User Compensation Mechanism and Benefit Analysis under Orderly Charging Mode

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Abstract. With the vigorous promotion of national and local policies, the number of electric vehicles has been greatly increased, and orderly charging has gradually become an effective means to relieve the pressure of charging and capacity. In order to enhance the participation of charging load aggregators and charging users, improve the effectiveness of orderly charging, and realize the win-win situation between the aggregators and users, in this paper, firstly, the analysis of charging station benefit model is carried out from two aspects of charging station operation cost and compensation price, and then the user charging supplement mechanism based on response mechanism is studied and finally through simulation examples, different scenarios of charging equipment utilization are set, and the benefits of charging load aggregators and charging users are analysed, which provides suggestions for charging load aggregators to choose appropriate user compensation scheme under orderly charging mode.

1. Introduction

The electric vehicle industry is developing rapidly by virtue of its advantages in environmental protection, energy saving, emission reduction, and low energy consumption. With the support of relevant government support policies, the construction of charging facilities has been promoted on a large scale, and electric vehicles have achieved large-scale promotion and application across the country [1]. However, the mismatch between the construction of distribution network and the popularization of EV brings great pressure and instability to the operation of the power system. For this reason, people use various methods to evaluate and regulate the impact of electric vehicles connected to the grid. At present, most of the existing researches improve the acceptance of distribution network by improving the time sequence characteristic of EV loads. How to consider users' willingness to choose other charging periods to reasonably simulate the limitations and probability of EV users' charging period transfer is the key problem. The literature [3] based on the summarizing of influencing factors of charging load and the influence of its access to the grid system, the charging load regulation method and the charging model of optimal economic operation are analyzed. In the literature [4], the minimum which combines the distribution network load variance and the deviation of the scheduling plan of upper and lower layers is the upper target, and the charging time and cost of the EVs are the lower targets. The double-layer optimization model of the EV charging station with multiple charging modes is established. In the literature [5-6], an orderly charging strategy of EVs based on the
characteristics of driving behavior of users is proposed, and the charging behavior of EVs is scheduled according to the calculation of the charging amount of each charging and the load curve of local distribution network. Literature [7] based on the deterministic analysis method and the reverse recursion principle, a control method which realizes the orderly charging of the EV group without collecting the state of charge of the EV battery is studied. So far, the theoretical research on the orderly charging of EVs mainly focuses on the regulation strategy of orderly charging. There are few literatures on the incentive mechanism of economic return of users and the strategy of demand respond of users, and even some researches on control decision ignore the subjective intention of users.

In order to explore the regulation function of the orderly charging response and return strategy of electric vehicle users in the electricity market, further, this paper firstly establishes the operation mode of electric vehicles participating in the electricity market under the conditions of fully considering the advantages of electric vehicles. Then, the cost and benefit of price compensation of operators are analyzed, and the price compensation mechanism and two-layer optimization model of charging users are established accordingly. Finally, combined with actual calculation examples, the effectiveness of this method is verified.

2. Operation Mode of Electric Vehicles Participating in Power Market

Different from the operation mode of “profit from price difference by unified purchase and sale” in the previous market mode, the open electricity sales market under the background of power market reform has joined a new market transaction subject, which is power sales company. Because of the large number of power selling companies, it can fully mobilize the market competition consciousness of the generation and the user. In this mode, the multi-directional trading options around the power selling companies are mainly reflected in the fact that the consumers can freely choose the power selling companies, and the power selling companies can purchase electricity from different power suppliers in various ways. The operation mode of power market is shown in figure 1.

![Figure 1. Operation mode of electric vehicles participating in power market](image)

As a new consumer in the power market, the inherent characteristics of electric vehicles can provide support conditions for them to participate in electricity market-oriented transactions. Compared with other demand side resources, electric vehicles have certain advantages in response time, response reliability, response controllability and energy saving and emission reduction effect, as shown in table 1.

| Characteristic | Response time | Response reliability | Response economy | Response controllability | Energy saving and emission reduction |
|---------------|---------------|----------------------|------------------|--------------------------|-------------------------------------|
| Electric vehicle | longer commonly | high | commonly good | easy | excellent |
| Others | commonly | low | good | difficult | good |
The main modes of electric vehicles participating in the electricity market include direct access and indirect access shown in figure 2. Electric vehicles directly participate in the power market, and the charging and discharging of electric vehicles are directly controlled by the power grid as the main operation body. On the one hand, it can improve the stability of the power grid operation and promote the consumption of renewable energy; on the other hand, when the power grid is abnormal, it can respond to the power grid more quickly and reliably, but it also increases the complexity of the grid operation. Electric vehicles indirectly participate in the power market, through the control of the third-party operators, not only can fully absorb renewable energy, but also has strong controllability. It can achieve hierarchical optimal dispatching with the power grid, reduce the pressure of power grid operation and management, which is in line with the trend of power market reform, and is the main direction of electric vehicles participating in the power market.

Figure 2. Operation mode of electric vehicles participating in electricity market

3. Analysis on Benefit and Cost of Operator’s price compensation

In order to improve the benefits of charging stations and achieve a win-win situation for users and charging stations, the charging operators need to ensure the operating benefits of charging stations, calculate the profit margins and payback periods of the charging stations, and then determine on the basis of the profitability requirements of the charging stations The upper limit of the incentive compensation price lays the foundation for formulating a reasonable incentive and compensation mechanism for users.

3.1 Operating Benefits of Charging Station

In the context of power system reform, if the users’ incentive compensation expenditure is not considered, the annual profit of the charging station \( G_{\text{ev}} \) is the total revenue of the charging station minus the investment cost \( G_{\text{evco}} \), plus the government environmental subsidy \( S_{\text{ev}} \). The operating income of charging stations generally includes four aspects: purchase and sale of electricity revenue \( I_e \), charging fee income \( I_e \), advertising revenue \( I_v \) and consumer cooperation dividends \( I_c \). Purchase and sale of electricity revenue \( I_e \) means that large charging stations can be used as large customers in the electricity market to purchase electricity directly from power generation companies, and then develop a unified charging price plan for users, sell them to users in the form of basic electricity prices, and obtain some income from them. The main form of charging fee income \( I_e \) is charged by charging service fee. In addition to the basic electricity fee, EV users pays the charging service fee when charging the public charging facility. The charging limit fee per kWh is subject to local regulations. The income of the charging fee of charging station is related to the charging power of the charging station. Advertising revenue \( I_v \) and consumer cooperation dividend \( I_c \) are the profit points derived from the charging station[8].
\[G_{evo} = I_e + I_a + I_d - C_{evo} + S_{ev}\]

\[I_e = \sum_{y=1}^{n_y} \sum_{t=1}^{n_t} \left[ h_{y,t}^c L_{y,t} - \varepsilon h_{y,t}^c L_{y,t} - \xi h_{y,t}^c L_{y,t} \right]
\]

\[I_e = \sum_{y=1}^{n_y} \sum_{t=1}^{n_t} (L_{y,t} \times f_t) \tag{1}\]

Where, \(h_{y,t}^c\) is the day-ahead price of electricity sold during the period \(t\) of the day \(y\); \(h_{y,t}^c\) is the purchase price of electricity in the medium and long-term contract market; \(\alpha (\omega + \xi = 1)\) is the proportion of electricity purchased in the medium and long-term contract market; \(L_{y,t}\) is the total number of charging power of the charging station during the period \(t\) of the day \(y\) kWh; \(n_y\) is the charging amount of the charging station during the period \(t\) on the day \(y\), kWh; \(f_t\) is the charging service fee of the station, RMB/kWh.

### 3.2 Operating Cost of Charging Station

The cost of investing an EV charging station \(C_{evo}\) is mainly composed of three parts: infrastructure cost \(C_b\), distribution facility cost \(C_o\) and operating cost \(C_o\).

\[\begin{align*}
C_{evo} &= C_b + C_o + C_o \\
C_b &= \gamma C_{rland} + \eta C_{bland} + C_{install} + \xi C_{char eq} + n_m \times C_{moneq} \\
C_o &= \xi C_{battm} + C_{distm} + n_e \times C_{emp}
\end{align*}\]

Where, the infrastructure cost \(C_b\) is composed of land lease/acquisition cost \(C_{land}/C_{bland}\), equipment construction cost \(C_{neq}\) and installation cost \(C_{install}\), charging equipment cost \(n_e \times C_{char eq}\), charge monitoring and safety monitoring equipment cost \(n_m \times C_{moneq}\). \(\gamma = 1(\eta + \xi = 1)\) indicates that the charging station chooses to rent a site to build a charging station, and lease fees are paid annually or monthly; \(\eta = 1\) means to purchase the charging station site, pay the site fee of the upfront investment; if the site ground is natural ground, you need to add the site leveling and curing costs to the land lease/purchase cost \(C_{palt}\); \(C_{char eq}\) and \(C_{moneq}\) indicate the unit price of the charging device and the monitoring device respectively; \(n_e\) and \(n_m\) indicating the number of charging devices and monitoring devices respectively. The cost of distribution facilities \(C_o\) consists of box-type substation costs \(C_{sub}\), user distribution cabinet costs \(C_{cabinet}\), and cable costs \(C_{cable}\). The operating cost of the charging station \(C_o\) is composed of battery maintenance equipment and maintenance costs \(C_{battm}\), maintenance costs of distribution facilities \(C_{distm}\), and staff costs within the station \(n_e \times C_{emp}\). Besides, \(n_e\) is the number of employees in the station, \(C_{emp}\) is the annual salary of the employees; the maintenance cost of the
distribution facilities can be 3% of the distribution cost.

4. Charging User Compensation Mechanism and Model

4.1 Price Ceiling of Compensation

Charging operators should determine the user incentive compensation price in case that their own revenue is guaranteed. According to the operating benefits and costs above, the payback period $T_f$ of the charging station can be estimated.

$$0 \leq q \leq f_s - \left( C_{ecco} / T_f + C_{ecco} - S_{ev} - I_s - I_e \right) / \left( \sum_{y=1}^{y_n} \sum_{x=1}^{x_n} L_{x,y} \right)$$

Where, $f_s$ is the service charge, RMB/kWh; $q$ is the user incentive compensation price, RMB/kWh.

4.2 Compensation Price of Response

The compensation amount is determined by the responses that the users participate in. This paper defines the responses of users’ participation compensation mechanism as $K$ and defines the user compensation price amount as $D$.

$$D = \sum_{m=1}^{M} \left[ K_m \times q_m \right]$$
$$K = \sum_{t=1}^{T} \left( \beta_t \times p_t \times \Delta t \right)$$

Where, $\beta_t$ is the compensation coefficient of the user charging during the period $t$, the value of which is determined by the operator and adjusted according to the electricity price trend. Generally, the compensation coefficient of the lower electricity price period is higher. At non-compensation period, $\beta_t = 0$, and $\sum_{t=1}^{T} \beta_t = 1$. $p_t$ is the charging power during the period $t$. $M$ is the number of intervals to divide the response $K$; $q_m$ is the compensation price of each response interval.

4.3 Bi-level Optimal Model of Compensated Excitation

In order to ensure that operators and users can maximize their own interests in the market transaction process, that is, operators pursue the shortest investment recovery time for charging stations, while users pursue the maximum compensation income.

4.3.1 Optimal Objective. For operators, Minimum payback period of charging station:

$$\min \ T_f = \frac{C_{ecco} / (I_s + I_e + I_e - C_{ecco} + S_{ev} - D_{evo})}{}$$

Where, $D_{evo}$ is the annual expense of users’ compensation, and the annual compensation expense of the charging station can be calculated by accumulating the compensation amount of EV users: $D_{evo} = \sum_{U} D_v \times U$ is the total number of charging services provided in the station every year; $D_v$ is the compensation amount that users can get after each charging response.

The users aim at the maximum compensation amount after response: max $D$.

4.3.2 Constraints. In order to fit the actual charging scenario, this model restricts the charging power of EVs further while ensuring the charging demand of EVs.
\begin{equation}
\begin{cases}
0 \leq p_i \leq p_{ni} \\
Soc_u = Soc_0 + \eta \sum_{i=1}^{n} p_i / E_i \geq Soc_{\text{exp}}
\end{cases}
\end{equation}

Where, \( p_i \) is the actual charging power of EV, kW; \( p_{ni} \) is the rated charging power of EV, kW. \( Soc_u \) is the actual state of charge of the battery when the EV leaves the charging station; \( Soc_{\text{exp}} \) is the expected battery state that the EV user expects to achieve through this charging; \( Soc_0 \) is the initial state of charge; \( \eta, E \) are the charging efficiency and rated capacity of battery respectively.

5. Illustrative example

5.1 Parameter Settings

Taking a public charging station in a certain area as an example, a charging scene simulation is performed. Analyze the investment cost and operating income of the charging station and formulate the user charging compensation strategy.

The charging station is equipped with 30 sets of 10kW AC charging piles, while \( n_i = 3, \gamma = 1, n_i = 30, n_j = 1, n_u = 2, n_r = 365, n_r = 24, \eta = 0.9, f_p = 0.6 \text{ RMB/kWh} \). This example does not consider the advertising revenue and consumption cooperation dividend of the charging station, \( I_0 = 0, I_v = 0 \).

From May 2019, the Guangdong electric power spot market began to operate and pre-settled in the spot market. The value of the electricity price on May 15th are selected as the day-ahead electricity price \( h_i \). The value of the above day real-time electricity price is taken as the electricity purchase price. The specific values are shown in the figure 3:

![Figure 3. Operation mode of electric vehicles participating in electricity market](image)

5.2 Result Analysis

The investment cost is calculated according to the operation benefit model. At present, many charging stations are jointly constructed by power grid and the government. The land acquisition or lease costs are low. Assuming that the unit price of land lease for the construction of charging stations is 360 RMB per square per year. The residual value of equipment for charging facilities and distribution facilities is 5%.
The depreciation period of charging, monitoring equipment and power distribution equipment is 6, 3 and 10 years, respectively. Depreciation of fixed assets and annual cost are obtained. The specific calculation results are shown in the table 2:

| Specific cost | Annual expenditure | Fixed assets | Annual cost after depreciation |
|---------------|--------------------|--------------|--------------------------------|
| $C_{\text{land}}$ | 17.2               | --           | 17.2                           |
| $C_{\text{pool}}$ | --                 | 9.5          | 1.0                            |
| $C_{\text{net}}$ | --                 | 15           | 2.3                            |
| $n_{1}C_{\text{dev}}$ | --                | 15           | 2.1                            |
| $n_{2}C_{\text{rev}}$ | --               | 4            | 1.1                            |
| $C_{\text{cap}}$ | --                 | 70           | 4.7                            |
| $C_{\text{op}}$ | --                 | 25           | 1.7                            |
| $C_{\text{sec}}$ | --                 | 40           | 2.0                            |
| $C_{\text{cm}}$ | 0.4                | --           | 0.4                            |
| $C_{\text{sale}}$ | 10                 | --           | 10                             |
| $C_{\text{op}}$ | 20                 | --           | 20                             |
| **Total**     | 57.1               | 108.5        | 62.5                           |

It is estimated that the total cost of investment in the construction of a charging station equipped with 30 sets of 10kW AC piles is about 625,000 RMB per year.

According to the optimization model of users charging compensation, the charging process of EVs is simulated, and the compensation coefficient of each period in combination with the trend of electricity price are determined. The specific values are shown in the figure 4:

As can be seen from the above figure that the non-compensation period is the peak period of power consumption. If the user chooses to charge during this period, they will not get corresponding compensation. During the period of power consumption, the value of the compensation coefficient corresponds to the level

![Figure 4. Compensation Coefficient](image-url)
of the electricity price. The compensation coefficient of charging at 05:00~07:00 in the morning reaches 0.9, so the responding user can obtain higher rebate.

The simulation results show that when the utilization ratio of charging pile $\alpha$ is less than 0.35, the charging station cannot achieve profit. In this paper, three charging scenarios are set, and the compensation price is solved when the utilization ratio of charging post $\alpha$ is $\alpha=0.4$, $\alpha=0.5$ and $\alpha=0.6$ respectively. The specific results are shown in the table 3:

| $\alpha$ | Compensation price $q_m$ | Example objective optimization result |
|----------|--------------------------|--------------------------------------|
|         | $q_1$ | $q_2$ | $q_3$ | $q_4$ | $\min T^*_n$ (years) | $\max D$ (RMB) |
| 0.4      | 0.1   | 0.2   | 0.4   | 4.3   | 2.2                   | 0.4              |
| 0.5      | 0.2   | 0.3   | 0.5   | 2.1   | 4.8                   | 0.5              |
| 0.6      | 0.2   | 0.4   | 0.6   | 1.3   | 7.9                   | 0.6              |

The operator of the charging station can choose the corresponding compensation scheme according to the average utilization rate of the charging piles in the station.

6. Conclusions

In this paper, the operation mode of electric vehicles participating in the power market is analyzed, and the cost and benefit of price compensation for operators are comprehensively analyzed based on the indirect mode. On this basis, the price compensation mechanism and optimization model of charging users are elaborated and established, and the effectiveness of the optimization method in this paper is verified by a calculation example, which has reference value for the regulation and application of electric vehicles in the power market.

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