Design of Safe Operation Scheme of Charging Station Based on AI Particle Swarm Optimization

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Abstract. In view of the safe and optimized operation of urban EV charging stations, this paper considers satisfying travel needs of users as the premise, improving social and economic benefits as the means, and aimed at ensuring the safe and optimal operation of EVs, puts forward the design scheme of EV charging station that considers user satisfaction, cost of investment and operation, and cost of failure operation and maintenance. The scheme establishes a charging station design model with the goal of minimizing the total social cost. The AI particle swarm optimization algorithm based on chaotic simulated annealing is used to solve the problem, and the chaos theory is introduced for dynamic assignment. Combined with the probability of sudden jump of the simulated annealing algorithm, the algorithm has a higher global optimization ability. The validity and practicability of the design scheme are verified by an example.

1. Introduction
China's new energy vehicles are developing rapidly, and the supporting charging facilities industry is also accelerating. As the charging and discharging service network becomes more and more dense, frequent failures in the charging and discharging process will cause great harm to users and to the operation and maintenance service network. Therefore, in order to cater to the market development, building a safe and efficient EV charging station has important practical significance for ensuring the safety of EV charging.

The planning and design of EV charging station is a high-dimensional non-linear programming problem. In order to obtain the optimal planning scheme, scholars at home and abroad have improved and optimized some commonly used solving algorithms[1][2]. In [3], the particle swarm optimization algorithm is combined with genetic algorithm, and a location-based planning scheme for EV charging station based on particle swarm genetic algorithm is proposed. [4] considers the cost of EV group and the maximum charging station. The charging load is solved by genetic algorithm, and the planning scheme with the lowest cost of establishing the station is selected. At the same time, domestic and foreign scholars mainly study the location of charging stations based on the economic goals of charging station access[5][6]. [7] considers the influence of EV distribution and establishes a multi-level charging station optimization model aiming at maximizing the revenue of charging stations. In [8], the weighted Voronoi diagram is used to adjust the service area division, and the maximum revenue model of the charging station is established. [9] determines the charging station candidate station based on the
geographical factors and service radius of the planning area, and determines the best site based on the minimum total cost of the charging station.

The above research is based on a certain angle to propose a design model for the optimization of the operation of EV charging stations. In order to realize the optimal operation of the charging station, based on chaotic simulated annealing (SA) AI particle swarm optimization (PSO), a charging station planning scheme considering social cost is proposed in this paper.

2. Charging station optimization operation design model

2.1. Charging station location model

In the EV charging station planning scheme of this paper, the total social cost proposed includes not only the charging station investment cost and troubleshooting cost, but also the user's charging cost into the model.

(1) The annual investment cost \( C_1 \) of the EV charging station \( j \) is:

\[
C_1 = (A_j C_j^f + \beta N_{aw} + \alpha N_{aw}^2) \left[ \left( r_n (1 + r_k)^{r_w} \right) \left( (1 + r_k)^{r_w} - 1 \right) \right] \tag{1}
\]

Where, \( A_j \) and \( C_j^f \) are the land acquisition area and unit price of the charging station \( j \), respectively; \( \alpha \) represents the equivalent investment coefficient of equipment purchase and charging station construction cost of the charger; \( N_{aw} \) is the number of chargers; \( r_k \) is the discount rate of the charging station; \( \beta \) is the cost of each charger; \( r_n \) is the age of the charging station.

(2) The annual maintenance cost \( C_2 \) of the EV charging station \( j \) is as follows:

\[
C_2 = (A_j C_j^f + \beta N_{aw} + \alpha N_{aw}^2) \delta \tag{2}
\]

Where, \( \delta \) represents the proportional coefficient of initial investment maintenance.

(3) The user's charging cost \( C_3 \) includes the cost of the idle loss \( C_{DL} \) when the user needs to charge and the waiting cost \( C_{WT} \) of the user:

\[
\begin{align*}
C_3 &= C_{DL} + C_{WT} \\
C_{DL} &= 365 \sum_j \gamma S_{it} \cdot n_{ev} \cdot E_{it} \cdot p \\
C_{WT} &= 365 \sum_i \zeta (W_{it} \cdot \sum_{pn_{ev}})
\end{align*}
\tag{3}
\]

Where, \( \gamma \) is the road tortuosity coefficient \(^{[10]}\); \( S_{it} \) is the distance from the user location \( i \) to the destination charging station \( j \); \( n_{ev} \) is the average number of vehicles to be charged daily in the planning area; \( E_{it} \) is the average power consumption per kilometer; \( p \) is the charging price of the station; \( \zeta \) indicates the travel time cost; \( W_{it} \) represents the queue waiting time expectation of each charging station.

(4) The minimum total cost optimization model for the whole society is:

\[
\min F = \lambda \sum_{j=1}^{N} C_1 + \psi \sum_{j=1}^{N} C_2 + \eta \sum_{j=1}^{N} C_3 \tag{4}
\]

Where, \( N \) represents the number of EV charging stations to be built in the planning area. \( \lambda, \psi \) and \( \eta \) respectively represent the weights of \( C_1 \), \( C_2 \), and \( C_3 \), which are set to 0.5, 0.2, and 0.3.

2.2. Constant volume method based on M/M/S queuing theory

Based on the M/M/s model of queuing theory in \(^{[11]}\), the queuing theory is applied to the optimization design. The number of charging stations in the charging station should be based on the expectation of queue waiting time to establish the charging station capacity optimization model. The mathematical model for the waiting time expectation of EVs is:

\[
W_e = \frac{N_{aw} \rho^{N_{aw}+1} P_0}{e N_{aw} \left( (N_{aw} - \rho) \right)} , \quad P_0 = \sum_{i=0}^{N_{aw}} \frac{\rho^i}{i!} + \frac{N_{aw} \rho^{N_{aw}}}{N_{aw} \left( (N_{aw} - \rho) \right)} \tag{5}
\]

Where \( P_0 \) is the probability that all the charging piles in the charging station are empty; \( W_e \) queues users for waiting time expectations; \( \rho \) represents the average service efficiency of the charger, \( \rho = e \mu \), \( e \) represents the average number of vehicles that the electric car arrives at the charging station per hour,
and \( \mu \) represents the charging rate of the charger. In order to find the minimum number of chargers in the charging station, the traversal method can be adopted. First, the initial value of the number of chargers is set to \( N_{\text{ist}} \), the maximum time is expected to be \( W_{\text{max}} \), and \( N_{\text{ist}} = \lceil F \rho \rceil \), and then the number of chargers is increased. Until \( W_t < W_{\text{max}} \), the resulting \( N_{\text{ist}} \) is solved.

2.3. Charging station safety operation constraints

(1) System flow constraints

\[
P_n = V \sum_{j=1}^{N} \left( G_j \cos \theta_j + B_j \sin \theta_j \right)
\]
\[
Q_n = V \sum_{j=1}^{N} \left( G_j \sin \theta_j - B_j \cos \theta_j \right)
\]

(2) Node voltage constraint

\[V_i^\text{min} \leq V_i \leq V_i^\text{max} \quad i = 1, 2, ..., M\]

(3) Branch transmission power constraint

\[P_{\text{min}} \leq P_i \leq P_{\text{max}} \quad i = 1, 2, ..., L\]

(4) Number of charging stations

\[F_{\text{crit}} \left( P_{\text{total}} \cdot S_{\text{max}}^{-1} \right) \leq N_i \leq F_{\text{crit}} \left( P_{\text{total}} \cdot S_{\text{min}}^{-1} \right)\]

Where, \( P_{\text{total}} \) represents the total charging demand in the planning area; \( S_{\text{max}} \) represents the maximum capacity of the charging station, and \( S_{\text{min}} \) represents the minimum capacity of the charging station.

3. Joint solution method of weighted V-pattern and chaotic simulated annealing particle swarm optimization algorithm

3.1. Weighted V diagram

Supposing \( Q = \{q_1, q_2, ..., q_n\} \) (\( 3 \leq n \leq \infty \)) is the set of points on the plane, and set the weight \( \omega_m (m = 1, 2, ..., n) \) to be a given set of positive real numbers, then The weighted Voronoi diagram of any point can be expressed as \(^{[12]}\):

\[V \left( q_m, \omega_m \right) = \left\{ x \in V \left( q_m, \omega_m \right) | d \left( x, q_m \right) \omega_m^{-1} \leq d \left( x, q_i \right) \omega_i^{-1} \right\} \quad j = 1, 2, ..., n, l \neq m\]

The global optimization ability of the particle swarm optimization algorithm is used to optimize the weighted V map. A weighted V map of each planning area is calculated according to equation (11).

\[\omega_i = \left( R_c \left( P_s \right) \right)^{1/2}\]

Where, \( R_c \) is the reference capacity; \( \omega_i \) represents the service capacity of each charging station in the planning area; \( P_s \) is the charging demand of each charging station in the planning area.

3.2. Algorithm improvement

In this paper, chaos theory is introduced in the simulated annealing algorithm, and an improved particle swarm optimization algorithm (CSAPSO) is proposed, which makes the particle swarm search for the optimal solution more locally. The calculation steps of the CSAPSO algorithm are as follows:

(1) Initialize the parameters first, randomly generate particle populations, and initialize particle position and velocity.

(2) Calculate the fitness value for each individual in the population, and record the current position \( P_{id} \) and the global optimal position \( P_{pd} \) of each particle.

(3) Select the optimal fitness value \( Z_{best} \) from the whole population and calculate the initial temperature \( T \) of the annealing algorithm using equation (15).

(4) Calculate the fitness value of the annealing algorithm for each particle at the initial temperature:

\[f_T \left( P_{id} \right) = e^{\frac{f \left( P_{id} \right) - f \left( P_{pd} \right)}{T}} \left( \sum_{i=1}^{n} e^{\frac{f \left( P_{id} \right) - f \left( P_{pd} \right)}{T}} \right)^{-1}\]

\[f_T \left( P_{id} \right) = e^{\frac{f \left( P_{id} \right) - f \left( P_{pd} \right)}{T}} \left( \sum_{i=1}^{n} e^{\frac{f \left( P_{id} \right) - f \left( P_{pd} \right)}{T}} \right)^{-1}\]
(5) Use the roulette selection strategy, select an optimal position among all individual positions into \( P_{zd} \) and update the particle speed:

\[
V_{id}^{k+1} = \omega V_{id}^{k} + c_1 r_1 (P_{id}^{k} - X_{id}^{k}) + c_2 r_2 \left( P_{zd}^{k} - X_{id}^{k} \right)
\]

(13)

(6) Calculate the fitness value of each particle and update the optimal position of the particle and the optimal position of the population.

(7) Perform a cooling annealing operation:

\[
T = \delta T
\]

(14)

(8) If the termination condition is met, stop and output the result. If not, go to step (4).

3.3. Setting of relevant parameters

(1) Initial temperature. The following formulas are used to calculate the initial temperature.

\[
T = -Z_{\text{best}} \left( \ln 0.2 \right)^{-1}
\]

(15)

(2) Inertial weight. Linear decreasing strategy is used to adjust inertia weight in order to improve the ability of the algorithm to search the optimal solution.

\[
\omega(t) = \omega_{\text{start}} - \left( \omega_{\text{start}} - \omega_{\text{end}} \right) k_{\text{max}}^{-1} k
\]

(16)

Where, \( k \) is the number of iterations; \( \omega_{\text{start}} \) is the initial inertia weight, and \( \omega_{\text{end}} \) is the termination inertia weight.

(3) \( r_1, r_2 \). Chaos theory is used to assign \( r_1 \) and \( r_2 \):

\[
r_{i}^{k+1} = 4r_{i}^{k} \left( 1 - r_{i}^{k} \right), \quad r_i \in (0,1); \quad i = 1, 2
\]

(17)

Where, \( r_{i}^{k} \) is the value of \( r_i \) at the \( k \)th iteration. According to the chaos theory, the variable \( r_i \) can traverse the whole search space randomly.

(4) Annealing speed. Set the annealing speed to 0.95 to increase the probability of searching for the global optimal solution.

4. Charging station planning model solution

The solution flow of the EV charging station planning configuration model is shown in Figure 1.

5. Case analysis

This paper analyzes a typical planning area in Nanjing. The planned area is about 34.02 km\(^2\). The road intersection map is shown in Figure 2. The number of road nodes in the figure is the intersection number.
Figure 2. Road network structure of planning area.

The location of the proposed charging station is the intersection of each road. The information and traffic flow of the city intersection are shown in Table 1.

| A | B | A | B | A | B | A | B | A | B |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 2310 | 2 | 3670 | 3 | 2543 | 4 | 1611 | 5 | 960 |
| 7 | 4110 | 8 | 3865 | 9 | 3240 | 10 | 1550 | 11 | 2620 |
| 13 | 3760 | 14 | 3265 | 15 | 2675 | 16 | 2210 | 17 | 1876 |
| 19 | 2012 | 20 | 2114 | 21 | 1754 | 22 | 1043 | 23 | 955 |
| 25 | 2877 | 26 | 3250 | 27 | 3319 | 28 | 2870 | 29 | 2765 |
| 31 | 1654 | 32 | 2761 | 33 | 2237 | 34 | 2982 | 35 | 2675 |
| 37 | 2858 | 38 | 1980 | 39 | 1266 | 40 | 879 | 41 | 1340 |
| 43 | 1579 | 44 | 1732 | 45 | 1620 | 46 | 1533 | 47 | 1145 |

A: Road node number, B: Traffic flow / vehicle

Referring to the technical parameters of Nissan Leaf, the lithium battery capacity of each electric vehicle is set at 24 kW·h. The land cost of each land type in the planning area of EV charging station is shown in Table 2 and the planning parameters of charging station are shown in Table 3.

Table 2. Costs of different types of land use in planned areas.

| Land type | Commercial land | Residential land | Industrial land |
|---|---|---|---|
| Price (10^4 yuan/m²) | 0.8296 | 0.6174 | 0.2551 |

Table 3. Charging station planning parameters.

| α/ (10^4 yuan /platform²) | 2 | βl/ (10^4 yuan /platform²) | 10 | p/ (yuan /kW·h) | 0.7 |
|---|---|---|---|---|---|
| r0 | 0.08 | λf/ (yuan /h) | 20 |
| n/ (year) | 20 | Pe (kW) | 96 |
| γ | 1.3 | Smax | 25 |
| E/ (yuan / kW·h) | 0.15 | Smin | 6 |

Considering the local demand of the planning area, after preliminary planning, the recharging stations needed for the planning area can be roughly 2-7. Based on CSAPSO algorithm, the optimal configuration of charging station is solved. The parameters of the algorithm are as follows: The population size is set to 50, ωstart and ωend are set to 0.9 and 0.4, learning factor c1 and c2 are both 1.494, δ is 0.95, and k is set to 100. The optimization results are obtained by running the program. Through calculation, it can be concluded that when 2 to 7 charging stations are built, the whole social cost is shown in Figure 3.

Figure 3. Charging station social cost diagram.
It can be seen that when four charging stations are built, the whole society has the lowest cost and can meet the needs of users. The specific capacity allocation scheme of charging station is shown in Table 4.

**Table 4. Charging station configuration scheme.**

| Charging station | Road node | Number of Chargers | Service node |
|------------------|-----------|--------------------|--------------|
| 1                | 12        | 15                 | 1,2,6,7,11,12,13,18 |
| 2                | 16        | 8                  | 3-5,8-10,14-17,19-22 |
| 3                | 29        | 8                  | 28-30,34-38,43-47 |
| 4                | 32        | 20                 | 23-27,31-33,39-42 |

6. Conclusion

This paper proposes a design scheme for an EV charging station that considers user satisfaction, investment operating costs, and fault operation and maintenance costs. The scheme establishes the charging station design model with the goal of minimizing the total social cost. The AI particle swarm optimization algorithm based on chaotic simulated annealing is used to solve the problem. The model is applicable to the planning of EV charging station, balancing the benefits of EV users, charging station investors and grid enterprises, and has certain guiding significance for the future planning of EV charging station.

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