Collaborative Planning of Charging Station and Distribution Network Considering Electric Vehicle Mobile Energy Storage

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Abstract. A collaborative planning model for electric vehicle (EV) charging station and distribution networks is proposed in this paper based on the consideration of electric vehicle mobile energy storage. As a mobile charging load, EVs can interact with the power grid. Taking EVs as planning considerations, subsidies for EVs are used to shift the charging load to the feeder network area with a large margin, reducing the transformer capacity and reducing the overall planning cost. Finally, the article uses CPLEX to solve the optimization problem, and uses an 18-node distribution system for simulation verification.

1. Introduction
In recent years, in order to ease the pressure on the environment and energy, the EV industry has received widespread attention for its clean and efficient energy model [1]. The charging load of EV is affected by factors such as battery characteristics, user behaviours, and roads. It has random, intermittent, and fluctuating uncertainties in time and space distribution. Large-scale EVs connected to the grid will affect the safe operation of the grid. At the same time, EVs have considerable energy storage value. Based on 2020’s holdings of 5 million units and a simultaneous rate of 0.3, their charging and discharging power will reach 525 MW, equivalent to 2.3 total installed capacities of the Three Gorges. Therefore, in order to effectively play the energy storage characteristics of large-scale EV, it is of great research value to consider the coordinated planning of charging stations and distribution networks under the EV mobile energy storage.

At present, many researches have been done on the layout planning of EV charging stations [2-4]. Ref. [5] studied the coping strategies of the distribution network in consideration of EV, and established an optimal planning model for EV power station replacement with economic optimality as the objective function and power balance as the constraint conditions. Ref. [6] aimed at the load uncertainty caused by the random charging and discharging of grid-connected EV, with the objective function of optimal economy and minimum network loss, and established a new power source location and capacity model for EV. Ref. [7] built the objective function to minimize the overall cost of commissioning, and used Voronoi diagram to do the charging station location planning.

While research on the planning of EV and distribution networks is still lacking. Ref. [8] used economic optimization as the objective function, and used an orderly optimization algorithm to solve the distribution network planning model. Ref. [9] built the substation location optimization model with the minimum load spacing as the goal and the grid optimization planning model with the minimum
investment and operation cost as the goal. The above studies rarely consider the collaboration between EV and distribution networks.

Based on the above considerations, this paper considers the collaborative planning of the EV charging station and the distribution network in the case of EV mobile energy storage to complete the transfer of the EV charging load from peak power to valley. Based on the power demand of each load point during the planning period and the update of the electric vehicle’s mobile state, this paper establishes a charging station-distribution network collaborative planning model that takes EV mobile energy storage into consideration.

2. EV Mobile Energy Storage Model
EV mobile energy storage refers to the exchange of energy between the power grid and the energy storage battery when EV connected to the power grid in stationary state [10, 11]. Due to the relatively small capacity of EV battery energy storage units, this paper examines the mobility characteristics of EV groups between stopping and driving state from a macro perspective. An area is divided into different areas according to the nature of land use. EVs can be parked in the area or driven across the area according to the owner’s needs. Utilizing the characteristics of EV mobile energy storage, on the one hand, when the SOC of the EV is high, it can realize the release of electricity at the peak of the regional power load and reduce the peak load of the grid; on the other hand, when the SOC of the EV is low, at the same time the load is relatively high, you can update the running status of EV to achieve area transfer and conduct electric vehicle charging in other areas.

Regarding the mobile energy storage of EV, this paper mainly reflects the mutual movement characteristics through different types of building land. As shown in figure 1, in order to avoid excessive vehicle movement distance and the next time the vehicle position is reachable in unit time, this article assumes that vehicle movement occurs only in the adjacent area. For example, when the vehicle is located in area 4 at a certain moment, if the electricity load on the area is low, the vehicle will be charged in area 4. If the vehicle needs to be charged urgently and area 4 is at the peak of electricity load, then the vehicle will have a position state transition and move to area 1, area 2 or area 5 for charging. If the vehicle has a high SOC at this time and area 4 is at the peak of the power load, the owner can be subsidized by encourage the owner discharge to the grid.

![Figure 1. Schematic update of EV movement status.](image)

After the introduction of EV mobile energy storage, the load of charging stations in each area can be expressed by equation (1).

\[
E_m(t) = E_m(t) - E_{m_{\text{dis}}}(t) - \sum_{n \in N} E_{m_{\text{dis}}}(t)
\]

where \(E_m(t)\) is the actual charging load of the \(m\)-th area at time \(t\); \(E_m(t)\) is the EV charging demand of the \(m\)-th area at time \(t\); \(E_{m_{\text{dis}}}(t)\) is the EV discharge capacity to the grid of the \(m\)-th area at time \(t\); \(E_{m_{\text{dis}}}(t)\) is the amount of electricity transferred from the EV charging load in the \(m\)-th area to its neighboring \(n\)-th area at time \(t\); \(N\) is the set of all areas neighboring to the \(m\)-th.

The distribution network subsidizes car owners involved in the discharge of EV to the grid and the transfer of charging loads. A subsidy cost of 24 hours can be expressed as in the equation (2).
\[
f_c = \sum_{i \in \mathcal{G}} \left( b_1 \cdot E_{\text{dis}}^i(t) + b_2 \cdot \sum_{n \in \mathcal{N}} E_{\text{m-n}}(t) \right) \quad (2)
\]

where \( f_c \) is the subsidized cost of the distribution network to the owner; \( b_1 \) and \( b_2 \) are the unit price of the subsidized electricity price.

3. Collaborative Planning Model

3.1. Objective Function

This paper mainly analyzes the economics of the charging station-distribution network collaborative planning model that considers the EV mobile energy storage. In addition, the planning process needs to consider meeting the electricity demand in the planning area. The objective function is to minimize the cost of regional transfer subsidies for the EV charge load, construction cost of the distribution network and charging station and operation cost of the distribution network and charging station, which can be expressed by equation (3).

\[
\min f = f'^\mu + f'^{op}
\]

where \( f \) is the annual value of the total cost of the collaborative planning of the charging station and the distribution network; \( f'^\mu \) is the annual value of the construction cost; \( f'^{op} \) is the average annual operating cost.

3.1.1. Annual Value of the Construction Cost \( f'^\mu \).

The construction cost includes the cost of substation construction, line construction and charging station construction, specifically expressed by equation (4):

\[
f'^\mu = \alpha \cdot \left( f_{\text{sub}} + f_{\text{line}} + f_{\text{EV}} \right)
\]

where \( f_{\text{sub}} \) is the construction cost of the substation; \( f_{\text{line}} \) is the construction cost of the line; \( f_{\text{EV}} \) is the construction cost of the charging station; \( \alpha \) indicates the annual value of construction cost, which can be calculated by equation (5):

\[
\alpha = \frac{r(1+r)^\gamma}{(1+r)^\gamma - 1}
\]

(1) Construction cost of the substation \( f_{\text{sub}} \)

Substation construction cost mainly includes the sum of substation construction costs at all nodes, as shown in equation (6):

\[
f_{\text{sub}} = \sum_{p \in \mathcal{P}} \chi_{\text{sub},p} \cdot f_{\text{sub},0} \cdot k_p
\]

where \( \mathcal{P} \) is the set of all nodes; \( \chi_{\text{sub},p} \) is a decision variable, 1 represents the construction of a substation at node \( p \), 0 represents don’t construction the substation at node \( p \); \( f_{\text{sub},0} \) is the unit capacity construction cost of the substation; \( k_p \) is the capacity of the substation constructed at the \( p \)-th node.

(2) Construction cost of the line \( f_{\text{line}} \)

The construction cost of the line mainly includes the sum of all line construction costs in the distribution network, as shown in equation (7):

\[
f_{\text{line}} = \sum_{i,j \in \mathcal{G}} \chi_{\text{line},ij} \cdot f_{\text{line},0} \cdot s_{ij}
\]

where \( \chi_{\text{line},ij} \) is the decision variable of the line between nodes \( i \) and \( j \), 1 represents a new feeder between the two nodes, 0 represents there is no new feeder between the two nodes; \( f_{\text{line},0} \) is the construction cost per unit length of the line; \( s_{ij} \) is the length of the line between node \( i \) and node \( j \).
Construction cost of the charging station ($f_{EV}$)

The construction cost of the charging station mainly includes the changing cost and the inherent cost of the charging station, as shown in equation (8):

$$f_{EV} = \sum_{q_{d\in d_{ev}}} \chi_{EV,q} \cdot f_{EV,q} + \sum_{q_{d\in d_{ev}}} \chi_{EV,q} \cdot f_{EV,1}$$

where the former is the changing cost of the charging station, which is directly proportional to the capacity of the charging station; the latter is the inherent cost of the charging station, which represents the cost of the land occupied by the charging station. $\chi_{EV,q}$ is the decision variable, 1 represents the construction of a charging station at the $q$ node, else it will be 0; $f_{EV,q}$ is the cost per unit capacity of the charging station; $E_{cap,q}$ is the installed capacity of the charging station; $f_{EV,1}$ is the inherent cost of the charging station.

3.1.2. Average Annual Operating Cost ($f^{op}$). The average annual operating cost includes the annual cost of grid operation and maintenance, the annual cost of charging station operation, and the annual cost of mobile energy storage to compensate users for EV, which are specifically expressed as:

$$f^{op} = f_{op\_sub} + f_{op\_EV} + f_{op\_c}$$

where $f_{op\_sub}$ represents the annual cost of grid operation and maintenance; $f_{op\_EV}$ represents the annual operating cost of the charging station; $f_{op\_c}$ represents the annual cost of user subsidies.

(1) Annual cost of grid operation and maintenance ($f_{op\_sub}$)

$$f_{op\_sub} = \sum_{i,j} \chi_{line,ij} \cdot \pi_{line,ij} + \sum_{i,j} \alpha_{line,ij} \cdot \pi_{line,ij} + \sum_{p} \chi_{sub,p} \cdot \pi_{sub,p}$$

where $\alpha_{line,ij}$ is the decision variable of the line between node $i$ and node $j$, 1 represents the existence of an inherent feeder between the two nodes, and 0 represents the absence of an inherent feeder between the two nodes; $\pi_{line,ij}$ is the annual operating cost of the line between node $i$ and node $j$; $\pi_{sub,p}$ is the annual operating cost of the substation constructed at node $p$.

(2) Annual operating cost of the charging station ($f_{op\_EV}$)

The annual operating cost of the charging station is mainly the maintenance cost of the charging facility, which is directly proportional to the capacity of the load in the charging station. Therefore, the annual operating cost of the charging station can be expressed as:

$$f_{op\_EV} = \sum_{q \in d_{ev}} \chi_{EV,q} \cdot \pi_{EV,q} \cdot P_{EV,q}$$

where $\pi_{EV,q}$ is the unit load cost of the charging station operation; $P_{EV,q}$ is the magnitude of the charging station load at the $q$ node, which can be expressed by equation (12):

$$P_{EV,q} = 365 \times \sum_{t=1}^{1440} E_m(t)$$

(3) Annual cost of user subsidies ($f_{op\_c}$)

$$f_{op\_c} = 365 \times f_c$$

3.2. Restrictions

In the collaborative planning model for charging stations and distribution networks that consider EV mobile energy storage, the charging and discharging of electric vehicles and the safe operation of the power grid are subject to multiple constraints.

(1) Power balance constraint
All nodes in the distribution network must meet the power balance constraints.

\[
P_i = U_i \sum_{j \in I_{node}} U_j \left( G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij} \right) \\
Q_i = U_i \sum_{j \in I_{node}} U_j \left( G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij} \right) \quad \forall i \in I_{node}
\]

(14)

where \( P_i \) and \( Q_i \) are injective active power and injective reactive power for node \( i \); \( G_{ij} \) and \( B_{ij} \) are conductance and susceptance on the line between node \( i \) and node \( j \); \( \theta_{ij} \) is the phase angle difference between node \( i \) and node \( j \).

(2) Node voltage constraints

For all nodes in the network, including load nodes and substation nodes, the voltage amplitude needs to be kept within the allowable range at each stage. In this section, the upper and lower limits of the voltage fluctuation of the load node are set to ± 5% of the rated voltage, and the rated voltage of the substation node is \( U_N \).

\[
0.95 U_N \leq U_i \leq 1.05 U_N \quad \forall i \in I_{node}
\]

(15)

(3) Logical constraint

Generally, a radial network is used, so the following constraints can be obtained: the generalized node connectivity; the number of distribution network lines should be equal to the number of nodes except the substation and the load nodes are connected to the network by only one branch. Specific radiation constraints are shown in equations (16) and (17).

\[
\chi_{node,i} \leq \sum_{i,j \in I_{node}} \chi_{line,ij} \leq A \chi_{node,i}
\]

(16)

\[
\sum_{j \in I_{node}} \chi_{line,ij} = \sum_{i \in I_{node}} \chi_{node,i} - \sum_{p \in I_{sub}} \chi_{sub,p}
\]

(17)

where \( A \) is a sufficiently large real number; \( \chi_{node,i} \) is a 0-1 decision variable, 1 means that the \( i \) load node is connected to the distribution network, and 0 means that the \( i \) load node is not connected to the system.

(4) Battery constraint

Battery constraints are mainly current constraints and capacity constraints. If the battery is charged / discharged with a large current in a short time, it will increase the loss and shorten the service life [12]. At the same time, deep charge and discharge will also exacerbate battery loss, and deep charge and deep discharge phenomena should be restricted during battery operation.

\[
-I_{bat, dis} \leq I(t) \leq I_{bat, cha}
\]

(18)

\[
S_{bat, min} < S_{OC}(t) < S_{bat, max}
\]

(19)

where \( I_{bat, cha} \) and \( I_{bat, dis} \) are respectively the maximum charge and discharge current of the battery; \( I(t) \) are the charge / discharge current of EV during \( t \) period; \( S_{bat, max} \) and \( S_{bat, min} \) are the upper and lower limits of the SOC of EV which are proposed to ensure the battery performance, the upper limit is set to 0.95, and the lower limit is set to 0.2 [13].

4. Case Study

In this paper, an 18-node distribution network system with EV loads is used for simulation and verification. The voltage level of the distribution network is 10 kV. The initial grid structure is shown in figure 2.
Figure 2. An 18-node distribution network system.

Among the distribution network, nodes 17 and 18 are substation nodes, and the remaining nodes are load nodes. Among the load nodes, candidate nodes for charging stations are 7, 10, and 12 nodes. The solid line indicates the inherent lines in the distribution network, and the dotted line indicates that feeders can be added. The load demand of each node [14] is shown in table 1.

Table 1. System load demand (MW).

| Node number | Peak period | Valley period | Node number | Peak period | Valley period |
|-------------|-------------|---------------|-------------|-------------|---------------|
| 1           | 1.2         | 0.24          | 9           | 2.4         | 0.48          |
| 2           | 1.2         | 0.24          | 10          | 2.4         | 1.2           |
| 3           | 1.2         | 0.24          | 11          | 2.4         | 1.2           |
| 4           | 1.2         | 0.24          | 12          | 1.2         | 0.24          |
| 5           | 1.2         | 0.24          | 13          | 2.4         | 1.2           |
| 6           | 1.2         | 0.24          | 14          | 2.4         | 0.48          |
| 7           | 1.2         | 0.24          | 15          | 2.4         | 0.48          |
| 8           | 1.2         | 0.24          | 16          | 1.2         | 0.24          |

The other model parameters [14, 15] involved in this example are shown in table 2.

Table 2. Planning model parameters.

| Parameter                           | Value  | unit     |
|-------------------------------------|--------|----------|
| Rated voltage (UN)                  | 10.38  | kV       |
| Transformer installation cost       | 20     | $/Tai    |
| Transformer rated capacity          | 8.5    | MVA      |
| Transformer power factor            | 1      | -        |
| New feeder cost                     | 1,5000 | $/miles  |
| Inherent cost of charging station   | 50,0000| $        |
| Changing cost of charging station   | 7,2500 | $/MW     |
| Original charging requirements      | 8.4    | MW       |
| Unit capacity subsidy electricity price b1, b2 | 0.3, 0.8 | $       |
| Planning period                     | 20     | year     |

The model established in this paper is a mixed integer linear programming model, and can be calculated by commercial mathematical programming software. Its built-in algorithm is based on the branch and bound principle, which can efficiently obtain the global optimal solution. This section uses the MATLAB programming environment, uses the YALMIP toolkit to define each decision variable,
enters the expressions of objective functions and constraints, and calls the mathematical optimization software CPLEX to solve. The distribution network planning structures without considering EV mobile energy storage and considering EV mobile energy storage are obtained respectively, as shown in figures 3 and 4. Figure 3 constructs charging stations at nodes 7 and 12, and figure 4 constructs a charging station at node 7.

**Figure 3.** Distribution network planning results without considering EV mobile energy storage.

**Figure 4.** Distribution network planning results when considering EV mobile energy storage.

Table 3 shows the results of the collaborative planning of the charging station and the distribution network in the case of EV mobile energy storage is taking into consideration or not.

|                  | \( f_{\text{line}} \) | \( f_{\text{EV}} \) | \( f_{\text{sub}} \) | \( f_{\text{op,sub}} \) | \( f_{\text{op,EV}} \) | \( f_{\text{op,c}} \) | \( f \) |
|------------------|------------------------|-------------------|-----------------|----------------|----------------|----------------|------|
| Without EV mobile energy storage | 10.580                | 8.046             | 5               | 1.6            | 19.565         | 0              | 44.791 |
| With EV mobile energy storage    | 9.563                 | 4.741             | 4               | 1.378          | 18.347         | 2.346          | 40.375 |

From table 3, we can know that:

1. Due to the exist of EV mobile energy storage, some EVs are subsidized and encouraged to move to other regions for charging or discharging with the grid when the grid is on load peaks, the total installed capacity of charging stations has decreased, and the number of charging stations has also been reduced from 2 to 1. So the inherent costs of charging stations have decreased, and the construction costs of charging stations have decreased.

2. The mobile energy storage of EV reduces the total load of the power grid during peak period, the number of matched transformers can be reduced, and the cost of substation construction is reduced. At the same time, the cost of grid operation and maintenance also be reduced because it’s relevant to the cost of substation and line construction.

3. Because some EVs are transferred to other areas for charging, the total charging load of the charging station decreases within one day, and the operating cost of the charging station is reduced;

4. Although there is a need to subsidize EV users due to the mobile energy storage of EV, the increased subsidies for mobile energy storage account for a small proportion of the overall construction of the distribution network. Considering the situation of mobile energy storage, the total cost of the charging stations and distribution grid collaborative planning is lower than the total cost without considering mobile energy storage.

5. **Conclusion**

This paper proposes a charging station and distribution network collaborative planning model while considering EV mobile energy storage, and optimized the model. Comparing the model with EV mobile energy storage or not, the conclusions of the study are as follows: Through the electricity price subsidy, EV owners respond to the electricity price subsidy and consider the state transfer of EV under mobile energy storage. It can transfer part of the charging load to other areas and can discharge to the
grid when the grid in load peak periods. Therefore, the cost of mobile energy storage subsidies has increased, but overall planning costs are still falling.

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