Planning method for charging piles of intelligent networked electric vehicles in consideration of charging safety

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Abstract. As the number of electric vehicles in cities increases, the charging demand has surged. Optimizing deployment planning of electric vehicle charging piles is of great significance to safe charging. Based on the analysis of the factors affecting the planning of electric vehicle charging piles and the spatial distribution characteristics of electric vehicles, this paper proposes a new planning method for urban intelligent networked electric vehicle charging piles that takes into account the charging safety. Using the point clustering algorithm, the optimal division of the urban electric vehicle service range is calculated, and then the central point selection algorithm is employed to allocate the optimal site. Taking the actual electric vehicle charging pile planning in one of the central cities as the experimental example, and comparing with two of existing charging pile planning methods, the calculation results show that the method proposed in this paper has better planning effects and obtains more reasonable service regional division, balanced services amount, and shorter charging path distance, thus ensuring the safety of charging pile operation and service capabilities.

1. Introduction
The intelligent internet connected vehicle system connects the city's intelligent transportation, the urban power distribution system and the travel and life of urban residents, and is one of the key elements of a smart city. As the basic setting of the intelligent internet connection system, the electric vehicle charging pile is the core component of connecting new energy vehicles, transportation and the power grid. However, the current imperfection of charging infrastructure is in sharp contrast with the rapid development of urban electric vehicle ownership, and has become an important factor restricting the development of intelligent networked electric vehicles[1-2]. Therefore, optimizing and reasonable electric vehicle charging pile deployment planning is of great significance for safe charging and coordinated development of city.

The planning of charging piles for urban intelligent internet connected electric vehicles that takes into account charging safety is a multi-objective, multi-variable, non-linear optimization problem[3]. The existing methods mostly use intelligent algorithms to plan and solve the optimal solution. In the optimization process, parameter selection depends on experience and the algorithm complexity is high. Different from the existing algorithms, this paper proposes a new planning method for charging piles...
for urban intelligent networked electric vehicles that takes into account charging safety. First, a graph theory abstract model of charging demand points and road network structure is established, and then based on the point clustering algorithm to achieve the optimal division of the urban electric vehicle service range, and finally based on the central point selection algorithm for optimal site selection and deployment.

Other chapters of the thesis are arranged as follows: Chapter 2 gives an analysis of the domestic and foreign current situation of the electric vehicle charging pile/charging station planning problem, and the third chapter carries out the mathematical modeling of the problem. The urban intelligent networked electric vehicle charging service area division and charging and optimal deployment algorithm for facilities are described in detail in Chapter 4. The fifth chapter verifies the effectiveness of the algorithm proposed in this paper through an example of an intelligent networked electric vehicle charging plan in a large city center. Chapter 6 gives a summary.

2. Related work
In recent years, scholars at home and abroad have conducted research from different angles on the planning of electric vehicle charging piles/charging stations. References [5-6] all made the minimum sum of charging station development and construction costs and user charging costs as the objective function to establish a mixed integer nonlinear optimization model for the location and capacity of fast charging stations. Reference [7] considered the captured maximum traffic flow, minimum power distribution system network loss and minimum node voltage deviation as the goals to establish a multi-objective decision-making model for the optimal planning of charging stations, and used DEA (Data Envelopment Analysis) evaluation method to determine the weight of each target. The multi-objective optimization problem is transformed into a single-objective problem solution, but the DEA method has the disadvantage of being sensitive to outliers, which may lead to unstable output results. Reference [8-9] considered the characteristics of residents' travel activities, determined the EV charging demand, and selected the charging station location with the goal of minimizing the cost of EV group empty driving. Correspondingly. However, the initial location of the charging pile/station in the above method has a greater impact on the final calculation result and calculation speed. And the final result is only the minimum average distance from each charging demand point to the center of the charging pile/station in a mathematical sense, which is quite different from the actual road conditions, and it is difficult to meet the planning requirements based on actual scenarios.

3. Mathematical modeling of the location of charging piles
Charging piles for urban intelligent networked electric vehicles mainly provide electric vehicles for surrounding residents, and can provide electric energy for public transportation-taxis. According to actual research needs and planning experience, charging demand points generally include hospitals, schools, large supermarkets, and stations. Considering the road network structure between charging demand points, based on graph theory, an undirected connected graph model $G=(V, E)$ for the location of charging piles for urban intelligent networked electric vehicles is established. Where $V$ is the set of charging demand points $v_i$, $E$ is the set of roads connecting the charging demand points, which is different from the traditional graph structure. Here we need to consider the road non-linear coefficient $\beta$, $\beta>1$. In addition, we define the centralized charging demand $p_i$ corresponding to $v_i$ as the weight of the vertex; the length $\beta \cdot d(v_i, v_j)$ of the shortest road between demand points $v_i$ and $v_j$ is recorded as the weight of the edge. Since the primary goal of centralized charging stations is to provide convenient charging services to EV users, the site selection problem of charging stations can be mathematically abstracted as the problem of finding the central point of the graph, that is, when formula (2) gets the minimum value central point set.

$$\text{Obj: Min } \sum_{i=1}^{N} w_i , \text{ where } w_i = \sum_{j=1}^{n} p_i [\beta \cdot d(g_i, v_j)] \quad (1)$$
In the formula, \( N \) is the number of divided areas, and \( n \) is the number of charging demand points in a single planned area.

4. Urban electric vehicle charging service area division and optimal deployment of charging facilities

4.1. Calculation of the number of charging facilities in consideration of charging safety

First, the upper limit \( N_{\text{ch, max}} \) and the lower limit \( N_{\text{ch, min}} \) of the number of charging stations to be built in the planned area are determined according to the capacity of a single charging device and the upper and lower limits of the allowable number of charging devices. It can be calculated by the following formula (2):

\[
\begin{align*}
N_{\text{ch, min}} &= \left\lceil \frac{Q_{\text{total}}}{n_{\text{max}} S_{\text{ch}}} \rightceil \\
N_{\text{ch, max}} &= \left\lfloor \frac{Q_{\text{total}}}{n_{\text{min}} S_{\text{ch}}} \right\rfloor
\end{align*}
\]

Where \( \lceil \cdot \rceil \) is rounded up; \( Q_{\text{total}} \) is the centralized charging demand for electric vehicles in the planned area, \( n_{\text{max}}, n_{\text{min}} \) are the maximum and minimum allowable charging devices in the charging station; \( S_{\text{ch}} \) is the capacity of a single charging device.

4.2. Electric Vehicle Charging Piles Location and Service Range Division Algorithm

Furthermore, the \( (N_{\text{ch, max}} - N_{\text{ch, min}} + 1) \) planning schemes calculated in the previous section are checked for constraints such as line flow, voltage offset, and current overruns to screen out feasible schemes to ensure charging safety. That is, determine the number of charging facilities that can be deployed in the area; for feasible solutions that meet the charging safety constraints, the service range of charging stations is divided based on the K-means clustering method. Furthermore, the central point is calculated in the sub-graph composed of charging demand points within each service range as the location to be constructed of the charging station, the power supply access point of the charging station is determined, and the most optimal location planning is completed. The specific algorithm flow is as follows:

Step1. Use GIS to obtain the coordinates of charging demand points in the planned area, and establish an undirected connected graph model \( G=(V, E) \) for the charging planning of urban intelligent networked electric vehicles. And according to formula (2), calculate the range of the required number of charging points in the area to be planned \([N_{\text{ch, min}}, N_{\text{ch, max}}]\).

Step2. Based on the K-means clustering algorithm, cluster the charging demand points in the planning area and the number of clusters \( m \in [N_{\text{ch, min}}, N_{\text{ch, max}}] \). In each cluster divided sub-areas, the graph central point algorithm is used to calculate the central point \( \theta_m^{k} \) of the sub-areas.

Step3. Assuming that the kth clustering is currently performed, calculate the driving distance \( D_{inm}^{k} \) from each charging demand point \( v_i \) to the initial cluster center \( \theta_m^{k} \) in the whole network according to formula (3), and perform a new K-means for each demand point according to the nearest neighbor principle cluster division to form the k+1th cluster.

\[
D_{in}^{k} = \beta \times d(v_i, \theta_m^{k})
\]

\[
d(v_i, \theta_m^{k}) = \sqrt{(x_{vi} - x_{\theta_m^{k}})^2 + (y_{vi} - y_{\theta_m^{k}})^2}
\]

\( d(v_i, \theta_m^{k}) \) is the Euclidean distance from the charging demand point to the initial cluster center; \( (x_{vi}, y_{vi}) \), \( (x_{\theta_m^{k}}, y_{\theta_m^{k}}) \) are the coordinates of the charging demand point and the initial cluster center, respectively.

Step4. In the new cluster division planning area \( m \), the graph central point algorithm is again used to calculate the central point \( \theta_m^{k+1} \) of the sub-region. Calculate the travel distance \( D_{inm}^{k+1} \) from each
charging demand point \( v_i \) to the initial cluster center \( \theta_{mk}^{k+1} \), and verify whether the total distance difference between the two travels meets the convergence condition according to formula.

\[
||J^{k+1} - J^k|| < \varepsilon
\]

(5)

Where \( J = \sum_{i=1}^{N_c} \sum_{j=1}^{N} D_{ij} \). If not, return to Step 3 and continue clustering to find better charging area division and charging site selection; if the convergence condition is met, each cluster set is the divided charging service area, and its central point coordinates \((x_{mk}, y_{mk})\) are the coordinates of the charging station.

5. Planning calculation and performance evaluation

5.1. Actual urban planning example

This article takes the intelligent networked electric vehicle charging plan of a large city center as an example. The planned area has a total area of 9.98 km\(^2\), including large supermarkets, hospitals, schools, tourist attractions, government and enterprise surrounding areas, and large residential areas, etc. Plan charging demand points 265 locations and the geographic location of each charging demand point and a 110kV transformer substation which power for demand point is obtained by GIS, as shown in Figure 1.

According to the current situation of the power distribution system in the area, 10kV lines can be provided for charging piles, the model is JKLYJ-150. The area population density \( \gamma_3 \), car occupancy rate \( \gamma_4 \), road non-linear coefficient \( \beta \), and charging station investment and operating costs are given in Table 1. Electric vehicle charging demand \( Q(v_i) \) at each charging demand point can be calculated by following

\[
\begin{align*}
Q(v_i) &= \gamma_1 \gamma_2 \gamma_3 \gamma_4 P_{charge} S(v_i) \\
Q_{total} &= \sum_{i=1}^{265} Q(v_i)
\end{align*}
\]

(6)

In the formula, \( S(v_i) \) is the area of the charging demand point \( v_i \).

| Parameters                      | Value | Parameters                      | Value |
|---------------------------------|-------|---------------------------------|-------|
| Charge frequency \( \gamma_2 \) (per day) | 0.5   | driving distance per unit \( c_{EV} \) (km) | 6.5   |
| population density \( \gamma_3 \) (km\(^2\)) | 27347 | of travel time \( k_{travel} \) (h) | 20    |
| car share \( \gamma_4 \) (Vehicle/person) | 0.15  | Charge cost (kW·h) | 1.5    |
Electric Vehicle Permeability $\gamma_5$ 0.1  unit price for charging equipment $p_{eq}$ (10,000 yuan/stations) 20
Charge power $P_{ch}$ (kW) 120  Operating life (years) 10
Simultaneous Coefficient of Charging Equipment 0.5  unit price for land acquisition $p_{land}$ (m²) 860
$\beta$ of road non-linear coefficients 1.3  Allowable transmission capacity (kVA) 6776

5.2. Calculation of the number of charging piles
According to the data in Table 1 and formula (5), the demand for intelligent networked electric vehicle charging piles in the planned area can be obtained $Q_{total} = 22.58$ MW, and then the lower limit of the number of charging stations is $N_{ch_{min}} = 6$ and the upper limit is calculated by formula (2) $N_{ch_{max}} = 24$. Check constraint conditions such as line power flow and voltage offset for the candidate options in $[N_{ch_{min}}, N_{ch_{max}}]$, and obtain that when the number of charging stations is selected as 8, 9, 11, and 15, the capacity constraints of charging stations are met, and consideration in terms of the construction and operation cost of charging stations and the unusual land occupation in the central city, choosing fewer 8 charging stations is more conducive to cost savings under the condition of ensuring the charge needs of users.

5.3. Performance evaluation of charging pile addressing and service area division algorithm
In order to evaluate the superiority of the new urban intelligent networked electric vehicle charging pile planning method proposed in this paper, the K-means clustering planning algorithm and the Voronoi diagram calculation geometry method [10] are selected as the comparison algorithm. The division of service scope and addressing calculation are also carried out for the 8-site plan. Count the number of demand charging points divided in each service sub-area, as shown in Figure 2, and the distance and the distance between the demand point and the respective charging station, as shown in Figure 3. As can be seen from the figure, the new urban intelligent networked electric vehicle charging pile planning method proposed in this article divides the service sub-regions more evenly. In comparison, the charging distance of 62.5% of the service area becomes longer after the pure K-means algorithm planning. However, the use of Voronoi diagram to calculate the geometric method has the worst planning effect. Therefore, the planning method of urban intelligent networked electric vehicle charging piles that takes into account the charging safety proposed in this paper has better economic efficiency. Table 2 shows the estimated economic cost of different planning algorithms.

| Table 2. Various costs of feasible scheme /10,000RMB. |
|-------------------------------------------------------|
| Construction costs | User charging cost | Customer Loss Cost | Total cost to society |
|---------------------|---------------------|---------------------|-----------------------|
| 8 stations          | 2970.51             | 1868.751            | 1343.6                | 6182.861 |
| 9 stations          | 3158.22             | 1866.308            | 1297.56               | 6322.088 |
| 11 stations         | 3492.35             | 1862.553            | 967.181               | 6322.084 |
| 15 stations         | 3884.59             | 1857.451            | 879.65                | 6621.691 |
6. Conclusion
In this paper, according to the charging demand of urban intelligent networked electric vehicles, the temporal and spatial distribution characteristics of electric vehicles in the area, and considering various influencing factors such as traffic conditions, user charging costs, and distribution network constraints, a graph model for the location of charging piles is constructed. On the basis of considering the electric vehicle charging demand in the planned area, the capacity of a single charging device and the rated capacity of the urban distribution network line, the central point theory of graph theory and the K-means clustering algorithm are combined to propose a planning method for charging piles for urban intelligent networked electric vehicles that takes into account charging safety. Based on the calculation example of the actual intelligent networked electric vehicle charging pile planning in a large city center, and comparing it with the K-means and Voronoi diagram calculation geometry method, it is determined that the urban charging station area division planned by the method proposed in this paper is more balanced and reasonable, and it has a smaller charging distance and better overall economy.

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