The Planning of Electric Vehicle Charging Stations in the Urban Area

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Abstract. With respect to the planning problems of electric vehicle charging stations in the urban area, the paper presents a planning model which considers the road network structure, vehicle flow information, distribution system structure and capacity constraints, etc. Under the relative constraints of distribution network, the model selects the station sites and plug-in locations with the objective of minimizing the sum of users' wastage cost on the way to the charging station and the investments of station lines, realizes the auto-partition of station service areas by the weighted Voronoi diagram, and also optimally allocates the station capacities based on the queuing theory. Finally, considering both the benefits of the power company and the electric vehicle users, the planning program optimization is finished by minimizing the costs of the whole society. The case studied shows that the presented methods and models are to some extent practical and reasonable to the optimal planning of electric vehicle charging stations in the urban area.

Introduction

With the increasing of environment pressures and resource shortages, energy saving is becoming more of a concern. Electric vehicles have become a focus of governments and enterprises, because they have the characteristics of energy saving and environmental protection. For the wide spread of electric vehicles, charging stations are the premise and foundation[1,2].

At present, many scholars have begun to study the charging behavior of electric vehicles and the planning and construction of charging stations. In [3], the impact of electric vehicles' charging on the power grid was analyzed in detail. In [4], the factors related to the demand on charging power of electric vehicles were analyzed. A statistical model of charging demand was built considering the probability distribution of some random factors. In [5], an optimized model for TOU power price time-period was proposed considering how to use ordered charging of electric vehicles to cut the peak and fill the valley of electricity power grid. In [6], Chinese current development of electric vehicle charging stations was described and the influencing factors and principles of charging station planning were proposed. In [7], the optimization cost model of locating and sizing of charging stations for electric vehicles was built. It simulated the number of electric vehicles based on the distribution of residents and conducted the sites planning at the target of maximizing charging stations' profits. In[8], the optimization model of charging mode choices was proposed, and the demand of each charging method could be forecasted based on this model. In [9], a two-step model was proposed: first converged the road information into 'demand clusters' by hierarchical clustering analysis and then applied optimization techniques to conduct the site planning, while certain constraints and cost were considered. In [10], a dynamic traffic network method was used to build a multi-objective optimization model with a hard time window constrains to obtain the optimal distribution and scale of charging stations. In [11], a model was proposed for the evaluation of charging station layout programs based on the game theory. Although these documents have built the mathematical model of electric vehicle charging station planning and defined a series of basic concepts, the combined effects of some important factors, such as the road network, the traffic flow, the structure and capacity constraints of distribution network, were less to be considered. Therefore, focusing on the impacts of these factors, an optimization model for urban charging stations planning was proposed in this paper.

The Mathematical Model

Planning Optimization Model

It is necessary to consider the cost of construction and operation, but also consider the social benefits after the completion for the planning and construction of charging stations. Taking the interests of the power company and users into account, the social cost is used to select the optimal planning program. So the objective function can be expressed as the following formula:

$$\min C = \sum_{i=1}^{N} (C_{1i} + C_{2i} + C_{3i} + C_{4i} + C_{5i}) \tag{1}$$

In the equation, N is the number of charging stations. For the charging station i, C_{1i} is the construction investments; C_{2i} is the operation and maintenance cost; C_{3i} is the loss cost; C_{4i} is the charging cost of users in the service area; C_{5i} is the loss cost of users on the way to the charging station.

The construction investments of charging station i:

$$C_{1i} = (e_i a + m_i b + c_l l_i + \omega_i) \frac{r_0 (1+r_0)^z}{(1+r_0)^z - 1} \tag{2}$$

In the equation, e_i is the number of transformers. a is the price of the transformer. m_i is the number of chargers. b is the price of a charger. l_i is the line length of the charging station i access to distribution network. c_l is the line price per kilometer. ω_i the cost of infrastructure. r_0 is the discount rate. z is the operating period.

The operation and maintenance cost can be calculated in accordance with the percentage of the initial investment. Suppose η is the percentage factor, the operation and maintenance cost of charging station i:

$$C_{2i} = (e_i a + m_i b + c l_i + \omega_i) \cdot \eta \tag{3}$$

The loss cost of charging station i:

$$C_{3i} = e_i (C_{Fe} + C_{Cu}) \cdot T_v \cdot 365 \cdot p + m_i (C_L + C_D) \cdot k_t \cdot T_v \cdot 365 \cdot p \tag{4}$$

In the equation, C_{Fe} is the iron loss and C_{Cu} is the copper loss of transformers. C_L is the line loss in the charging station i. C_D is the loss of a charger. k_t is the ratio of chargers for working at the same time. T_v is the effective charging time of the station. p is the charging price

The charging cost of users in the service area:

$$C_{4i} = \sum_{j=1}^{N_{um}} p \cdot q_j \cdot P_v \cdot 365 \tag{5}$$

In the equation, N_{um} is the number of charging demand nodes. q_j is the number of electric vehicles at the charging demand node j. P_v is the average capacity of electric vehicles.

There are two parts in the loss cost of users on the way to the charging station. One is the cost of power loss h_1 and another is the time cost h_2:

$$C_{5i} = h_1 + h_2 = \frac{\sum L_i}{g} \cdot p \cdot 365 + \frac{\sum L_i}{v} \cdot k \cdot 365 = \sum_{j=1}^{N_{um}} d_{ij} \cdot q_j \cdot \left(\frac{p}{g} + \frac{k}{v}\right) \cdot 365 \tag{6}$$

In the equation, g is the mileage per kilowatt-hour. k is the time cost of users in an hour [12] and v is the average speed of electric vehicles. d_{ij} is the distance between demand node j and charging station i. $\sum L_i$ is the sum of the weighted distance from the charging station i to the demand nodes in the service area.

Sizing and Locating Model

The location selection of the charging station is to consider two factors: the users' convenience and the line cost of the charging station access to the distribution network. The locating objective function can be expressed as the following formula:

$$\min C_{stationi} = c_l \cdot l_i \cdot \frac{r_0(1+r_0)^z}{(1+r_0)^z - 1} + C_{5i} \tag{7}$$

The charging service of the charging station is random. Therefore, the optimization of chargers can be solved by using the queuing theory[13].

Distribution Network Constraints

Distribution network constraints include equality constraints and inequality constraints. Equality constraints refer to the flow equations. Inequality constraints are to consider some factors, such as the capacity limit and the safe operation of the distribution network.

a. Substation capacity constraints

$$S_i \le S_{i\max} \tag{8}$$

In the Inequality, S_i is the load of the substation. S_{imax} is the maximum load that the substation can carry.

b. Charging power constraints

$$\sum_{i=1}^{N} P_{Ci} \le P_C^{\max} \tag{9}$$

In the Inequality, P_{Ci} is the charging power of the station *i*. $P_C^{\max}$ is the maximum charging power that the distribution network can accept.

c. Node voltage amplitude constraints

$$V_i^{\min} \le V_i \le V_i^{\max}, i = 1, 2, ..., M \tag{10}$$

In the Inequality, V_i is the voltage amplitude of the node *i*. $V_i^{\max}$ and $V_i^{\min}$ are the maximum and minimum voltage amplitude of the node *i*. *M* is the number of nodes in the distribution network.

d. Feeder maximum current constraints

$$\left| I_{ij} \right| \le I_{ij\max}, \quad i, j = 1, 2, ..., M \tag{11}$$

In the Inequality, I_{ij} is the current and I_{ijmax} is the maximum current of the feeder *ij*.

e. Access point capacity constraints

$$P_{Cij} \le P_{j\max} \tag{12}$$

In the Inequality, P_{cij} is the charging power of the charging station *i* which connects to the grid node *j*. P_{jmax} is the maximum charging power that the node *j* can accept.

The Overall Planning Process

The general idea of this paper is as follows:

First, the minimum and maximum number (N_{min} and N_{max}) of charging stations can be estimated in accordance with the maximum and minimum capacity (S_{max} and S_{min}) of the charging station [14]. So $N_{\min} \le N \le N_{\max}$.

Second, we can find an optimal planning program for each *N*. During the process, distribution network constraints should be considered. The initial locations are determined by using coordinate method [15]. The weighted Voronoi diagram is used to partition the service area [16]. The sites and access locations were chosen at the aim of minimizing the sum of the users' wastage cost on the way to the charging station and the investments of station lines. The allocations of charging stations were optimized by using the queuing theory.

Finally, taking the interests of the power company and users into account, we select the optimal planning program from the N_{max}-$N_{min}+1$ programs to minimize the social cost.

Case Study

In order to illustrate the methods and models, a study case is constructed. There are 48 intersection points, 110 road sections in the planning area which is 63km^2. The regional road network is shown in Fig. 1. The node coordinates and typical traffic data are shown in Table 1. There are 3 substations

(35/10kV, 2×16MVA) and 32 load nodes in the planning area. The network structure is shown in Fig. 2. The coordinates and load of the distribution nodes are shown in Table 2.

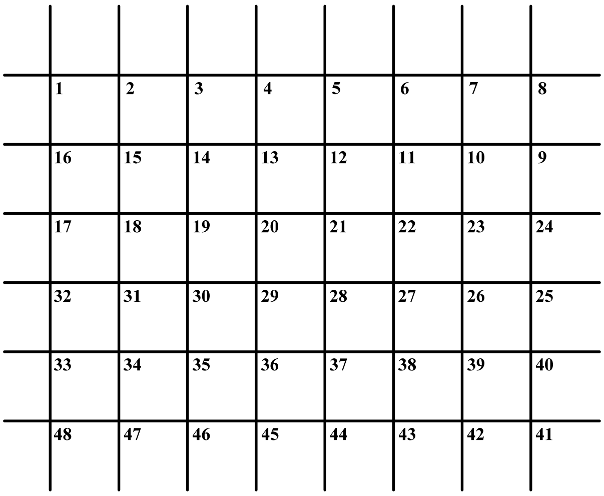

Fig. 1 The road network of the planning area

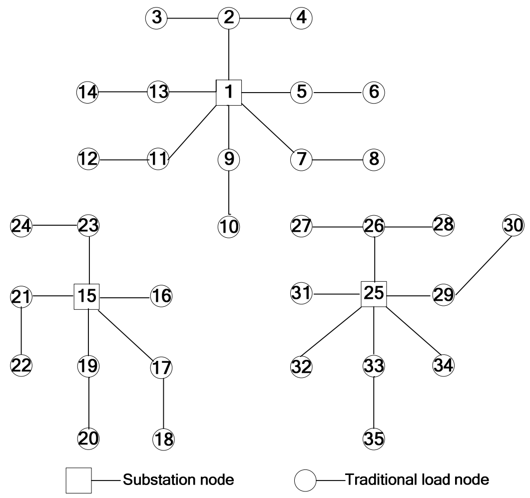

Fig. 2 The distribution network of the planning area

Table. 1 The coordinates and traffic flow of each intersection node

No.	X	Y	Traffic Flow	No.	X	Y	Traffic Flow	No.	X	Y	Traffic Flow
1	1	6	8990	17	1	4	4068	33	1	2	6110
2	2	6	5626	18	2	4	1918	34	2	2	4370
3	3	6	7190	19	3	4	2484	35	3	2	2654
4	4	6	6986	20	4	4	6080	36	4	2	5132
5	5	6	10940	21	5	4	5320	37	5	2	7052
6	6	6	8608	22	6	4	4198	38	6	2	8420
7	7	6	5368	23	7	4	2628	39	7	2	6802
8	8	6	8200	24	8	4	3424	40	8	2	8658
9	8	5	8658	25	8	3	4024	41	8	1	8400
10	7	5	4808	26	7	3	2870	42	7	1	5476
11	6	5	8420	27	6	3	4312	43	6	1	9022
12	5	5	6816	28	5	3	6422	44	5	1	6432
13	4	5	4530	29	4	3	5086	45	4	1	2986
14	3	5	2654	30	3	3	2484	46	3	1	7192
15	2	5	4170	31	2	3	2118	47	2	1	5686
16	1	5	6110	32	1	3	4264	48	1	1	10030

Table.2 The coordinates and load of each distribution network node

No.	X	Y	Load [MW]	No	X	Y	Load [MW]	No.	X	Y	Load [MW]
1	4.5	5.5	0	13	3.5	5.5	0.70	25	6.5	2.5	0
2	4.5	6.5	0.90	14	2.5	5.5	1.25	26	6.5	3.5	0.85
3	3.5	6.5	1.15	15	2.5	2.5	0	27	5.5	3.5	0.95
4	5.5	6.5	1.05	16	3.5	2.5	2.40	28	7.5	3.5	0.75
5	5.5	6.5	1.10	17	3.5	1.5	1.15	29	7.5	2.5	1.35
6	6.5	4.5	1.20	18	3.5	0.5	1.35	30	8.5	3.5	0.65
7	5.5	4.5	0.75	19	2.5	1.5	1.60	31	5.5	2.5	2.10
8	6.5	4.5	1.35	20	2.5	0.5	2.20	32	5.5	1.5	2.20
9	4.5	4.5	0.85	21	1.5	2.5	1.50	33	6.5	1.5	1.05
10	4.5	3.5	1.15	22	1.5	1.5	0.60	34	7.5	1.5	0.85
11	3.5	4.5	0.65	23	2.5	3.5	1.50	35	6.5	0.5	0.55
12	2.5	4.5	1.40	24	1.5	3.5	0.40				

At the time of target year, the percentage of the electric vehicle is 15%. The capacity of each electric vehicle is 50 kWh. The power of every single charger is 96 kW; there are at least 6, at most 30 chargers in the station; the charger's efficiency is 0.9, the coincidence factor is 0.9; the electric vehicle can run 7 km in each kilowatt-hour; the electricity price is 0.8 Yuan/kWh; the average speed of electric vehicles is 20 km/h; and the time cost of users is 17 Yuan/h.

The process of calculation is shown as below:

a. To estimate the number of charging stations: $N_{min}=5$, $N_{max}=20$.

b. To calculate the costs of the N_{max}-$N_{min}+1$ programs, the results are shown in Table 3.

c. It can be seen from Table 3, when the number of charging stations is 7, that the social cost of the planning program is the smallest (72.91 million Yuan).

d. To determine the optimal sites, capacities, service areas and acess locations of the 7 charging stations. So the sites and capacities are shown in Table 4. The layout and service areas are shown in Fig. 3 and the access locations are shown in Fig. 4.

Table. 3 The social cost of each planning program [Unit: Ten thousand Yuan]

N	C_1	C_2	C_3	C_4	C_5	C
5	160.30	151.11	800.31	6004.91	206.39	7323.03
6	171.86	162.01	801.20	6004.91	151.87	7291.85
7	169.95	160.21	816.83	6004.91	138.67	7290.58
8	192.17	181.16	825.75	6004.91	129.11	7333.10
9	201.52	189.97	834.23	6004.91	118.84	7349.47
10	204.06	192.36	835.12	6004.91	113.96	7350.41
11	222.13	209.40	835.56	6004.91	106.62	7378.63
12	229.60	216.44	850.30	6004.91	100.24	7401.51
13	244.17	230.18	851.19	6004.91	95.17	7425.62
14	240.62	226.83	859.23	6004.91	94.46	7426.04
15	256.95	242.23	866.82	6004.91	88.83	7459.75
16	261.14	246.18	874.41	6004.91	83.69	7470.34
17	276.64	260.79	882.89	6004.91	76.98	7502.22
18	291.69	274.97	876.63	6004.91	75.54	7523.74
19	298.67	281.55	883.78	6004.91	73.65	7542.57
20	303.14	285.77	898.52	6004.91	76.93	7569.26

Table. 4 The locations and capacities of the charging stations

No.	X-coordinate of the Station	Y-coordinate of the Station	The Number of chargers	The Road Nodes in the Service
S_1'	1.79	5.37	18	1,2,3,14,15,16,17,18,19
S_2'	4.16	1.53	14	35,36,37,44,45,46
S_3'	7.10	5.05	19	7,8,9,10,11,22,23,24
S_4'	1.30	1.63	14	31,32,33,34,47,48
S_5'	7.00	1.92	24	25,26,27,38,39,40,41,42,43
S_6'	5.00	6.00	15	4,5,6,12
S_7'	4.29	3.72	13	13,20,21,28,29,30

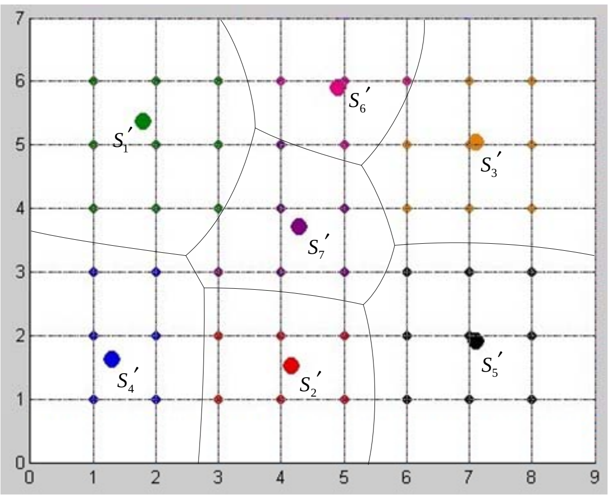

Fig. 3 The layout and the service areas of the charging stations

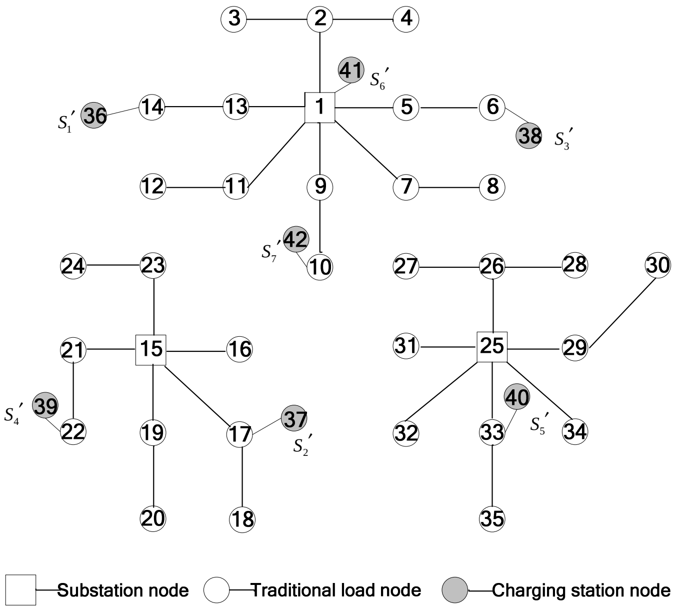

Fig. 4 The access locations of the charging stations

Summary

From the case study we can see that the road network and the traffic flow can directly affect the sites and service areas of the charging stations. And then the capacities will be indirectly affected by these factors. However, the distribution network structure and capacity constraints will have certain restrictions on the access locations, the number and capacities of the charging stations. Furthermore, they will have the influence on the sites and service areas and ultimately affect the social cost of the planning program. The impacts of these factors are interrelated. So the models and methods presented in this paper are mainly to coordinate the influence of these factors in order to find the optimal planning program. And the results of the example showed that the methods and models were feasible and reasonable for charging stations planning in the urban area.

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