Optimal Configuration Method for EV Charging Station in Distribution Network Considering User Adjustment under V2G mode

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Abstract. The existing charging piles planning method of distribution network does not consider the influence of user participation in regulation. Hence, an optimal planning method of electric vehicle charging piles in V2G mode is proposed, considering users’ influence of regulation. An EV charging pile planning model is established to minimize the investment and operation cost of distribution network and charging station, and the genetic algorithm with elitist retention strategy is used to solve the model. The examples show the effectiveness of the proposed method.

Keywords: EV charging station, distribution network, V2G, configuration, optimization

1. Introduction
As a new generation of vehicles, electrical vehicles have incomparable advantages over traditional vehicles in energy saving and emission reduction, reducing human dependence on traditional fossil energy. In recent years, the proportion of electric vehicles has increased significantly, and the annual output of electric vehicles in China will be close to 2 million in 2020. Driven by the long-term goal of carbon neutralization in 2060, the proportion of clean electric vehicles will be further increased.

With the rapid development of electric vehicle industry, charging piles, as the vital electric vehicle charging infrastructure, are also facing new opportunities and challenges. A typical problem at this stage is the incoordination between the development of electric vehicles and charging infrastructure and the imbalance of the quantity ratio of electric vehicles and charging piles is becoming more and more prominent. Therefore, it is of great significance to study the optimal planning method of electric vehicle charging piles. Not only do the scale and distribution of electric vehicles and users’ travel habits need taking into account but the security operation constraints of distribution network should be considered as well. In addition, with the maturity of V2G technology, electric vehicle users will take more part in the interactive regulation of power grid in the future, which also needs to be fully considered in the planning of electric vehicle charging piles.

Most of the existing studies on the planning of electric vehicle charging piles take the cost as the optimization objective. In [1], minimizing the construction cost is set as optimization objective, and four
different algorithms to solve the problem are put forward, and their effectiveness is verified by simulation. In [2], not only the construction cost, but also the maintenance cost, operation cost and the cost of power transmission and distribution loss are considered in the optimization objective. The improved Primal-Dual Interior Point Algorithm is used to solve the minimization problem. In [3], apart from the minimization of construction cost and operation cost, the maximization of the use of electric vehicles are also taken into consideration as the objective in the multi-objective optimization model, so as to obtain the location and size of charging piles. In [4], the concept of economic benefit is put forward, i.e., the location, capacity and number of charging piles are obtained by maximizing the economic benefit, in which the economic benefit is defined as the difference between the income obtained by the builder through the construction of charging piles and various costs (including construction cost, maintenance cost, etc.), and the traffic flow and cost are also considered when solving the optimization problem in the regional distribution network constraints.

In this paper, the influence of future electric vehicle users' participation in grid interaction on the grid is fully considered, and the planning model of electric vehicle charging piles is established with the objective of minimizing the investment and operation cost of distribution network and charging station, and the Genetic Algorithm with elite retention strategy is used to solve the problem.

2. Analysis of the impact of the access of electric vehicle charging stations on distribution network

Under the V2G mode, the access of electric vehicles may also cause bidirectional power flow, resulting in network loss and fluctuation of node voltage. The simplified i-j model of the branch before and after the access of the electric vehicle charging stations is shown in the figure.

![Figure 1. Simplified model of grid under V2G mode](image)

The system network loss before and after the charging station is connected, $P_0$ and $P$, and change of the system network loss, $\Delta P$, are defined as below:

$$P_0 = \frac{rL(P_m^2 + Q_m^2)}{3U^2}$$  \hspace{1cm} (1)

$$P = \frac{rL[(P_m + P_c)^2 + (Q_m + Q_c)^2]}{3U^2}$$  \hspace{1cm} (2)

$$\Delta P = P - P_0 = \frac{rL}{3U^2}(P_c^2 + Q_c^2 + 2P_mP_c + 2Q_mQ_c)$$  \hspace{1cm} (3)

In (1) - (3), $P_m$, $Q_m$, $P_c$, $Q_c$ are the active power and reactive power of the charging station which are absorbed from the system and injected into the node respectively.

If hoping $\Delta P < 0$, it needs:

$$P_mP_c + Q_mQ_c < 0$$  \hspace{1cm} (4)

The positive and negative of $P_c$ and $Q_c$ reflect the working state of the charging station. Therefore, when the charging station return the electric energy to the power grid, the network loss can be reduced. Similarly, when electric vehicle are connected as the charging load, the node voltage will decrease; on the contrary, when it return the electric energy to the grid, the node voltage will increase.

3. Optimization model and solution method of distribution network charging pile considering the influence of electric vehicle involvement in power grid regulation

This chapter introduces the optimization model and solution method of electric vehicle charging station planning.

In the planning of charging station location and capacity, we should start from economy, minimize
the investment and operation cost of distribution network and charging station. The objective function is that the sum of equal annual values of construction cost, operation cost and load transfer cost is the smallest, and the schedulable ability of the system is the largest. The formula is as follows:

\[
\text{minimize } C_{\text{total}} = C_{\text{inv}} + C_{\text{opr}} + C_{\text{crdchg}} + C_{\text{env}}
\]

(5)

\[
\text{min } C_{\text{enc}} = C_{\text{grid}} + C_{\text{cus}} - \Delta C_{\text{loss}}
\]

(6)

In the formula, \(C_{\text{total}}\) is the equal annual value of the total planning cost; \(C_{\text{inv}}\) is the investment construction cost, \(C_{\text{opr}}\) is the operating costs, \(C_{\text{crdchg}}\) is the load transfer cost, \(C_{\text{env}}\) is the environmental cost, which is used to quantify the influence of charging station construction project on the environment.

\(C_{\text{enc}}\) is the cost of electric vehicle users participating in power grid dispatching, \(C_{\text{grid}}\) is the cost of power grid company to encourage users to participate in dispatching, for example, incentive electricity price measures; \(C_{\text{cus}}\) is the cost for customers to participate in scheduling, such as comfort cost, time cost; \(\Delta C_{\text{loss}}\) is the reduced power loss cost after electric vehicles participating in dispatching.

The smaller \(C_{\text{enc}}\) is, the stronger the schedulable ability is.

1) The calculation formula of investment and construction cost is as follows:

\[
C_{\text{inv}} = C_{\text{inv}} \frac{r(1+r)^{yr}}{(1+r)^r-1}
\]

(7)

In the formula, \(C_{\text{inv}}\) is the planned total construction cost, \(r\) is the annual interest rate and \(yr\) is the service life of the equipment. The planned total construction cost includes the construction cost of distribution network and electric vehicle charging station:

\[
C_{\text{inv}} = C_{\text{grid}}^g + C_{\text{inv}}^{sn}
\]

(8)

\[
C_{\text{grid}}^g = \sum_{j \in \psi^{rep}} \sum_{t \in \phi^{rep}} c_{j,t}^{rep} x_{j,t}^{rep} + \sum_{k \in \psi^{add}} \sum_{t \in \phi^{add}} c_{k,t}^{add} x_{k,t}^{add} + \sum_{l \in \psi^{sub}} \sum_{t \in \phi^{sub}} c_{l,t}^{sub} x_{l,t}^{sub}
\]

(9)

\[
C_{\text{inv}}^{sn} = \sum_{m \in \psi^{load}} \left( c_{m}^{ch} x_{m}^{ch} + c_{m}^{var} r_{m} \right)
\]

(10)

In the formula, \(t\) is the subscript representing an optional type of line or transformer; \(j\), \(\psi^{rep}\) and \(\phi^{rep}\) are the subscript, line set and type selection set of upgradeable feeder respectively, \(c_{j,t}^{rep}\) is the cost of selecting linear expansion \(t\) for the upgradeable feeder \(j\), and \(x_{j,t}^{rep}\) is the 0-1 decision variable of selecting linear expansion \(t\) for the upgradeable feeder \(j\); \(k\), \(\psi^{add}\) and \(\phi^{add}\) are the subscript, line set and type selection set of the additional feeder respectively, \(c_{k,t}^{add}\) is the cost of selecting linear construction \(t\) for the addable feeder \(k\), and \(x_{k,t}^{add}\) is the 0-1 decision variable of selecting linear construction \(t\) for the addable feeder \(k\); \(l\), \(\psi^{sub}\) and \(\phi^{sub}\) are the substation node subscript, node set and transformer expansion selection set respectively, \(c_{l,t}^{sub}\) is the cost of selecting transformer \(t\) for the expansion in substation \(l\), and \(x_{l,t}^{sub}\) is the 0-1 decision variable of selecting transformer \(t\) for the expansion in substation \(l\).

\(m\) and \(\psi^{load}\) are the subscript and node set of the load node, \(c_{m}^{ch}\) and \(c_{m}^{var}\) are the fixed cost and variable cost of constructing the charging station respectively, \(x_{m}^{ch}\) is the 0-1 decision variable of constructing the charging station at load node \(m\), and \(P_{m}^{slot}\) is the capacity of charging facilities installed at load node \(m\), which is equal to the maximum charging load of the node.

2) The operation cost in the overall planning cost mainly includes the operation cost of power grid and charging station, the formula is as follows:

\[
C_{\text{opr}} = C_{\text{opr}}^g + C_{\text{opr}}^{sn}
\]

(11)

In the formula, \(C_{\text{opr}}\) is the planned annual operating costs, \(C_{\text{opr}}^g\) and \(C_{\text{opr}}^{sn}\) are the annual operating costs of power grid companies and charging stations respectively.

Among them, the annual operation cost of power grid is mainly the operation and maintenance cost
of each feeder, which can be obtained by adding the operation cost of every line in use, the formula is as follows:

$$C_{opr}^{grid} = \sum_{l \in \psi_{lfx}} o_{lfx}^{f} y_{lfx}^{f} + \sum_{l \in \psi_{rep}} \sum_{t \in \phi_{rep}} o_{ltx}^{rep} y_{ltx}^{rep} + \sum_{k \in \psi_{add}} \sum_{t \in \phi_{add}} o_{ktx}^{add} y_{ktx}^{add} + \sum_{l \in \psi_{sub}} \sum_{t \in \phi_{sub}} o_{ltx}^{sub} y_{ltx}^{sub}$$

(12)

In the formula, $i$ and $\psi_{lfx}$ are the subscript and line set of the existing fixed feeder respectively, $o_{lfx}^{f}$ is the annual operation cost of the existing feeder $i$, and $y_{lfx}^{f}$ is the 0-1 decision variable of using feeder $i$. $o_{ltx}^{rep}$ is the annual operation cost of using the type $t$ line for the upgrade feeder $j$, and $y_{ltx}^{rep}$ is the 0-1 decision variable of using the type $t$ line for the upgrade feeder $j$. $o_{ktx}^{add}$ is the annual operation cost of using the type $t$ line for the additional feeder $k$, and $y_{ktx}^{add}$ is the 0-1 decision variable of using the type $t$ line for the additional feeder $k$.

The annual operation cost of the charging station is mainly the maintenance cost of the charging facilities, which is proportional to the charging load in the station, the formula is as follows:

$$C_{inv}^{stn} = \sum_{m \in \psi_{load}} \sum_{s \in \phi_{p,f,s}} o_{m,s}^{chg} P_{m,s}^{chg}$$

(13)

In the formula, $s$ and $\phi_{p,f,s}$ are subscripts and time sets of the peak, flat and valley periods respectively. $o_{m,s}^{chg}$ is the operation and maintenance cost of charging station in stage $s$ of load node $m$, and $P_{m,s}^{chg}$ is the charging load in stage $s$ of load node $m$.

3) The cost of coordinated charging mainly includes the economic loss caused by the implementation of the price-based coordinated charging strategy and the subsidy paid to charging users by the real-time incentive-based coordinated charging strategy, the formula is as follows:

$$C_{crrchg} = C_{PBR} + C_{IBDR}$$

(14)

In the formula, $C_{crrchg}$ is the cost of implementing coordinated charging, $C_{PBR}$ and $C_{IBDR}$ are the cost of implementing price-based and incentive-based demand side response of electric vehicles respectively.

While taking the total cost as the minimum objective optimization, it is necessary to ensure that the optimization results meet the normal operation of the power system and the requirements of conventional loads and electric vehicles. Grid security constraints include power balance constraints, node voltage constraints, branch current constraints and power flow back-off constraints. The formula is as follows:

$$\begin{align*}
\sum_{k:(l,k) \in \Omega_b} P_{1k,t} & = P_{0,t} - P_{L,t} \\
\sum_{k:(j,k) \in \Omega_b} P_{1j,k} & = \sum_{l:(i,l) \in \Omega_b} (P_{1j,l} - r_{i,j,l} x_{i,j,l}) - P_{L,t} - (P_{c}^{ch} - P_{dis}) \\
\sum_{k:(j,k) \in \Omega_b} Q_{jkw,t} & = \sum_{l:(i,j) \in \Omega_b} (Q_{jkw,t} - x_{i,j,l} x_{i,j,l}) - Q_{L,t} \\
v_{j,w,t} & = v_{i,w,t} - 2(r_{i,j} P_{i,j,w} + x_{i,j,l} Q_{i,j,w}) + l_{i,j,l} (r_{i,j}^2 + x_{i,j,l}^2)
\end{align*}$$

(15)

In the formula, $\Omega_b$ represents the sequential set from node $j$ to node $k$; $P_{L,t}$ and $Q_{L,t}$ are the total resistive load and reactive load of node $i$ in time $t$; $r_{i,j}$ and $x_{i,j,l}$ are the resistance value and reactance value between nodes ($i,j$); $l_{i,j,l}$ is the square of branch current ($i,j$) in time $t$; and $v_{i,t}$ is the square of the voltage at node $i$ in time $t$.

Charging station device constraints:

In addition, the capacity constraints of substation and charging station allowed by power grid should also be considered:

$$Sta_{need} < \sum_{m \in \psi_{load}} x_{m}^{chg} \times F_{m}^{slot} < Sta_{total}$$

$$P_{m}^{slot} < Sta_{max}$$

$$0 < \sum_{m \in \psi_{load}} x_{m}^{chg} < n_{max}$$

(16)  (17)  (18)

In the formula, $Sta_{need}$ is the total charge of electric vehicles for customer side demand, $Sta_{total}$ is the maximum power sum of charging stations allowed in distribution network, $Sta_{max}$ is the maximum capacity allowed for a single charging station. $n_{max}$ is the maximum number of charging stations allowed to be installed.
The model established in this paper is implemented by genetic algorithm with fine reservation strategy. This paper introduces adaptive genetic algorithm into planning to speed up the convergence speed of the algorithm. In adaptive genetic algorithm, $P_c$, which means the crossover rate and $P_m$, which means the mutation rate are adjusted adaptively based on individual fitness value. In addition, in order to find the optimal solution in the global scope and avoid the local optimization, a certain genetic algebra should be guaranteed. But if only the genetic algebra is used as the criterion to exit the evolution, it is likely that the genetic algorithm will continue to calculate after finding the optimal solution, which increases the calculation time. Aiming at this situation, a termination evolution criterion is proposed, which combines the minimum retention algebra of the optimal individual with the maximum genetic algebra. If the optimal solution of a generation is still optimal after several successive genetic evolutions, the evolution will exit, otherwise the search will continue until the minimum reserved algebra of the optimal individual is satisfied. If the solution of the minimum reserved algebra of the optimal individual is not satisfied within the genetic algebra limit, the suboptimal solution is output.

4. Examples
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![Fig 2. Typology of distribution network](image)

The needed parameters of electric vehicle charging station and load data are shown in Table 1 and 2.

| Parameters                       | Values      |
|----------------------------------|-------------|
| Discount rate                    | 0.08        |
| Economic life / years            | 20          |
| Maximum capacity / kW            | 1000        |
| Investment cost / (CNY/kW)       | 25000       |
| Operation maintenance cost / (CNY/kWh) | 0.08  |
Table 2. District load situations

| Node serial number | Branch resistance | Branch reactance | Active load of the end node (kW) | Reactive load of the end node (kVar) |
|--------------------|-------------------|------------------|----------------------------------|-------------------------------------|
| 1                  | 0.271             | 0.320            | 200.00                           | 96.00                               |
| 2                  | 0.068             | 0.160            | 139.44                           | 66.93                               |
| 3                  | 0.208             | 0.280            | 60.22                            | 28.91                               |
| 4                  | 0.153             | 0.240            | 100.00                           | 48.00                               |
| 5                  | 0.038             | 0.120            | 120.00                           | 57.60                               |
| 6                  | 0.611             | 0.480            | 133.73                           | 64.19                               |
| 7                  | 0.153             | 0.240            | 129.61                           | 62.21                               |
| 8                  | 0.382             | 0.480            | 188.83                           | 90.64                               |
| 9                  | 0.038             | 0.120            | 100.00                           | 48.00                               |
| 10                 | 0.271             | 0.320            | 92.93                            | 44.60                               |
| 11                 | 0.271             | 0.320            | 192.93                           | 92.60                               |
| 12                 | 0.208             | 0.280            | 116.42                           | 55.88                               |
| 13                 | 0.259             | 0.440            | 200.00                           | 96.00                               |
| 14                 | 0.017             | 0.080            | 200.00                           | 96.00                               |
| 15                 | 0.106             | 0.280            | 174.02                           | 83.53                               |
| 16                 | 0.321             | 0.320            | 67.84                            | 32.56                               |
| 17                 | 0.156             | 0.200            | 128.62                           | 61.74                               |

Comparison is used to confirm the validity of the calculation method. We set two different approaches to compare. The first is planning with the optimized configuration model considering the load characteristic of electric vehicle, which is mentioned above. The second is the comparison group in which the electric vehicle’s load characteristic is not considered. We calculate the final total costs of these two ways by contrast and the results are as follows.

Scheme 1:

Table 3. Planning results and cost analysis of scheme 1

| Number of charging stations | Total number of charging piles | Construction costs of charging stations (10,000 CNY) | Costs of motivating users to participate in dispatching (10,000 CNY) | District construction and renovation costs (10,000 CNY) | Total costs (10,000 CNY) |
|-----------------------------|--------------------------------|-----------------------------------------------------|---------------------------------------------------------------------|-------------------------------------------------------|-------------------------|
| 2                           | 60                             | 185.65                                              | 10.75                                                               | 95.85                                                 | 292.25                  |
| 3                           | 61                             | 188.72                                              | 9.25                                                               | 92.75                                                 | 290.72                  |
| 4                           | 65                             | 192.44                                              | 8.87                                                               | 86.84                                                 | 288.15                  |

Scheme 2:

Table 4. Planning results and cost analysis of scheme 2

| Number of charging stations | Total number of charging piles | Construction costs of charging stations (10,000 CNY) | Costs of motivating users to participate in dispatching (10,000 CNY) | District construction and renovation costs (10,000 CNY) | Total costs (10,000 CNY) |
|-----------------------------|--------------------------------|-----------------------------------------------------|---------------------------------------------------------------------|-------------------------------------------------------|-------------------------|
| 2                           | 37                             | 125.75                                              | 19.75                                                               | 58.25                                                 | 203.75                  |
| 3                           | 39                             | 140.54                                              | 18.32                                                               | 62.75                                                 | 221.61                  |
| 4                           | 45                             | 156.43                                              | 17.21                                                               | 66.84                                                 | 240.48                  |
According to Scheme 1’s results, when the total number of charging stations is 4 and charging piles is 65, the comprehensive costs including investment, users’ motivation and district renovation are minimized and the district economy is optimal.

By comparing the results above, we can find that the various costs of Scheme 1 and 2 have the same changing trend when the number of charging piles differs. The load characteristic of electric vehicle is not considered in the second approach. Although its total costs are slightly lower than the first, less quantity of charging piles can not satisfy the load demand in the peak time, which means the cost of motivating users to participate in dispatch increased. Scheme 1 may be uneconomical, but the quantity of piles is much more than the second’s, bringing the greatest convenience to users, cutting their costs of grid dispatching participation and increasing the willingness to join in. For the long-term development planning, Scheme 1 is better, which is programmed by the solution mentioned above.

After installing the charging stations, voltage and power flow distribution will be influenced in the system because of the randomness of stations’ charging and discharging. Therefore, besides economic efficiency should be fully considered in the process of charging stations’ site selection and capacity settings, we need reasonably guide our clients to charge and discharge orderly by some measures like price motivation, consequently realizing maximization of economic benefit and optimization of system stability.

According to the analysis above, a specific scheme to allocate the electric vehicle charging station in the district is as followed.

### Table 5. Optimal allocation results of electric vehicle charging stations

| Charging station allocation nodes | Number of charging piles | Gross capacity (kW) |
|----------------------------------|--------------------------|---------------------|
| 13                               | 24                       | 4800                |
| 17                               | 14                       | 2800                |
| 9                                | 18                       | 3600                |
| 2                                | 9                        | 1800                |
| Total                            | 65                       | 13000               |

5. Conclusions

This paper proposed an optimal planning method of electric vehicle charging piles considering the users’ adjustment influence in a kind of V2G model. We built an electric vehicle charging piles scheme model which aims at minimizing the costs of distribution network and charging stations’ investment, and used the genetic algorithm with elitism strategy to calculate.

The influence and potential of electric vehicle adjustment is fully considered in the process of regulation, which can not only reduce investment costs and realize economic optimization, but also ensure the safe operation of power grid and the user satisfaction.

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