau+1,j}^{\mathrm{pa}} = 0 \\ SoC_{\tau,j}^{\mathrm{p}} = SoC_{\tau,j}^{\mathrm{a}}, \text{ if } S_{\tau,j}^{\mathrm{pa}} = 0 \text{ and } S_{\tau+1,j}^{\mathrm{pa}} = 1 \\ SoC_{\tau,j}^{\mathrm{p}} = SoC_{\tau-1,j}^{\mathrm{p}} + P_{\tau,j} \cdot \eta \cdot \Delta t / B_{\tau,j}, \text{ if } S_{\tau,j}^{\mathrm{pa}} = 1 \end{cases}, \quad \forall \tau \in \{t+1, \cdots, t+T\}, j \tag{18}$$

and (10).

In the above model, constraints (15) and (16) restrict the number of PEVs being charged at each time interval within I and the powers of chargers within P^{ra}. Constraints (17) and (18) are similar to constraints (8) and (9), respectively. Since the decision variable of the master problem is a one-dimensional variable, i.e., I, the two-stage model can be solved by touring all $I \leq J$.

D. A Reference Model for the Planning of an MCMP-IC Station

Here, we provide a planning method for an MCMP-IC station as a reference. In this method, the parking signal will instruct an incoming PEV to park according to Rule 1. Also, we add the constraints that the number of connections equals J, i.e., each parking space is only connected to one charger, and then the MCMP-IC station is equivalent to the SCMP station

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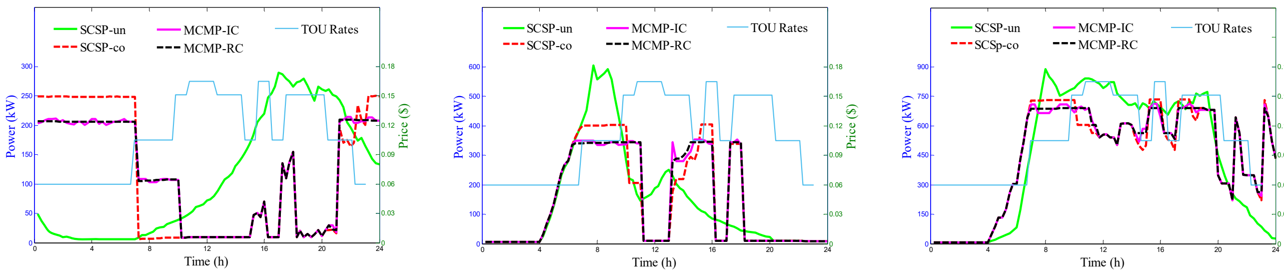
TABLE II
NUMERICAL SIMULATION RESULTS

Area Type	Station Type	Investment Stage			Operation Stage			Total Costs ($)
		Charger Costs ($)	Charger Number	Other Costs ($)	Electricity Costs ($)	Capacity Charge ($)	Penalty ($)	
Residential Areas	SCSP-un	81520.8	100	339.7	137175.3	120000	0	339036
	SCSP-co	81520.8	100	1111.4	77708.9	120000	0	280341
	MCMP-IC	19565.1	24	2019.1	83868.1	28800	2891.9	137144
	MCMP-RC	16304.1	20	6274.3	83843.6	24000	206.2	130628
Workplaces	SCSP-un	81520.8	100	339.7	155665.7	120000	0	357526
	SCSP-co	81520.8	100	1111.4	147263.5	120000	0	349895
	MCMP-IC	34238.7	42	2019.1	152625.1	50400	7462.9	246745
	MCMP-RC	26901.9	33	8393.9	152395.9	39600	905.7	228197
Other Places	SCSP-un	81520.8	100	339.7	592913.7	120000	0	794774
	SCSP-co	81520.8	100	1111.4	552142.7	120000	0	754774
	MCMP-IC	67662.3	83	2019.1	553673.4	99600	15903.2	738858
	MCMP-RC	55434.1	68	8393.9	553347.9	81600	2253.5	701029



(a) (b) (c)

Fig. 4. Load profiles of PEV charging stations in (a) residential areas, (b) workplaces, and (c) other places.

(for comparison). In consequence, the charging priorities only depend on the remaining charging requests of a parking space's connected charger (similar to that in [7]). For the model, the objective is same as (11), the expression of C^{I} need be rewritten as (19) and the expression of C^{O} is same as (3). For the subproblem, (4)-(10) are remained for the rolling time horizon optimization model but new constraints (20), which restrict the number of connections, are added. The new two-stage model here can also be solved by touring all $I \le J$.

$$C^{\mathrm{I}}(I) = \Gamma\left(cost^{\mathrm{ch}} \cdot I + cost^{\mathrm{co}} \cdot J\right) \tag{19}$$

$$\sum_{i=1}^{I} S_{i,j}^{\mathrm{co}} = 1, \forall j \tag{20}$$

IV. CASE STUDIES

A. Parameter Settings

The proposed planning methods are tested on three PEV charging stations with 100 parking spaces at residential areas, workplaces and other places, respectively. The Geely Emgrand PEV with battery capacity 45.3 kWh and driving range 253 km and the BYD E6 PEV with battery capacity 61.4 kWh and driving range 300 km are chosen as the representatives of the PEV population, both with the proportion 50% [19], [20]. Besides, we assume: 1) all the chargers for the MCMP system are with rated power $P^{\mathrm{ra}} = 10$ kW and charging efficiency η=0.92 [14]; 2) the investment costs of a charger $cost^{\mathrm{ch}} = 6000$ $ and the investment costs of a connection $cost^{\mathrm{co}} = 25$ $ [21]; 3) the life cycle of PEV charging facilities $\gamma = 10$ years and annual discount rate $\alpha = 0.06$; 4) the investment costs and the operation costs of the control equipment are respectively 2000 $ and 500 $/year under coordinated charging; 5) the investment costs and the operation costs of the parking instruction equipment are respectively 3000 $ and 500 $/year if using *instruction-needed connections*; 5) the stations have exclusive distribution transformer and the peak load excluding charging loads $\max_{\forall t}(L_t)$ is 10 kW.

The electricity rates adopted in our case are industrial TOU electricity prices in Beijing [22], which include four rate periods: the valley period (price: 0.060 $, time: 23:00-7:00), the shoulder period (price: 0.105 $, time: 7:00-10:00, 15:00-16:00, 17:00-18:00, and 21:00-23:00), the partial-peak period (price: 0.151 $, time: 10:00-11:00, 13:00-15:00, and 18:00-21:00) and the peak period (price: 0.165 $, time: 11:00-13:00 and 16:00-17:00). And the non-completion penalty function is set as $\pi^{\mathrm{pe}} = 0.4125\left[(E^{\mathrm{un}})^2 + 2E^{\mathrm{un}}\right]$ $, of which the marginal price is at least five times the peak electricity price. The capacity price for the charging stations is set as 10 $/kVA·month [23].

B. Scenario Settings

Each charging scenario includes parking behaviors and charging demands of the PEV population.

We describe the parking behaviors (different in residential areas, workplaces and other places), i.e., parking number distribution, arrival number distribution and parking duration distribution, according to the corresponding profiles shown in [24] (cf. Figs. 1-3 in [24]), which are derived from the travel data in [25]. Eventually, all the parking behaviors are used to generate the parking state matrix $\boldsymbol{S}^{\mathrm{pa}}$ with elements $S_{t,j}^{\mathrm{pa}}$. Note that $\boldsymbol{S}^{\mathrm{pa}}$ also needs to meet the parking signals if using parking instructions.

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The charging demands are generated from the trip distances d_x (x denotes the index of PEVs) before arriving at the charging station. We assume that d_x follow lognormal distributions $\ln(d_x) \sim N(4, 0.8^2)$ [25]. Also, we incorporate the impact of ambient temperatures on energy consumption [26].

We assume that there are 28 representative charging scenarios: Monday to Sunday in every season, in one year with equal probabilities 3.57%. All the scenarios are generated by Monte Carlo simulation based on the above description.

C. *Simulation Results*

Four kinds of station types are simulated in our case studies for comparison: an SCSP station under uncoordinated charging (SCSP-un station) and an SCSP station (SCSP-co station), a reference MCMP-IC station and an MCMP-RC station under coordinated charging. All the problems were solved by CPLEX [27]. The numerical simulation results and load profiles of PEV charging stations are presented in Table II and Fig. 4, respectively. All the costs listed in Table II are (equivalent) annual costs.

1) Comparing uncoordinated charging and coordinated charging: Among the four types of stations, the SCSP-un station runs uncoordinated charging and the other three implement coordinated charging. It can be observed that coordinated charging shifts the charging loads to low-price periods, flattens the load profiles and reduces the costs effectively (see Table II and Fig. 4). It is noteworthy that the effects are much better in residential areas. Because the average parking durations are long and overnight in charging stations in residential areas so that more charging loads can be shifted to the valley period of electricity prices, whereas the parking time is almost during the day time in workplaces and other places.

2) Comparing SCSP-co stations with MCMP stations: In SCSP-co stations, the charger number is same as the parking space number, so only the costs at operation stage can be improved. According Table II, the costs in MCMP stations further decrease by considering both the investment stage and the operation stage. Besides, since reducing peak loads can make profits from both charger investment costs and the capacity charge, the peak loads in MCMP stations are lower than in SCSP-co stations (see Fig. 4).

3) Comparing the reference MCMP-IC stations with MCMP-RC stations: Observed from Table II, the costs in MCMP-RC stations are a little lower than ones in the reference MCMP-IC stations and the reduction percentages are 4.75%, 7.52% and 5.12% in residential areas, workplaces and other places, respectively. Comparing detail costs of all the items in Table II, MCMP-RC stations need less chargers, achieve lower peak loads and satisfy more charging demands than the reference MCMP-IC stations, which can be well explained by Proposition 3.2. In other words, the reference MCMP-IC stations need more chargers and higher peak loads, and deliberately dissatisfy more charging demands to make up for the partial *power sharing*. The different peak loads can also be observed in Fig. 4 that the loads profiles of MCMP-RC stations are a little flatter than ones of the reference MCMP-IC stations. Because the property of partial *power sharing* also causes that the chargers cannot be scheduled completely flexibly in the reference MCMP-IC stations.

V. Conclusions

We design an MCMP system for PEV charging station and solve its planning problem to realize lower charging facility investment and operation costs. For the planning of an MCMP station, a general two-stage stochastic programming model is formulated. Further, the model is simplified for MCMP-RC stations and a reference planning method is presented for MCMP-IC stations. Simulation results show that the equivalent annual costs in MCMP stations are lower than traditional stations.

Our design and planning provide a promising option to reduce charging facility investment and facilitate large-scale PEV applications. Future work would involve more detailed comparisons between MCMP-IC and MCMP-RC stations.

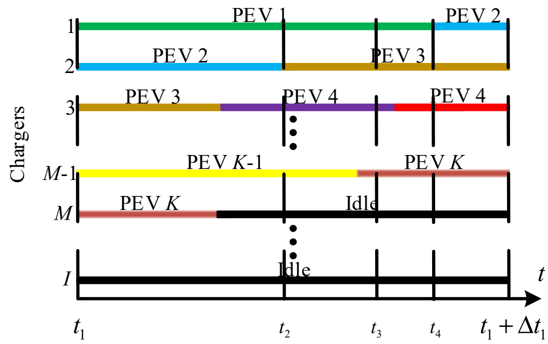

Fig. 5. The schematic diagram of PEV charging load schedule in an MCMP station with *reliable connections*.

Appendix A
Proof of Proposition 3.1

Since no PEV arrives or leaves from t_1 to $t_1 + \Delta t_1$, the charging loads of each PEV can be arbitrarily scheduled during the time. According to Definition 3.3, the chargers can serve arbitrary I parking spaces. Let all the chargers work at the rated power P^{ra}. Suppose there are K PEVs that must be charged during the time, i.e., from t_1 to $t_1 + \Delta t_1$, and their total charging demands are between $(M-1) \cdot P^{\text{ra}} \cdot \Delta t_1$ and $M \cdot P^{\text{ra}} \cdot \Delta t_1$ ($1 \le M \le I$). The schematic diagram of a feasible charging load schedule method is presented in Fig. 5, where we use different colors to represent charging periods of different PEVs and schedule all the charging loads from left to right and from top to bottom. For example, at time t_3, PEV 1, PEV 3, PEV 4, …, PEV K are charged simultaneously. And for each PEV, its charging process is divided into at most two time periods which are charged by two different chargers, e.g., PEV 2 are respectively charged by chargers 2 and 1. Note that for a PEV whose charging is finished by two periods, the end time of the first time period must be no later than the start time of the second time period (e.g., for PEV 2, t_2 must no later than t_4) because the upper bound of achievable charging request is $P^{\text{ra}} \Delta t_1$. Also, it can be seen in Fig. 5 that $O_{t_1,\Delta t_1}^{\max,\text{st}}$ equals the product of P^{ra} and the total duration of idle time periods. Using this charging load schedule method, the maximum remaining output for all available parking spaces equals $O_{t_1,\Delta t_1}^{\max,\text{ch}}$, i.e., $\min(O_{t_1,\Delta t_1}^{\max,\text{st}}, P^{\text{ra}} \cdot \Delta t_1)$. Hence, $O_{j,t_1,\Delta t_1}^{\max,\text{ch}} = O_{t_1,\Delta t_1}^{\max,\text{ch}}$, $\forall t_1, \Delta t_1, j = 1, \cdots, \tilde{J}$.

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Q.E.D.

APPENDIX B
PROOF OF PROPOSITION 3.2

According to Definition 3.2, there exist I parking spaces: if they are the only parking spaces full of PEVs with charging requests, all the chargers cannot work simultaneously. Suppose they are parking spaces 1, …, I and at most A chargers can work simultaneously for them ($A<I$). Also, suppose PEVs at parking spaces 1, …, A can be charged simultaneously. Hence, there exists $I-A$ idle chargers if only PEVs at parking spaces 1, …, A are being charged. Suppose the idle charger is charger 1, …, $I-A$. Then chargers 1, …, $I-A$ must not be connected to parking spaces A+1, …, I; otherwise, more than A chargers can work simultaneously for parking spaces 1, …, I. So all the chargers parking spaces A+1, …, I are connected to chargers among chargers $I-A+1$, …, I. Suppose they are chargers $I-A+1$, …, $I-A+B$ ($B \le A$). Use a bipartite graph G_1 to describe all the chargers, parking spaces 1, …, I and connections between them. G_1 must be a disconnected graph, and there is no path connecting charger i_1 , $\forall i_1 \in \{1,\cdots,I-A\}$, and charger i_2 , $\forall i_2 \in \{I-A+1,\cdots,I-A+B\}$. Otherwise, suppose charger $I-A+1$ are connected with charger 1 through a path, then we can let charger $I-A+1$ charge a parking space among parking spaces A+1, …, I and use charger 1 to keep PEVs at parking spaces 1, …, A being still charged so that more than A chargers can work simultaneously.

Based on above analysis, when the number of parked PEVs at parking spaces 1, …, I reaches to A, suppose these A PEVs are with charging requests $P^{\mathrm{ra}} \cdot \Delta t_1$ from t_1 to $t_1+\Delta t_1$ and parking spaces I+1, …, J are either available or filled with PEVs with sufficiently small charging requests. If these A PEVs cannot be charged simultaneously, avoidable charging request loss (the charging request can be satisfied in an MIMP-RC station) occurs due to the parking instruction method; otherwise, $O^{\max,\mathrm{st}}_{t_1,\Delta t_1} \ge P^{\mathrm{ra}} \cdot \Delta t_1$ and $O^{\max,\mathrm{ch}}_{t_1,\Delta t_1} = P^{\mathrm{ra}} \cdot \Delta t_1$, while $O^{\max,\mathrm{ch}}_{j,t_1,\Delta t_1} = 0$, $\forall j = A+1,\cdots,I$. **Q.E.D.**

APPENDIX C
PROOF OF THEOREM 3.1

Firstly, we prove that each charger need be connected to at least $J-I+1$ parking spaces. By using reduction to absurdity, suppose charger i is connected to less than $J-I+1$ parking spaces. Then there are at least I parking spaces unconnected to charger i and all the chargers cannot work simultaneously for these I parking spaces. Contradict Definition 3.3 and the station is not an MCMP-RC station, which is the premise of Theorem 3.1.

Secondly, we achieve the least connections by examples. Here, we give two examples. Example 1: Connect charger i with parking spaces $i, i+1, \cdots, i+J-I$. Example 2: Connect charger i with parking spaces $i, I+1, I+2, \cdots, J$. Equivalent bipartite graphs of example 1 and example 2 for a simple MCMP system with two chargers and four parking spaces are shown in Figs. 6 (a) and (b), respectively.

Proof of example 1: For arbitrary I parking spaces $j_1, j_2, \cdots, j_I$, suppose $j_1 < j_2 < \cdots < j_I$. It can be easily proved that $i \le j_i \le i+J-I, \forall i$, so we can let charger i charge the PEV at parking space j_i .

Proof of example 2: Since parking spaces $I+1, I+2, \cdots, J$ are connected to all the chargers, only parking spaces $1,2,\cdots,I$ need be discussed. For arbitrary I parking spaces $j_1, j_2, \cdots, j_I$, suppose $j_1 < j_2 < \cdots < j_D \le I < j_{D+1} \cdots < j_I$. Then let charger j_i charge the PEV at parking space j_i if $i \le D$. **Q.E.D.**

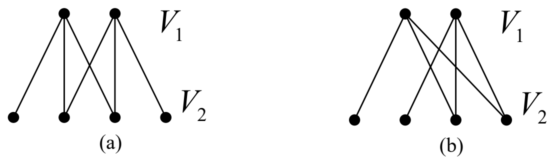

Fig. 6. Equivalent bipartite graphs of two examples of *reliable connections*.

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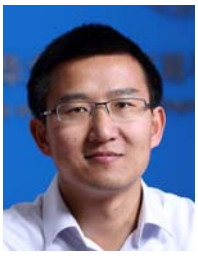

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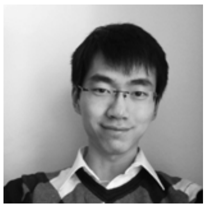

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This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TSG.2017.2735636, IEEE Transactions on Smart Grid

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