Research on Interruptible Load Management of Electric Vehicle Charging Considering Price Risk

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Abstract. The rapid development of electric vehicle industry promotes the construction of charging infrastructure and charging station. In the operation of charging station, how to ensure the stable profit of charging equipment under the condition of excessive charging load has become a crucial issue. Based on this, this paper focuses on how charging stations sign interruptible load contracts with users during peak load period and consider their risk coefficients to formulate optimal competition strategies so as to maximize expected profits. Finally, the problems and conclusions are summarized.

1. Introduction

1.1. The rapid development of electric vehicle industry and the construction momentum of charging facilities are vigorous.

Rising environmental problems and declining oil reserves have forced the development direction of vehicles to change, and the production and development of electric vehicles have begun to enter the stage of industrialization [1]. In 2015, China's production and sales of electric vehicles surpassed that of the United States and leapt to the top of the world. In order to promote the popularization of new energy vehicles, the Chinese government and local governments, automotive enterprises, electric power enterprises, charging operation enterprises and other enterprises vigorously develop charging infrastructure for new energy vehicles, which is the premise and cornerstone of the development of electric vehicles. However, the construction of charging infrastructure for electric vehicles is currently under way. The whole is still in its infancy. The state has promulgated the supporting policies of charging infrastructure for electric vehicles intensively from top-level design, construction incentives, preferential tariffs, industry management and other aspects. Local governments actively cooperate with national requirements and have issued implementation plans successively. The aim is to form a charging infrastructure system with advanced, rational layout and intelligent and efficient charging, so as to maximize the charging demand of charging vehicles and promote it. The development of charging infrastructure market has also created a new round of development opportunities for the development of charging stations. [2].

By the end of 2016, 141,000 public charging piles had been constructed and operated. Compared with the net increase of 49,000 by the end of 2015, China has the largest number of public charging facilities in the world. As of September 2017, the number of construction and operation of public charging piles in China totaled 190,600, an increase of 44,253 compared with the end of 2016. The rapid development of the industry has accelerated the layout of the charging infrastructure industry chain. The charging infrastructure market has huge business opportunities. [3] As electric vehicles enter the
initial stage of industrialization, the number of electric vehicles and charging infrastructure will grow rapidly in the future, and the charging demand of electric vehicles will increase accordingly, which will promote the rapid development of charging stations. [4-5].

1.2. Incentive interruptible load management provides an effective method for power supply design of charging stations
Interruptible load management (ILM) is a typical demand response. On the one hand, power companies give users certain incentive signals. By signing interruptible contracts, customers respond to the instructions of power grid dispatch during peak period of power consumption and implement short-term outages with specified time and capacity to reduce load peaks and ensure the balance of supply and demand of power grid [6]. Because ILM has the characteristics of notifying users in advance of the interruption time and relieving the power supply pressure during the peak load of the system, it can improve the power supply reliability of the system. Therefore, it can serve as a backup resource in the auxiliary service market and provide auxiliary services to the system through quotation just like the power plant [7-8]. Incentive interruptible load contract is a common tool for power companies to sign contracts with private parties. It can effectively alleviate the pressure of power grid and ensure the balance between supply and demand of power grid, and reduce the economic losses and social impact caused by power shortage. [9-10]. The existing research can be used as a reference for the charging mechanism of EV, but the previous research on incentive interruptible load management rarely mentions its application in the field of EV charging. Therefore, this research has great significance in the field of EV incentive interruptible load management.

1.3. Design of Incentive Interruptible Load Contract for Electric Vehicle Charging Station
The ILM contract between the charging station and the users of electric vehicles includes the distribution of interruptive load and compensation payment of the charging station. In order to realize the effective utilization of electric power resources in electric vehicle charging stations, electric vehicle charging stations need to know the true information about the cost of power shortage for electric vehicle users. However, in the actual market environment, charging station companies can only rely on survey information and automobile users' reporting information to determine the distribution of interruption load, so it may be difficult to achieve efficient distribution of electricity. Therefore, when determining the compensation and payment mechanism for interruption load, the incentive function of this mechanism for users to voluntarily disclose their true power shortage cost information should be fully considered. If users disclose their true cost information of power shortage to maximize their expected profits, the interruption compensation payment mechanism has incentive compatibility characteristics. This chapter will discuss how to introduce incentive interruptible load contracts and the significance of contract introduction in the charging industry of electric vehicles from the perspective of charging stations of electric vehicles.

As an electric vehicle charging station, it should deal with the following problems: on the one hand, the charging station of electric vehicle has to face the real-time fluctuation of the electricity price provided by the charging station; On the other hand, facing customers, we need to think about how to provide stable and reliable electricity for charging users, while bringing risks, it may also bring profit opportunities to electric vehicle charging stations by taking advantage of fluctuations in market prices. Therefore, we need a tool to avoid market risks or profits.

The interruptible load contract is signed by the charging station and the electric vehicle user. During the peak period of passenger flow, when the power system of charging station is overloaded or the charging plug is insufficient, the charging station will be interrupted or the charging time will be changed in consultation with the users, but the charging preference or economic compensation will be given to the users. If the appropriate charging preference can alleviate the pressure brought by the peak period of charging station, the users of electric vehicles will be encouraged to reduce the charging and improve the demand side when the electricity price is higher in the peak period. At the same time, the charging station can avoid market risks and save the power cost of the charging station.
2. Interruptible Load Contract Model of Charging Station Considering Price Risk

The cost of charging station is divided into two parts, one is the cost of electricity, Charging Station Purchase Price in \( P_C \), we use \( \beta \) to represent transmission and distribution costs and operating costs. At peak load, the available capacity of the power grid decreases, transmission and distribution costs rise sharply. In addition, the supply of the wholesale market is tight, and the electricity price rises. The fixed electricity price may lead to the loss of the charging station at peak load. If at this time the charging station uses interruptible load contract to reduce part of the load \( x \) to reduce cost, But it needs to give users some economic compensation \( S \), Then \( U_x \) can be calculated as

\[
U_x = \beta x + P_C x - S
\]

Assuming that an electric vehicle charging users and charging stations sign interruptible load management contracts, charging stations are faced with the risk of changing the purchase price when the contract is signed. The electricity price of charging stations is assumed to be logarithmic normal distribution. \( P_C \sim \log N(\ln P_C, \sigma_C^2) \), When the electricity price of the charging station is fixed, the cost can be saved by reducing the load of the charging station to the charging user. In disguise, the charging station is equivalent to increasing revenue. The expected variance is regarded as the risk of price change faced by the charging station, and the deterministic equivalent revenue of the charging station can be expressed as follows:

\[
U'_x = E(\beta) + \frac{1}{2}tE[U_x - E(U_x)]^2
\]

\[
= \beta x + P_C x + \frac{1}{2}t \sigma_x^2 - S
\]

\( t \) represents the risk preference coefficient of the charging station, When \( t \in (0,1] \), charging station is risk-driven; When \( t = 0 \) time, Charging station is risk neutral, When \( t \in [-1,0) \), Charging Station is Risk Avoidance Type.

When the charging station does not provide power to specific users or cuts load \( x \) in a certain period of time, automobile users will incur corresponding power shortage cost, which is proportional to the square of load interruption. By introducing the user type parameters \( \omega \), the power shortage cost function of the user can express the power shortage cost formula as follows:

\[
C(x, \omega) = ax^2 + bx - b\omega
\]

\( a, b \) Are constants, \( \omega \) is the type of electric vehicle users, \( \omega \in [0,1] \). The larger the \( \omega \), the lower the cost of power shortage, and the higher the value of power stopping for charging stations; conversely, the higher the cost of power shortage, the lower the value of power cut-off for charging stations.

If the charging user is risk neutral, the utility function is:

\[
U_C = S - C(x, \omega)
\]

Set the value of \( a, b \) and the type of typical users of class \( I \), and arrange the user types of charging stations in order from small to large as \( \omega = (\omega_1, \omega_2, \omega_3, \ldots, \omega_I) \). Estimate the probability that user \( i \) belongs to a certain user type \( \omega_i(i) \) is \( P_i(i) \). Then the user's type characteristics can be expressed as
When charging stations sign contracts with charging users, the expected goal is to maximize revenue. To encourage owners to participate, the interruptible load management provided by charging stations should simultaneously satisfy the profit maximization of charging users who sign contracts with charging stations (the principle of personal rationality); at the same time, the profit of disclosing their true information after users' participation is greater than that of the original strategic report. Household Profit (Incentive Compatibility Principle). In summary, the possible choice of user $i$ cannot be greater than the type of user set up, and its contract model can be described as

$$\text{Maximize } \sum_{i=1}^{I} \left[ \beta x_i(i) + \overline{P}_c x_i(i) + \frac{1}{2} t x_i(i) \sigma_c^2 - S_i(i) \right] P_i(i)$$

(5)

Constraint is

$$\text{s.t. } S_j(i) - (a x_j^2(i) + b x_j(i) \omega_j(i)) \geq 0, \forall I$$

$$S_j(i) - (a x_j^2(i) + b x_j(i) \omega_j(i)) \geq S_k(i) - (a x_k^2(i) + b x_k(i) \omega_k(i))$$

(6)

$$S_j(i) - (a x_j^2(i) + b x_j(i) \omega_j(i)) \geq S_k(i) - (a x_k^2(i) + b x_k(i) \omega_k(i))$$

(7)

$x_j(i), x_k(i)$ Represents the load reduction of the charging station to the charging user, $S_j(i), S_k(i)$ represents the compensation of charging station for charging user $i$. The two constraints are individual rational constraints and incentive compatibility constraints.

2.1. Solution method for model

Suppose the user's $U$ function is defined in the space of configuration $(x,s)$ and the space of user type $\omega$, Expressed as $U(x,s,\omega)$. $\forall (x,s,\omega)$, User utility functions satisfy the following properties

$$\frac{\partial}{\partial \omega} (U_x) > 0$$

(8)

Formula (7) can be reduced to

$$S_j(i) - a x_j^2(i) + b x_j(i) - b x_j(i) \omega_j(i) \geq S_{j-1}(i) - a x_{j-1}^2(i) + b x_{j-1}(i) - b x_{j-1}(i) \omega_j(i)$$

$I = (2,...N)$

(9)

Formula (9) Indicates that when a user reports his or her user type, the maximum profit is the profit under his or her real type, so it satisfies the global constraint, that is, when the user reports the real type, the utility reaches the maximum.

In the face of inequality (6) and (9) constraints, charging stations are required to maximize their equivalent utility, that is, to minimize expenditure when a certain load is interrupted. Under the condition of complete information described, all charging users who sign interruptible load contracts with charging stations can only get compensation equal to the cost of power shortage, and its utility is 0. Under the condition of incomplete information, the charging station cannot know the true type of users, so that charging users have a great advantage in information. How to motivate users to disclose the true information needs to pay a certain incentive fee. The incentive fee is the money paid by charging stations in order to attract users beyond the cost of power shortage. Therefore, when establishing incentive
contract model, on the one hand, we should satisfy users' needs, encourage users to disclose their true
types, on the other hand, we should try our best to control the expenditure of incentive fees and pay as
little incentive fees as possible. From equation (9), it can be seen that for the user type \( \omega_1 \) with the
highest cost of power shortage, the payment for it is less than that for other user type with lower cost,
which happens to be the cost of power shortage, and it can be deduced as follows:

\[
S_1(i) = ax_1^2(i) + bx_1(i)(1 - \omega_1(i)) + b \sum_{k=1}^{I-1}(\omega_{k+1}(i) - \omega_k(i))x_k(i), (I = 2, ..., N)
\]  
(10)

From the formula (10), (11), we can see that for the user type \( \omega_1 \) with the highest power shortage
cost, The lowest value for charging station is to stop power supply, and the incentive fee is 0. The higher
the type of user, the lower the cost of power shortage and the higher the benefit of power outage. The
more user types that users choose downward strategically, the more incentive fees they need to pay for
charging stations.

By substituting formulas (10) and (11) into formulas (5), the optimal solution brought into the model
is obtained, that is, the optimal load reduction scheme of charging station for users is as follows:

\[
x_i(i) = \frac{(\beta_I + P_c)P_i(i) - b[(1 - \omega_i(i))P_i(i) + (\omega_{I+1}(i) - \omega_i(i))]\sum_{k=I}^{I}P_k(i)}{(2a - t\sigma^2)P_i(i)}
\]  
(12)

As can be seen from the formula, for risky charging stations, the risk preference coefficient \( t > 0 \),
the higher \( t \) is, the higher the degree of risk and enterprise is. On the contrary, the smaller \( t \) is,
the lower the degree of risk and enterprise, and the lower the expected interruption load. For risk-averse charging
stations, Risk preference coefficient \( t < 0 \), the smaller \( t \) is, the higher the degree of risk avoidance and
the less the expected load interruption. On the contrary, the larger \( t \) is, the lower the degree of risk
avoidance and the higher the expected interruption load. When the purchase price fluctuates more, when
the price fluctuation of electricity purchase is larger, that is, \( \sigma^2 \) is larger, the less the expected load
interruption of the risk-averse charging station is, the higher the load interruption of the risk-aggressive
charging station is. Aggressive charging stations may earn higher incomes but face greater market risks.

3. Examples illustrate

| Type/ user | 0.1 | 0.3 | 0.5 | 0.7 | 0.9 |
|-----------|-----|-----|-----|-----|-----|
| 1         | 0.6 | 0.3 | 0.1 | 0   | 0   |
| 2         | 0.3 | 0.5 | 0.2 | 0   | 0   |
| 3         | 0.1 | 0.3 | 0.3 | 0.2 | 0.1 |
| 4         | 0   | 0.3 | 0.4 | 0.3 | 0   |
| 5         | 0   | 0   | 0.6 | 0.3 | 0.1 |
| 6         | 0   | 0   | 0   | 0.5 | 0.5 |
Five users are set to participate in the interruptible load contract. According to the survey data of power shortage cost of users, the coefficient of power shortage cost function of charging users is set to $a = 0.014 \text{RMB/(kW)}^2 \cdot h$, $b = 0.26 \text{RMB/(kW)}^2 \cdot h$, Five Typical User Types for Setting up Charging Station: 0.1, 0.3, 0.5, 0.7, and 0.9. Determine the characteristics of user types among different users, and evaluate the probability that each user belongs to a certain user type. As shown in Table 1, the purchase price of electricity conforms to the lognormal distribution, $P_t \sim \logN(\ln 0.61, 0.05^2)$, The risk preference coefficient of charging station is 0.5, the cost $\beta$ of power supply per unit of electricity for different users is respectively 0.1, 0.07, 0.16, 0.14, 0.08, 0.15 $\text{RMB/KWh}$. If the true type of each user is 0.1, 0.3, 0.5, 0.7, 0.9, the types of possible strategic reports and the profits that each user can obtain are shown in Table 2.

**Table 2. User Profit of Contract Scheme Provided by Power Supply Company under Five User Types (RMB)**

| User Profit | 0.1 | 0.3 | 0.5 | 0.7 | 0.9 |
|-------------|-----|-----|-----|-----|-----|
| 1           | 0   | -4.56 | -8.97 | 0   | 0   |
| 2           | 0   | 0   | -3.10 | -1.45 | 0   |
| 3           | 0   | 0   | -6.35 | -7.46 | -15.21 |
| 4           | 0   | 0   | 5.65 | 0   | 0   |
| 5           | 0   | 0   | 5.43 | 3.39 | 6.76 |
| 6           | 0   | 0   | 13.89 | 12.76 | 15.21 |

From this table, it can be seen that when the user chooses the contract of his real user type, he will not actually bring about a decrease in personal profit. But when the user chooses the contract strategically, the user's profit is negative. Therefore, it can be considered that the user's best choice strategy is to choose the contract of the real user type.

**4. Conclusion**

In view of the market risk and power outage strategy faced by charging stations, this chapter considers the risk preference of charging stations and the maximum utility of contracts. Based on the basic principles of mechanism design theory, a different type of incentive interruptible load contract model for users is proposed. The research shows that the incentive interruptible load contract can improve the demand elasticity of users and help to ensure the power security and utility maximization of charging stations during peak charging period. Regardless of the risk preference of the charging station, the contract model can encourage users to disclose their true information, so as to realize the effective allocation of power resources, and the charging station can save costs and gain profits from it. Especially the risky charging station expects to interrupt more load. The incentive interruptible load contract will become an effective tool for market competition and risk management.

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