Planning of Regional Urban Bus Charging Facility: A Case Study of Fengxian, Shanghai

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Abstract—The electrification of public transport is of great significance to alleviating environmental pollution and energy problems. The construction of charging stations for electric buses (EBs) is the key step for the electrification of public transport and receives more and more attention. This paper proposes a new urban electric bus charging station planning algorithm which consists of two parts, park-maintaining (PM) charging station planning and midway supply (MS) charging station planning. Firstly, bus routes are classified based on charging demands. Accordingly, the PM charging station planning model is divided into full slow charging (FSC) model, Bus Rapid Transit (BRT) model and Hybrid model. Secondly, the improved grid AP algorithm is applied to plan MS charging stations to enhance the EB operation reliability. Then by multi-terminal charging pile optimization model, the economics of charging facilities construction is enhanced. Finally, via an ordered control charging algorithm, the economic profits of overall planning schemes are enhanced. The bus system in Fengxian, Shanghai is taken as an example to demonstrate the proposed method. Results prove that the proposed method can effectively meet the charging demands of EBs and improve the operating reliability of the EB system.

***Index Terms*—electric bus; charging station planning; AP clustering algorithm; Criteria importance though inter-criteria correlation (CRITIC); ordered charging**

I. Introduction

With global industrialization and urbanization, the environmental pollution problems and global warming caused by road transport emissions have received more and more attention [1]. Carbon emissions from the transportation sector come mainly from the burning of fuel on road, water, and air transport. According to the International Energy Agency (IEA), 80 percent of China's carbon emissions from the transportation sector are from road transport in 2018 [2]. In China, especially in Chinese megacities, such as Beijing, Shanghai, and Guangzhou, urban bus transportation is one of the most important modes of travel. Therefore, the electrification of public bus transportation is not only an ideal solution to the environmental problems but also an urgent need [3].

The successful implementation of bus electrification should first meet electric bus (EB) operation requirements [4]. There exist three primary aspects influencing EB operation regarding bus electrification: EB network design, charging scheduling, and charging facility planning. Beltran et al. [5] and Pternea et al. [6] adopted heuristic algorithms to the actual traffic network designing. Combining the transportation network with the power grid, Lin et al. [7] developed a model to solve large-scale bus charging station planning problems.

In terms of EB charging facility research, there are three main ways to supply electric energy for EBs: battery swapping charging [8-9], wireless charging [10-11], and plug-in charging [12-17]. While battery swapping has the advantages of short waiting time and convenient battery management [8-9], the safety issues associated with frequent battery swapping and the difficulty of implementing battery standardization hinder its application in public transport electrification. Wireless charging facilities can be installed at bus stations or along bus routes, which allows EBs to be charged in time [10-11]. However, the technology and business model of wireless charging methods are not mature enough to be put into large-scale application. Wang et al. [12] proposed an urban EB plug-in charging station placement planning method and they studied in detail the charging station placement in two cases, with and without considering the limited battery size. Rogger et al [13] analyzed the extent of electrification by using fast charging buses on the existing bus network (in Münster, Germany). Both research of Wang et al. [12] and Rogger et al [13] show that the battery size has a significant impact on EB charging facility planning. Kunith et al. [14] propose a mixed-integer linear optimization model to determine the minimum number and location of required charging stations for a bus network. Zhang et al. [16] proposed to establish the urban fast charging network and studied optimal planning of PEV (Plug-in electric vehicle) fast charging stations considering the interactions between transportation and electrical networks. A mixed-integer linear programming model that minimizes total expenditures is proposed [17] to locate the fast-charging stations and design the optimal battery size for the EBs. Plug-in charging, though, requires buses stop and take considerable time to charge, this just matches the spatio-temporal characteristics of buses operating during the day and resting at night. Thus, considering bus operation and plug-in charging characteristics, plug-in charging, which is also the main focus of this paper, is currently the most ideal measure to realize the bus electrification.

When high-power charging stations are connected to the power grid, the local load will increase. It is important to conduct research on effective charging scheduling strategies.

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Wang et al. [18] design a pricing-aware real-time charging scheduling system which reduces the overall charging and operating costs. Bagherinezhad et al. [19] proposed a model to schedule the spatio-temporal charging flexibility of EBs, which can effectively minimize power distribution system cost. Qiao et al. [20] applied mixed-integer programming to model the robust optimization problem of large-scale EV integration, achieving a balance between interests and robustness. In [21], a novel EV intelligent integrated station and a charging and discharging control strategy were proposed to fully use ex-service batteries. Trough hierarchical optimal frameworks and scheduling strategies, the difficulties of centralized control of large-scale EV charging are studied in [22].

The above-mentioned studies point that there are various elements and issues that need to be solved to realize bus electrification. However, most of the research have been discussed separately, which bring challenges to the bus electrification implementation due to the lack of considerations of many practical factors. For example, Beltran et al. [5] and Pternea et al. [6] did not consider the influence of EB charging facilities and charging demand. And the studies in [14],[15],[16] only considered fast-charging stations along the route and did not include bus overnight longtime charging at bus stations. In the aspects of systematic transit system electrification method [23]-[26], with minimizing the total cost of ownership of the electric bus fleet, Teicher et al. [23] present a method to choose the optimal battery size, number of charging stations and other environmental conditions. Wei et al. [24] introduces a spatio-temporal optimization model to identify the optimal deployment strategies for EB system. The authors in [25] identify the impacts of bus route electrification through two electrified bus routes and analyzes the possibilities of full electrification. The degree of electrification of replacing diesel-fueled buses by electric buses is studied in [26]. The studies in [24]-[26] can help transit agencies make strategic decisions regarding EB systems planning and design. However, to the best of our knowledge, there are very limited studies about a specific bus electrification method to upgrade the regional bus system. To address these issues, the main contributions of this paper are:

1) To meet the operation demands of all EBs, we propose a comprehensive bus electrification method taking factors of bus station types, optional EB types, charging pile constructions and charging scheduling into account. The proposed bus electrification method, which includes park-maintaining (PM) charging station planning algorithm and midway supply (MS) charging station planning algorithm, can realize the upgrade of the existing public transportation system and obtain the specific charging facilities plan.

2) To effective utilizing the areas of the bus station, we propose a multi-terminal charging piles optimization construction algorithm based on the take-turn model, which increases the economics of charging facilities planning and contributes to the implementation of ordered charging control. We match the 35 kV substations in the region with the planned charging facilities to ensure the planning meet the power grid operation requirements. Our charging strategy can meet the operating needs of the grid while achieving the effect of peak shaving and valley filling.

3) By using actual bus and power grid operation data, the proposed bus electrification method is the electrification of optional bus stops in the region under the existing bus network and scheduling plan, which significantly facilitates the bus company and power grid company to implement. The scheme has been applied in Fengxian, Shanghai, which can be a good practical reference for regional bus electrification.

The structural arrangement of this paper is as follows. The second part introduces the flowchart of charging station planning; The third part involves the algorithms of charging facility planning and optimization; The fourth part carries out the charging facility planning simulation of a real public transport system. Finally, conclusions are given.

II. Flowchart of Charging Facility Planning

A. The analysis of EB charging facility planning elements

Public bus paths and shifts are normally fixed, making the charging demands of electric buses closely related to their routes. Also, the locations of charging stations, the detailed information of charging piles, and power grid influences all should be considered in the charging stations planning.

1) The charging demands of EBs

Electric bus charging demands are decided by the operating day cycle, and all buses should be fully charged during the night to ensure sufficient energy needed for daytime operation. The locations of charging stations also affect no-service distances of buses, which are the distances for buses return to charging stations from where they finish operation.

2) EB charging station location

The selection of charging stations' positions is the key to EB charging device planning. Given the scarcity of urban land and high renovation costs, it is more economical and safer to electrify existing bus stations by building plug-in charging piles at them. There are five types of bus stations according to the urban bus company, bus PM stations, bus starting stations, bus hubs, bus stops, and rural bus stations. Bus PM stations and bus starting stations are usually equipped with parking lots for all buses parking after their daily operations. Thus, charging piles can be directly installed in these parking lots. Bus hubs, bus stops, and rural bus stations generally do not have the conditions for long hours parking, making them unsuitable as planning places for charging station.

3) The types of EB route

Meeting the operational demands of each EB route is the basis for the electrification of regional public transportation. Considering the charging demands and economic factors, this paper classifies electric bus routes as follows:

(1) Full slow charging (FSC) route: Buses in this kind of routes can complete daily operation through charging at the slow charging piles. Charging facility planning just involves slow charging buses and slow charging piles.

(2) Bus Rapid Transit (BRT) route: It is directly planned by the bus company and the government, and the operation track is fixed. Thus, its planning is not considered here. It is assumed that all buses in the route are fast charging.

(3) Hybrid route: After replacing fuel buses, the electric buses in the route cannot finish the daily operation only by using slow charging piles. The route operation requires the mixtures of fast charging and slow charging buses.

4) Grid consideration

The planning of the charging facility must consider whether the charging station access to power grid meets the requirements of the power grid. In addition, the economic costs of electrification should also be considered. Therefore, the economics needs to be incorporated into the planning objectives, while all charging stations should be validated for grid capacity as well as grid safety.

B. The flowchart of EBs charging facility planning

Because all public buses park in fixed parking lots after daily operation, charging stations in such parking lots are the basis of the charging facility planning for public EBs, referred as PM stations. The positions of PM charging station planning only include all PM stations and the bus starting stations of BRT routes. In this paper, we firstly consider that using the PM charging station to meet the charging demands of all EBs and realize the electrification of all bus routes in the region. Then designing a MS charging station model enhances the reliability of electric buses operation.

In the PM charging station planning, all bus routes are first classified into three types. Thus, the PM charging station planning model also includes three parts, which are FSC, BRT and hybrid. By planning all routes in the region, the planning results of PM charging station and charging facilities are obtained simultaneously. However, the PM charging station planning is only able to achieve the basic operation of all regional bus routes. In view of factors such as unnecessary no-service miles or battery performance degradation during bus operation, the MS charging station planning is very necessary. Meanwhile, the construction of MS charging stations can also relieve the pressure of the local key load.

The MS charging stations, equipped with 120kW charging pile, serve all slow charging buses. The alternative positions of MS charging stations include all bus stations in the region. Firstly, the distribution information of all slow charging buses and the actual traffic network are extracted. Then, the regional geographic map is gridded, and the importance of grid is assessed. Last, the planning results of MS charging stations are synthesized by the combining of several grid AP clustering algorithm calculations.

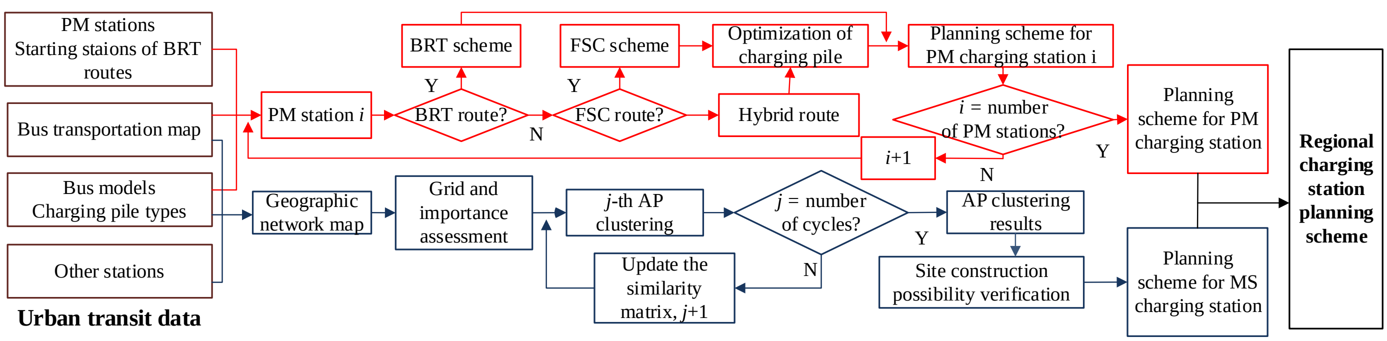

Fig.1 The flowchart of planning for urban electric bus charging analysis

The above charging stations planning just involves traditional one-bus-one-pile construction. Most charging piles are only used for nighttime centralized charging, which increases power load in a short period and reduces the utilization of charging piles. This paper proposes a multi-terminal charging pile optimal algorithm based on the take-turn model to optimize the number of piles. Thus, the final EB charging facility planning scheme is formed. Lastly, the EB ordered charging scheme is supplemented to obtain the regional bus electrification scheme. The proposed EB charging facility planning flowchart is in Fig.1.

III. Planning and Optimization Algorithm for PM Charing Station

A. Classification criteria for EB routes

In this paper, we consider the charging demands of EBs by dividing bus routes into three types, which is mentioned in section II. BRT routes are firstly informed by bus companies. For other routes, the maximum driving mileage D_m and the actual battery usage ratio λ of the electric bus in the route are first to be considered. If the average mileage of buses in a route is less than λD_m, this route is directly assigned to the FSC route. As to the routes in which the average mileage of buses is higher than λD_m, as is shown in equation (1), the route types are divided by judging whether the buses in the route can be supplementary charged to complete daily operation during daytime rest interval. In equation (1), a route is got into a FSC route when the charging demand $c_{li,demand}$ of route l_i is less than the maximum amount of power that the buses in the route can be charged $c_{li,provide}$. Otherwise, it is classified as a hybrid route.

$$\begin{cases} \Delta t'_{l_i,j} = \Delta t_{l_i,j} - \Delta d_{l_i,j} / \bar{v} - \varepsilon_{op} \\ c_{l_i,demand} = \sum_{j=1}^{n_{l_i}} f_{c,v_{l_i,j}} \left(d_{l_i,j} + \Delta d_{l_i,j} \right) \\ c_{l_i,provide} = \sum_{j=1}^{n_{l_i}} \left[\lambda s_{l_i,j} + \Delta t'_{l_i,j} \cdot \eta_p p_{l_i,j} \right] \end{cases} \quad (1)$$

Where $\Delta t_{li,j}$ is all possible charging time of l_i according to the schedule operation interval. $\Delta d_{li,j}$ is the distance between the station the buses' parking in break time and the nearest PM station. $\bar{v}$ is the average speed of buses. ε_{op} is the redundant time during the charge. n_{li} is the number of buses allocated on the route l_i. $f_{c,vli,j}(d_{li,j})$ is the energy consumed by driving distance $d_{li,j}$ and $d_{li,j}$ is j-th bus's mileage in a single day. $s_{li,j}$ is the rated capacity of the bus batteries. $p_{li,j}$ is the rated power of charging pile and η_p is charging efficiency.

B. *PM charging station planning algorithm*

1) *FSC route planning model*

The FSC charging facility planning can be achieved through replacing fuel buses by electric buses and building the corresponding charging piles. With the goal of minimizing the construction costs, the FSC planning model can be expressed as equation (2-3).

$$min\sum_{p=p_1,p_2,\cdots,p_{max}}\left(m_{Pli,p}n_{pl_i,p}+m_{Vli,p}n_{vl_i,p}\right) \tag{2}$$

$$s.t.\begin{cases} num_{pl_i,p}=\max\limits_{t\in t_{l_i,work}}\left(\sum_{j=1}^{n_{l_i,p}}h_{l_i,j}(t)\right), p=p_1,p_2,\cdots,p_{max} \\ c_{l_i,provide}\le \sum\limits_{p=p_1,p_2,\cdots,p_{max}}\eta_p p\cdot\left(num_{pl_i,p}\cdot t_{l_i,work}+n_{pl_i,p}\cdot t_{l_i,night}\right)\end{cases} \tag{3}$$

Where $m_{Pli,p}$ is the purchase and installation costs of charging piles with capacity p. $m_{Vli,p}$ is the purchase costs of new electric buses using charging piles with capacity p. $n_{pli,p}$ and $n_{vli,p}$ are the number of charging piles with capacity p and new electric buses respectively. $p_1,p_2,\ldots,p_{\max}$ is charging powers of charging piles. $num_{pli,p}$ indicates the number of charging piles can be used during daytime operation. $t_{li,work}$ and $t_{li,night}$ are the daytime charging hours and nighttime charging hours respectively. $h_{li,j}$ indicates the state whether the bus can be charged, and 1 means the bus can be charged, 0 means the bus cannot be charged.

2) *Hybrid route planning model*

We propose two solutions to meet the charging demands of hybrid routes. (1) Increasing slow charging buses to alternate with the existing buses for completing a daily task. (2) Replacing parts of slow charging buses with fast-charging buses and building fast charging piles to meet demands. So, equation (4-5) is a hybrid route planning model with the least cost objective function. The constraint conditions aim at both fast-charging buses and slow charging buses, as shown in equation (5). Where $r_{li,j}$ is the operation distance between two charges. $C'_{li,provide}$ is the amount of power supply after the addition of new buses.

$$min\sum_{p=p_1,p_2,\cdots,p_{max}}\left(m_{Pli,p}n_{pl_i,p}+m_{Vli,p}n_{vl_i,p}\right) \tag{4}$$

$$s.t.\begin{cases} \left.\begin{matrix}\lambda D_m > r_{l_i,j} \\ \Delta d_{l_i,j}=0\end{matrix}\right\} for \quad fast \quad charging \quad bus \\ num_{l_i,p}=\max\limits_{t\in t_{l_i,work}}\left(\sum_{j=1}^{n_{l_i,p}}h_{l_i,j}(t)\right), p=p_1,p_2,\cdots,p_{max} \\ c'_{l_i,provide}\le \sum\limits_{p=p_1,p_2,\cdots,p_{max}}\eta_p p\cdot\left(num_{l_i,p}\cdot t_{l_i,work}+n_{l_i,p}\cdot t_{l_i,night}\right) \\ c_{l_i,demand}<c'_{l_i,provide}\end{cases} \tag{5}$$

3) *BRT route planning model*

All BRT route electric buses are fast charging buses. So, BRT routes are equipped with 360kW charging piles. Because fast-charging buses can charge fast and have shorter driving mileage, the construction principles of BRT charging stations are that setting charging stations at BRT starting stations if the starting stations are far from the nearest PM charging stations.

4) *Planning algorithm flow of PM charging station*

The flowchart of the planning algorithm of PM charging station for the three types of bus routes is shown in Fig 2. By performing different types of planning according to route types, the PM charging station planning result will be formed.

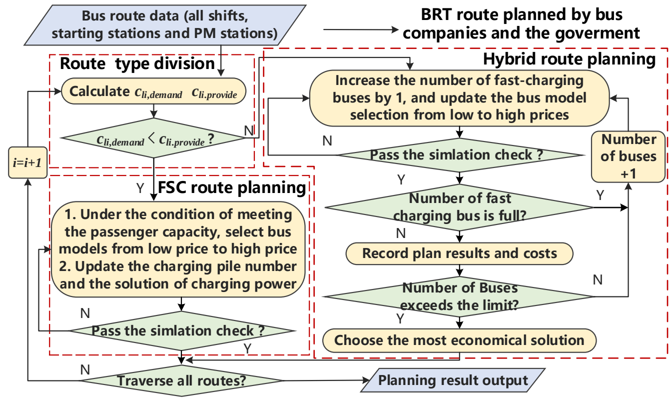

Fig. 2 Flowchart of the planning of PM charging stations

C. *MS charging station algorithm based on an improved grid AP clustering algorithm*

The number of MS charging stations should be appropriate, and the functionality needs to be maximized to serve as many buses as possible. Thus, the MS charging stations should be in areas where multiple routes converge. And their locations are relatively dispersed.

1) *Grid AP clustering algorithm*

The AP clustering algorithm [27] proposed by B J Frery and D Dueck has been widely used for fast clustering of high-dimensional and multi-class data. Its characteristics can be applied well for selecting the MS charging station locations. To improve the effectiveness of the algorithm, we make the route map to grids and merges closer stations. Then using the grid AP clustering algorithm plans the MS charging stations.

The application of AP clustering algorithm need construct the similarity matrix S, the responsibility matrix R and the availability matrix A The matrix S describes the suitability of the grids for each other to be selected as clustering centers. The larger the value of the diagonal element $S(k,k)$, the greater the probability that the grid will become a clustering center, which indicates the possibility of grids being used as charging stations. By changing the values of $S(k,k)$, it is possible to produce a different number of clusters, that is, a different number of charging station locations. We define $S(k,k)$ as (6).

$$s(k,k)=-step\cdot C_k \tag{6}$$

Where $step$ is the basic value of the algorithm, and C_k determines the probability of a grid to be a cluster center, which is determined by the importance values assessment algorithm in the next section. Then through continuously iterating the matrix A and R according to [27], the grid AP clustering results are obtained.

2) *Improvement based on the CRITIC weighting method*

Based on the real traffic network and the construction characteristics of MS charging stations, we need to determine the importance values of different grids. The values can provide the weights of the grid AP algorithm candidates, which enhances the effectiveness of the algorithm.

TABLE I INFLUENCE FACTORS OF GRID IMPORTANCE

Type	Influence factors	Symbol
Grid factors	Proportional to the load margin of the power network	θ_1
	Inversely proportional to the cost of line modifications	θ_2
Social factors	Proportional to the scale of the grid	θ_3
	Inversely proportional to grid land cost	θ_4

Transportation factors.	Proportional to grid charging demand	θ_5
	Proportional to the number of buses in grid design	θ_6

As shown in Table I, the weighting configuration of grid importance is related to grid factors, social factors, and transportation factors.

CRITIC is an objective weighting evaluation method which is suitable to determine weights in multi-attribute decision problems. It determines the objective weights of indicators based on their comparative strength and conflicting characteristics. The evaluation matrix of *m* grids, with *n* indicators for each grid, can be expressed as:

$$C=\begin{pmatrix}\theta_{1,1} & \theta_{1,2} & \cdots & \theta_{1,m}\\ \theta_{2,1} & \theta_{2,2} & \cdots & \theta_{2,m}\\ \vdots & \vdots & & \vdots\\ \theta_{n,1} & \theta_{n,2} & \cdots & \theta_{n,m}\end{pmatrix} \tag{7}$$

Where $\theta_{n,m}$ represents the *n*-th index of the *m*-th grid.

The values of the negative indexes θ_2 and θ_4 are changed by equation (8) to convert them into positive indexes.

$$\theta'_{i,j}=1\Big/\left(p+max\left|C_i\right|+\theta_{i,j}\right) \tag{8}$$

Where $\theta_{i,j}$ and $\theta'_{i,j}$ are the values of the indicators before and after the change. *P* is a fixed coordination coefficient (0.1). $max|C_i|$ is the maximum value of the *i*-th indicator. C' is the processed evaluation matrix. Because the range of different indicator values can vary considerably, resulting errors in the weight calculations, the input indicators are normalized by the equation (9).

$$\theta''_{i,j}=\theta'_{i,j}\Big/\sqrt{\sum_{k=1}^{m}\left(\theta'_{i,k}\right)^2}\qquad i=1,2,\cdots,n \tag{9}$$

Where $\theta''_{i,j}$ is the normalized indicator values.

The standard deviation of indicators s_i is used to express the contrast between the importance of different grids. The correlation coefficient $\zeta_{i,j}$ is used to reflect the conflicting character between indicators. The equations are as follows.

$$s_i=\sqrt{\frac{1}{m}\sum_{k=1}^{m}\left(\theta''_{i,k}-\bar{\theta}''_i\right)^2}\qquad i=1,2,\cdots,n \tag{10}$$

$$\xi_{i,j}=\operatorname{cov}\left(C''_i,C''_j\right)\Big/\left(s_i s_j\right)\qquad i,j=1,2,\cdots,n \tag{11}$$

Where $\bar{\theta}''$ is the average of the *i*-th indicator, that is, the average of all elements in row *i* of the matrix C''. $\operatorname{cov}(C_i'',C_{ij}'')$ is the covariance of row *i* and row *j* of C''.

Based on s_i and $\zeta_{i,j}$, the conflict values between each indicator and the others are calculated in equation (12).

$$G_i=s_i\sum_{j=1}^{n}\left(1-\xi_{ij}\right)\qquad i=1,2,\cdots,n \tag{12}$$

Where G_i directly reflects the conflict level between the *i*-th indicator and the others. The greater G_i, the less relevant the indicator is to the others, which means the more information the indicator contains and needs to be assigned with high weight. Finally, the equation for calculating the importance of the grid is obtained as equation (13).

$$\begin{cases}\beta_i=G_i\Big/\sum_{k=1}^{n}G_k\\ \gamma_j=\sum_{k=1}^{n}\beta_k\theta''_{k,j}\end{cases} \tag{13}$$

Where β_i indicates the weight of indicator *i* and γ_j is the importance value of grid *j*. The flow of the MS charging station planning algorithm is shown in Fig 3.

Combining the information of public transportation stations, the grid is divided, and the corresponding weight is set to calculate the importance of the grid. On this basis, considering that the construction of MS charging stations may increase when buses are fully electrified, the planning result can be obtained by adjusting the *step* value.

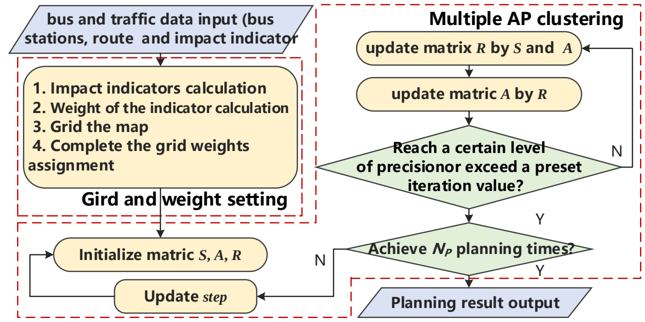

Fig. 3 Flow of the planning of MS charging stations

0. *Optimization for Multi-terminal Charging Pile Construction Based on Take-turn Model*

Traditional charging stations are usually equipped with one-terminal charging piles, which results in low utilization of charging piles. In the actual electric bus charging station, it can be considered that several electric buses can share one charging pile by installing charging piles with dual-terminal charging piles between two parking spaces, or by manually swapping the positions of electric buses, as shown in Fig 4(a). Further analysis shows that dual-terminal charging piles are suitable for regular areas, as shown in Fig 4(b). For the irregular areas of charging station, multi-terminal charging piles can be used for more reasonable layout as shown in Fig 4(c). It reduces the charging pile number, construction costs and enhances ground utilization.

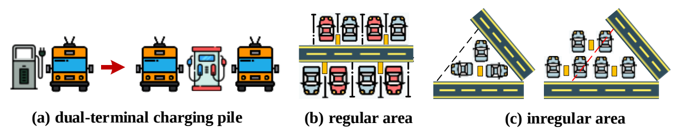

Fig. 4 Optimization of charging piles layout

The universal optimal equations are shown in (14).

$$\begin{cases}\max & \sum_{j\in Q_j}K_j\\ s.t. & \sum_{j\in Q_j}S_j\cdot n_j\le S_d\\ & K_j=k_j\cdot n_j\end{cases} \tag{14}$$

Where K_j is the pile terminal number of all *j*-type charging piles. Q_j is the set of charging pile types. S_d is the areas which need be planned. S_j is the area of *j*-type charging piles. N_j is the number of *j*-type charging piles and k_j is the pile terminal number of one *j*-type charging pile. The decision variable in the model is the number of *j*-type charging piles n_j.

While reducing the number of charging piles, the charging reliability and controllability should be ensured. Specifically, (1) the number of charging terminals should not be less than the number of existing buses; (2) to maintain the power capacity of charging piles, the take-turn model requires one charging pile to charge only one electric bus at the same time; (3) in centralized charging period, the charging pile with the most terminals should afford the charging demands of all buses connected to it. This is the take-turn model, which changes "one-bus-one-pile" to "one-bus-one-terminal". Meanwhile, take-turn model avoids EBs to be charged intensively in a short period and facilitates the central control system to optimize the charging time. Therefore, the final number of charging piles is related to night parking time T_{ci}, the number of terminals of each charging pile k_{ci}, the time spent by employees to swap charging buses t_{op} and the remaining power of bus when it enters charging station $SOC_{0,li,j}$. The take-turn model can be expressed as (15).

$$\begin{cases} \min\left(n_{op}\cdot m_{op}+\sum_{n_{cp}} m_{c_i}\rho_{c_i}\right) \\ s.t.\begin{cases} p_{c_i}\eta_p\left(T_{c_i}-\left(n_{c_i}-1\right)t_{op}\right)\ge \sum_{j=1}^{n_{c_i}}\Delta SOC_{c_i,j}, i=1,2,\cdots,N \\ n_{c_i}\le k_j, c_i\in L_j, j\in Q_j \\ n_{vp}\le \sum_{i=1}^{N}k_{c_i} \qquad \sum_{i=1}^{N}\left(n_{c_i}-1\right)\le \sigma_{op}n_{op} \\ \sum_{i=1}^{N}\sum_{j=1}^{n_{c_i}}\Delta SOC_{c_i,j}=\sum_{c_i\in L_S}\sum_{j=1}^{n_{c_i}}\Delta SOC_{c_i,j}+\sum_{c_i\in L_F}\sum_{j=1}^{n_{c_i}}\Delta SOC_{c_i,j}+\sum_{c_i\in L_A}\sum_{j=1}^{n_{c_i}}\Delta SOC_{c_i,j} \end{cases} \end{cases} \tag{15}$$

Where m_{op} is the average annual salary of night employees in the PM charging station p. n_{op} is night employees' number; m_{ci} and ρ_{ci} represent the cost and depreciation rate of the charging pile c_i respectively. N is the number of slow charging piles. p_{ci} is the charging power of charging pile c_i; n_{ci} is the number of buses served by charging pile c_i. $\Delta SOC_{ci,j}$ represents the charging amount that bus required to be fully charged. σ_{op} is the maximum number of buses that each employee can manage at night. n_{vp} is the total number of buses in PM charging stations. L_j is the set of j-type charging pile. L_S, L_F and L_A indicate that the routes served by routine slow charging piles, fast charging piles and slow charging piles added by hybrid routes. The $\Delta SOC_{ci,j}$ for a routine slow charging bus is obtained by simulating route operation, and the $\Delta SOC_{ci,j}$ for a fast-charging bus or an added slow charging bus is the amount of electricity required for a single round trip.

3) *Ordered charging control algorithm*

Since bus companies can control the operation of buses, the ordered charging is easy to implement. The ordered charging tasks of the EBs include daytime short charging and nighttime long charging. Compared to the short daytime charging, the nighttime charging requires each bus to be fully charged before it is put into operation on the next day. Therefore, nighttime charging has a long controllable time and a large charging amount. The implementation of ordered charging control should also take real-time characteristics into account. So, after every certain time interval Δt, the buses and their electrical information in the charging station are collected to update the charging model.

Firstly, the information of the buses entering the charging station, including the charge state SOC, route information and so on, is read during the interval. Then, with the objective of least costs of electricity consumption and the electrical and transportation constraints, the charging control solution to the next period T is calculated through a simulated annealing algorithm. The calculation uses the optimal solution at the previous interval as the initial value.

Aiming at minimizing total charging costs and power loss costs, the objective function of the optimal model is (16).

$$min\left\{\sum_{t=1}^{T}\sum_{m=1}^{M}c_m(t)\cdot P_{em}\left[p_i^l(t)+p_a(t)\right]\Delta t\right\} \tag{16}$$

Where $c_m(t)$ is a decision variable that indicates whether the m-th bus should be charged, 0 means no charge, 1 means on charge. P_{em} is the rated charging power of the m-th bus. $P^l_i(t)$ and $p_a(t)$ are the power loss costs and the remaining electrical costs at time t respectively. Δt is the update interval (15 min). T is the number of time periods on schedule. M is the total number of buses in the charging station.

The charging power constraints include the constraints on distribution transformer power capacity, number of charging piles, power balance, and charging continuity.

$$s.t.1\begin{cases} \sum_{m=1}^{M}c_m(t)P_{em}\le\lambda_s\left[1-r(t)\right]S_m, t=1,2,\cdots,T \\ \sum_{m=1}^{M}c_m(t)\le N_c, t=1,2,\cdots,T \\ \sum_{t=1}^{T}\left[c_m(t)\eta_p P_{em}\Delta t\right]=E(d_m), m=1,2,\cdots,M \end{cases} \tag{17}$$

Where λ_s is the capacity margin coefficient. $R(t)$ is the proportion of capacity occupied by the remaining loads. S_m is the transformer capacity. N_c is the upper limit on the number of buses to be charged at the same time. $E(d_m)$ represents the electricity consumed by bus m driving distance d_m.

The bus constraints consist of a time limit constraint and a charge amount constraint. The time constraint requires that a bus cannot be assigned a charging pile when it is not rechargeable or not at a charging station.

$$c_m(t)=0, t\in t_{c,m}, m=1,2,\cdots,M \tag{18}$$

Where $t_{c,m}$ is all non-rechargeable times for bus m.

The charging amount constraint is reflected in two aspects. (1) In order to arrange a reliable charging time and ensure the bus operation schedule, it is necessary to set an appropriate charging quantity for each bus according to its route information and actual state. (2) When bus supplementary charging during daytime operation, the buses must be able to complete at least one round trip; When charging at night, the buses must have a full charge for the next day operation. The charging quantity constraint is shown in equation (19).

$$s.t.2\begin{cases} \Delta SOC_m=\sum_{t=1}^{T}\left[c_m(t)\Delta t\cdot\eta_p P_{em}\right] \\ \Delta SOC_m=1-SOC_m(t_{in}), z=0 \\ max\left\{0, SOC_{m,set}\right\}\le\Delta SOC_m\le 1-SOC_m(t_{in}), z=1 \end{cases} \tag{19}$$

Where $SOC_{m,set}$ represents the minimum amount of SOC at the start of operation of each bus, and $SOC_m(t_{in})$ represents the amount of SOC remaining in the bus at the time of entering charging station. $Z=1$ means that the bus requires no full charge, and $z=0$ means that a full charge is required.

The flow of ordered charging control are as follows：

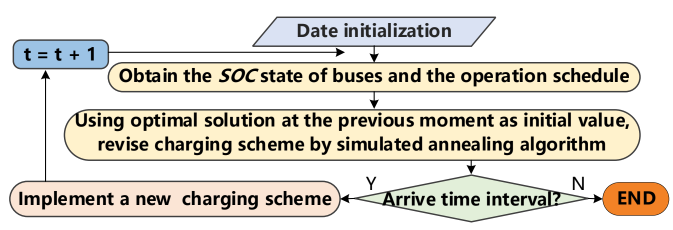

Fig.5 Flow of orderly charging control

IV. CASE STUDY

An actual transportation network in Fengxian district, Shanghai, China, is chosen to prove the above planning algorithm. There are 73 routes in the area, with a total of 536 buses. All buses in the area are parked in the nearest PM station after the daytime operation for nighttime charging.

It should be noted that in the case study, the slow charging bus (SLK) [28] and the fast charging bus (TEG) [29] provided by bus company are used to replace the existing fuel buses, and the 60 kW, 120 kW slow charging piles and 360 kW fast charging piles provided by Shanghai Power Grid Company are used in the charging pile constructions. In addition, to ensure the life of battery, the SOC state of each bus should be maintained at more than 20% during operation, and the SOC state must reach 90% after nighttime charging.

A. The simulation results of charging station planning

Fig.6 shows the types of the 73 routes divided by SLK's average daily mileage. There are 2 BRT routes, 50 FSC routes and 21 hybrid routes. The BRT routes are all equipped with TEG and constructing 360kW charging piles. The 60kW and 120kW charging piles are applied in the FSC routes.

1) The results of PM charging station planning

The planning results of PM charging station are shown in Table II. The fast charging piles at the Nanqiao PM station and the Situan station are built to meet the operational demands of two BRT lines. The rest of the fast charging piles are built as a result of hybrid route planning.

In Fig.6, the green part is the excess of the average daily mileage of route allocated bus over route demands after the PM charging station planning. All routes which their demands exceeding the average daily mileage of SLK have been. Planned by the PM charging station planning. The average daily mileage of each bus exceeds their route demands after planning. Thus, the PM charging station planning achieves the basic operation demands for all routes in the region

TABLE II PLANNING RESULTS OF PM CHARGING STATION

Name	Number of charging piles		
	60kW	120kW	360kW
Jinhai PM station	260	/	/
Fengcheng PM station	63	13	/
Shaochang PM station	40	3	/
Nanqiao PM station	131	26	10
Situan station	/	/	5
Zhuangxing station	/	1	1
Haiwan station	/	1	1
Xidukou station	/	/	1
Wusi station	/	2	2
HuQiao station	/	1	1

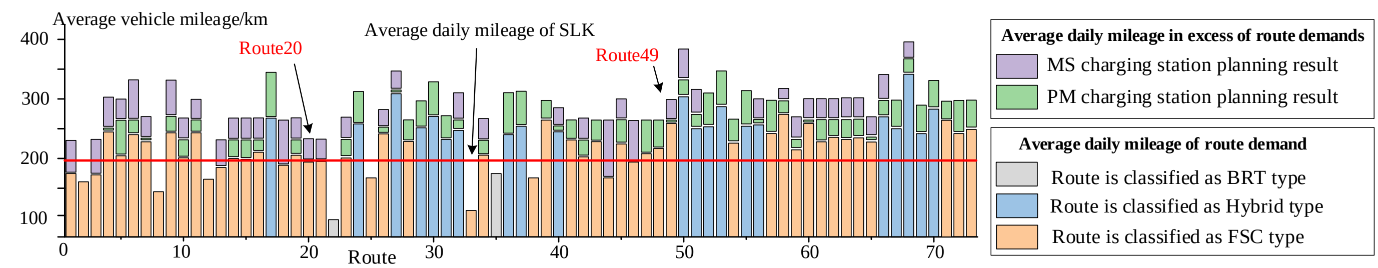

Fig.6 EB route classification and planning effects

2) The results of MS charging station planning

The MS charging station planning is based on all bus stations in the region. Optimal locations of MS charging stations are extracted from the result by grid AP algorithm.

The suitability rank in left top of Fig.7 is obtained by taking step as -2000, -100, -10, -1 respectively. The red circles are the most suitable cite. The order of orange, yellow, light yellow, grey means the suitability rank is gradually decreasing. The planning results of MS charging stations after construction possibilities validation is in Table III.

TABLE III PLANNING RESULT OF MIDWAY SUPPLY CHARGING STATION

Name	Rank of importance	The number of buses involved	The construction number of 120kW charging
Xidukou station	high	27	27
Zhuangxing station	high	20	20
Haiwan station	high	13	13
Touqiao station	high	8	8
Fengpu station	low	28	28
Huqiao station	low	6	6
Jinhui station	low	9	9
Yurenmatou station	low	8	8
Liaoyuan station	low	4	4
Situan station	low	16	16
Wusi station	low	16	16
Puxiucun station	low	5	5

In Fig.6, the purple part is the increase in the average daily mileage after the MS charging station planning. As it can be seen, route 20 and route 49 can represent two typical types route, which need enhance operation reliability. Their average daily mileage of route allocated buses after PM charging station planning is slightly higher than the route demands. The average daily mileage of route 20 demands is 193.95km, which is slightly less than the average daily mileage of SLK (196km). Thus, route 20 is not involved in the PM charging station planning. The average daily mileage of EBs on route 49 after the PM station planning is 262 km, while the route demand is 258.6 km. Considering the redundant factors such as battery aging, these two kinds of routes may not operate properly. After MS charging station planning, the average daily mileage of EBs on route 20 is 228km, and the average daily mileage of EBs on route 49 is 294km. Obviously, the MS charging station planning significantly improves the reliability of the route operation.

3) The results of the charging pile optimization algorithm

The optimization algorithm results are in Table IV. By optimizing the charging facilities layout, 60kW and 120 kW charging pile number shaded in green are reduced compared to Table II and Table III. It solves the economic waste problems caused by a large number of idle charging piles.

TABLE IV OPTIMIZATION RESULT OF PM CHARGING STATION

Name	Number of charging piles		
	60kW	120kW	360kW
Jinhai PM station	163	/	/
Fengcheng PM station	33	7	/
Shaochang PM station	24	2	/
Nanqiao PM station	59	13	10
Situan station	/	8	5
Zhuangxing station	/	11	1
Haiwan station	/	10	1
Xidukou station	/	14	1
Wusi station	/	10	2
Huqiao station	/	4	1
Touqiao station		4	/
Fengpu station	/	14	/
Jinhui station	/	5	/
Yurenmatou station	/	4	/
Liaoyuan station	/	2	/
Puxiucun station	/	3	/

The comprehensive results of charging station planning can be drawn as Fig.7. It contains the locations of PM charging stations and MS charging stations, with the detailed information of buses and charging facilities. Also, the diagram of the power grid load after ordered charging control and the harmonic analysis data of important substations are obtained.

B. Analysis of ordered charging control and harmonic status

Fig.7 shows part of the 35kV~220kV grid in the area. The load curve of the regional power grid in a typical day is taken as the conventional load. The 35kV substation is matched with the charging stations, as it shows in Appendix Table B1, to analyze the effects of ordered charging by calculating the changes of power grid load curve. Disordered charging in this case starts charging for all buses immediately after daytime operation ending, and the charging behavior is only considering to meet the operation demand. We can get the conventional load curve, ordered charge load curve and disordered charge load curve in a typical day.

Table V lists parts of the peak-valley differences of the load curve. The electric buses start to enter the charging stations about 19:00. And 21:00 to 3:00 (next day) is the period for a wide range of buses charging, which makes the load curve of this period higher than the conventional load. The peak load curve increases from 583.74MW to 596.39MW at 21:00. With the gradual completion of charging, the electric bus charging load decreases to 0 about 2:30. The power grid load reaches the lowest point at 3:30. While ordered charging transfers the charging load at evening peaks to the load valley of 1:00~6:00, which makes the load curve maintain the conventional load between 21:00 to 1:00. Ordered charging load starts increasing greatly after 1:30 in the valley period. The maximum load shifting effect is realized at 3:30, increasing from 466.83MW.

TABLE V REGULATION EFFECTS OF ORDERLY CHARGING ON POWER GRID

Type	0:00-6:00, 19:00-24:00		10:30-16:00		standard deviation
	peak(MW)	valley(MW)	peak(MW)	valley(MW)	
Conventional load	583.74	466.83	605.74	549.86	49.41
Disordered load	596.39	466.83	616.39	557.23	51.38
Ordered load	583.74	483.22	606.78	565.97	44.80

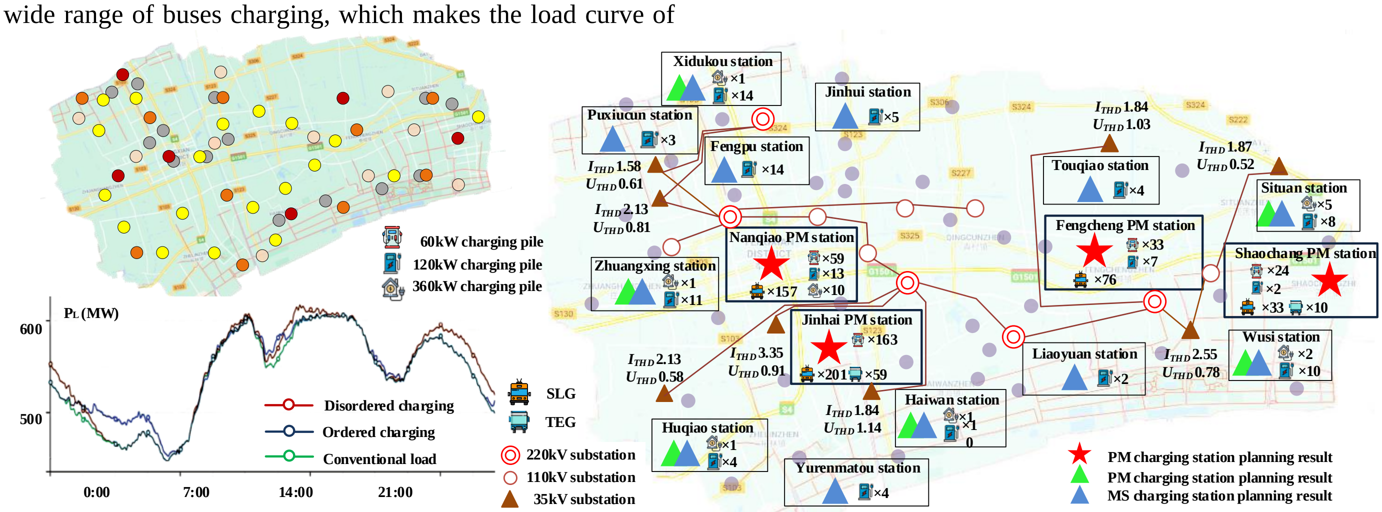

Fig. 7 Results of bus charging facilities

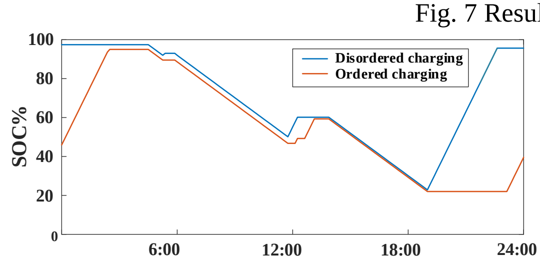

Fig.8 SOC state of EB in route 5

Fig.8 shows the SOC state of an electric bus in route 5. According to the charging schedule, the operation time of the bus is from 6:00 to 11:45, and 13:50 to 19:00 and the bus arrives at the starting station from Nanqiao PM station at 5:20. In the disordered charging process, the SOC value drops from 96.46% to 49.14% during 6:00 to 11:45. Then the bus starts charging immediately and the SOC value increases to 59.18% at 12:25. During 13:50 to 19:00, the SOC value varies from 59.18% to 21.87%. The bus stops charging at 22:45 and the SOC value is 94.66%. In the ordered charging process, the daytime charging time is transferred from 11:45-12:30 to 12:15-12:30 and 13:00-13:30, and the battery SOC status is from 45.77% to 48.28% and 48.28% to 58.32%, respectively. The night charging time are transferred from 19:00-22:45 to 23:45-4:45, which proves the valley-filling effects of the charging strategies and reduces the charging fees.

C. Scenario comparison

As a result of the unique characteristics associated with bus service and network, considering bus operation reliability, the PM charging station planning results cannot be changed which is decided by the number of regional EBs and their nighttime charging schedule. However, the second level of the proposed comprehensive planning algorithm — MS charging station planning —can be obtained by different models. Thus, we use typical p-media and set covering model, which are both solved by GA (genetic algorithm), to compare with the proposed improved AP algorithm. And the planning results are in Fig.9 and Table VI.

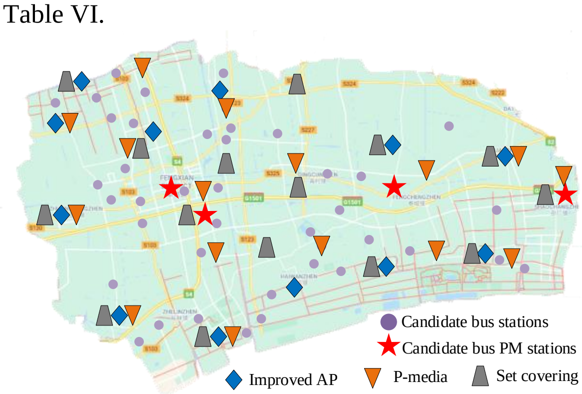

Fig.9 The positions of different planning model

TABLE VI COMPARISON OF PLANNING RESULTS

	Improved AP	P-media	Set covering
Charging station number	12	16	15
Charging pile number	160	194	188

From Fig.9 and Table VI, it can be seen that the typical models are not applicable to EB system. First, the typical methods strive to minimize the distance between charging stations and spatial distributions of activities throughout the day. However, the difference of the bus station importance is neglected. Through CRTIC weighting, the improved AP algorithm considers the constructions of PM charging station. Routes operating around the PM charging station will be serviced by PM charging station, which greatly reduces the charging pile numbers and enhances the economic effects. Furthermore, EBs are mainly operating on fixed routes with fixed schedules. The planning results of p-media and set covering exist the situation that routes are far away from their service charging station, which may make the charging activity violate bus schedule and make the charging activity costly.

D. Economic evaluation

1) Economic evaluation of bus company

The economic evaluation indicators for bus company mainly include initial purchase costs, operation expenditures, government subsidies and operating incomes. The bus fuel consumption of 100 km is 20 liters, and the cost of fuel is 0.98$/liter. The average electric bus power consumption is 0.8kWh/kM. The electricity price is 0.16$/kWh in 6:00-22:00 and 0.087$/kWh in 0:00-6:00 and 22:00-24:00. The daily mileage of all buses in the region is 103,731.06 kilometers. The results are in Table VII.

TABLE VII ECONOMIC ANALYSIS OF BUS COMPANY

Type	Detail	Annual income ($)
Initial purchase costs	Purchase cost of electric buses	-5061.97 k
Government subsidies	Purchase subsidy	148.84 k
	Operation subsidy	148.84 k
Operation expenditures	Charging fares	-1634.45 k
	Employment costs	-52.74 k
	Maintenance savings	1393.11 k
Operating incomes	Fare income difference	0 k
Savings	Fuel cost savings (fuel fares - charging fares)	4770.20 k
Total profits		1346.28k

Above all, the bus company can save 1,346,280 dollars per year after the electrification of buses in the region.

2) Economic evaluation of power grid company

The economic indicators for the construction of charging stations by power grid companies consist of initial purchase costs, operation expenditures and operating incomes. The initial purchase costs include purchase costs of charging piles, the costs of laying transmission lines and equipment installation. Operation expenditures include charging pile overhaul costs, additional overhaul costs and power generation costs; Operating incomes refer to the power sales incomes.

TABLE VIII ECONOMIC ANALYSIS OF POWER GRID COMPANY

Type	Detail	Annual income ($)
Initial purchase costs	purchase costs of charging piles	-140.16 k
	the costs of laying transmission lines and equipment installation	-22.90 k
Operation expenditures	charging pile overhaul costs	-121.16 k
	remaining additional overhaul costs	-33.50 k
	Cost of producing electricity	-1148.72 k
Operating incomes	Profits of selling electricity	3447.95 k
Total profits		1981.51 k

The cost of laying cable is $532.82/km, and the planned length of transmission lines is 100 km. The number of constructions is shown in Table IV. The average electricity purchase cost by power grid company in the electricity market is 0.029$/kWh and the average daily electricity consumption is 71645.31 kWh. Thus, Table VIII can be obtained.

The power grid company can earn 1,981,510 dollars per year after the electrification of buses in the region.

V. CONCLUSION

This paper proposes an urban electric bus charging station planning algorithm which consists of PM charging station algorithm and midway supply charging station algorithm. The conclusions reached are as follows.

(1) The comprehensive urban electric bus charging station planning algorithm can meet the operation of bus routes and realize the replacement of fuel buses with electric buses in the region. The MS charging station based on the improved grid AP algorithm reduces the load pressure on the power grid and improves the reliability of electric bus operation. The take-turn model changes “one-bus-one-pile” to “one-bus-one-terminal”, which reduces the charging piles, and lays the foundation for the implementation of ordered charging. The ordered charging control is with a friendly interaction between the bus company and the power grid.

(2) The economic effect of the proposed scheme is remarkable. Simulation results show that the bus company spending expenditures can decrease by 18.11% per year and the power company profits can increase 0.22% per year when the bus-electrification is completed by the proposed algorithm.

(3) This scheme has been successfully implemented in an actual system. Because of good versatilities, it can provide a reference for the electrification of other cities’ buses and help realize the upgrading of the Chinese public bus system.

APPENDIX

A. The economics Analysis

1) Calculation method of bus company

The initial purchase cost C_b refers to the purchase cost of new electric buses, as shown in equation (1), where $c_{v,f}$, $c_{v,s}$ represent the unit price of fast charging buses and slow charging buses respectively. $n_{v,f}$, $n_{v,s}$ are the number of fast charging buses and slow charging buses. R_0 is the discount rate. Z is the number of planned years.

$$C_b = \left(c_{v,f} n_{v,f} + c_{v,s} n_{v,s}\right) \cdot r_0 \left(1+r_0\right)^z \Big/ \left(\left(1+r_0\right)^z - 1\right) \tag{1}$$

Under the condition of replacing fuel vehicles with electric buses, the operation expenditures C_o includes charge savings employment costs for new employees and maintenance savings, as shown in equation (2). Where M is the total number of electric buses. c_p, c_{op}, c_{oil_m} represent the peak price, off-peak price, and average fuel price. n_{p_m}, n_{p_m}, n_{oil_m} are the charging amount in peak time, off-peak time and the average amount of fuel consumed one day of the bus m. c_{s_m} is the average working salary. n_s is the number of new employees. Δc_{fix} is the maintenance difference.

$$C_o = 365 \sum_{m=1}^{M} \left(n_{p\_m} c_p + c_{op} n_{op\_m} - n_{oil\_m} c_{oil\_m}\right) + 12 c_{s\_m} n_s + \Delta c_{fix} \tag{2}$$

The government subsidies C_s include the purchase subsidy for new energy buses and the operation subsidy difference, as shown in equation (3). Where $c_{buy,f}$, $c_{buy,s}$, $c_{run,f}$ and $c_{run,s}$ represent the purchase subsidy and operating subsidy for fast charging bus and slow charging bus respectively.

$$C_s = \left(c_{buy,f} n_{v,f} + c_{buy,s} n_{v,s}\right) \cdot r_0 \left(1+r_0\right)^z \Big/ \left(\left(1+r_0\right)^z - 1\right) + c_{run,f} n_{v,f} + c_{run,s} n_{v,s} \quad (3)$$

The operating incomes C_t is the fare income difference of the new energy buses compared to the fuel buses, as in equation (4). Where c_{t_m} is the fare for a single bus ride. n_{t_m} is the average number of passengers a bus carried per day.

$$C_t = 365 \sum_{m=1}^{M} c_{t\_m} n_{t\_m} \quad (4)$$

2) Calculation method of power grid company

The initial purchase costs C'_b is shown in (5). Where l_{all} is the total length of newly laid cable. c_{ls}, $c'_{c,p}$, c_{tri} and $c_{c,p}$ represent the cost of laying a cable per unit length, the construction cost of charging piles with rated power p and the construction cost of transformer t_{ri} and the unit price of charging pile with charging power p respectively. $ns_{c,p}$ is the charging pile number.

$$C'_b = \left(l_{all} c_{ls} + \sum_{p=p_1 \cdots, p_{\max}} c'_{c,p} n_{c,p} + \sum_{tr_i} c_{tr_i} + \sum_{p=p_1, \cdots, p_{\max}} c_{c,p} n_{c,p}\right) \cdot \frac{r_0 \left(1+r_0\right)^z}{\left(1+r_0\right)^z - 1} \quad (5)$$

The operation expenditures c'_o can be expressed as equation (6). Where $c_{o,c}$, c_{s_m}, and c_{g_m} represent the cost of overhauling a charging pile, the average salary of additional overhaulers, and the average power purchase cost by power grid company in the electricity market, respectively. n'_s is the number of additional overhaulers.

$$C'_o = \sum_{p=p_1 \cdots, p_{\max}} c_{o,c} n_{c,p} + 12 c_{s\_m} n'_s + 365 c_{g\_m} \sum_{m=1}^{M} \left(n_{p\_m} + n_{op\_m}\right) \quad (6)$$

The operating incomes c'_t is shown in equation (7). Where c_{d_m} is the average power purchase cost by power grid company in the electricity market.

$$C'_t = 365 c_{d\_m} \sum_{m=1}^{M} \left(n_{p\_m} + n_{op\_m}\right) \quad (7)$$

B. The selection results of charging station to substation

TABLE B1
SELECTION RESULT OF CHARGING STATION

Charging station	Substation	Does it need to be expanded	Capicity （MW）
Jinhai PM station	Yangwang substation	N	14.10
Fengcheng PM station	Chengzhong substation	N	4.44
Shaochang PM station	Xueshi substation	N	1.98
Nanqiao PM station	Yangwang substation, Yuxiu substation	N	11.76
Situan station	Pengcheng substation	N	2.76
Zhuangxing station	Zhuangxing substation	N	1.56
Haiwan station	Baishi substation	N	0.84
Xidukou station	Fulan substation	N	2.04
Wusi station	Nongchang substation	N	1.68
Huqiao station	Chihua substation	N	0.72
Touqiao station	Lukou substation	N	0.48
Fengpu station	Chenqiao substation	N	1.68
Jinhui station	Qixian substation	N	0.60
Yurenmatou station	Xinhai substation	N	0.48
Liaoyuan station	Liaoyuan substation	N	0.24
Puxiucun station	Wuqiao substation	N	0.36

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