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RESEARCH ON CHARGING USER DISCOUNT REBATE AND RESERVATION PRIORITY STRATEGY FOR ELECTRIC VEHICLE ACCESS

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ABSTRACT

Path anxiety is a major problem for electric vehicles, and charging infrastructure is indispensable to solve this problem. How to guide an electric vehicle to the optimal charging facility is a problem worth studying. This paper proposes a charging user discount rebate and reservation priority strategy for large scale electric vehicles (EV) access. First of all, the response characteristics of EV users to the discounts and reservation strategies of charging stations are analyzed and the user satisfaction decision model including economic satisfaction and reservation satisfaction is established. Secondly, the charging station benefit model with the goal of maximizing the benefits of the charging station is established. Eventually, the effectiveness of the proposed model is verified by a simulation considering two types of charging stations. The simulation is solved by using genetic algorithms (GA) and the simulation results show that the strategy can effectively attract users to charge and improve the interest of the charging station, as well as improve user satisfaction.

Keywords: electric vehicles (EV), Charging Strategy, User Satisfaction, Discount, Genetic Algorithm (GA)

1. INTRODUCTION

With the deepening of the global energy crisis, the depletion of petroleum resources and the danger of air pollution have intensified, so EVs have received more and more attention. Although EVs are effective measures to solve these crises, the short mileage of EVs and the shortage of charging stations have become the main concerns for people to purchase EVs. Therefore, solving and optimizing the charging problem of EVs is a key issue in the process of promoting EVs.

Many researchers have studied the charging process of electric vehicles. Based on the Dijkstra algorithm, the improved Dijkstra algorithm combined with simulated annealing algorithm and the road segment weights was proposed to solve the path planning problem, respectively [1-2]. An EV charging demand model based on Agent-cell automata was proposed, and the path planning problem was solved by the correlation algorithm of the cell layer [3]. In literature [4], Time-of-use (TOU) price mechanism was introduced, and the EV path planning model based on the optimal travel time of the user and the optimal charging cost was established. However, these scholars only make path planning from the least time or the shortest distance, without considering multiple factors and user satisfaction.

Some researchers studied the reservation process of charging for electric vehicles. An EV charging reservation strategy based open charge point protocol (OCPP) was proposed [5]. Users could reserve charging stations in advance to negotiate charging parameters, so that customers can control the process of reserving and charging. Considering the demand of EV orderly charging and user self-selection response, a scheme based on EV time-sharing reservation charging was proposed combined with time-of-use price period division and local area distribution fluctuation [6]. Literature [7] analyzed the potential problems of EV reservation charging system, and combined with intelligent navigation system to establish a rapid reservation charging system for EVs. The charging priority was respectively defined from different aspects, and the charging order was based on the charging priority [8-9]. A new consensus priority algorithm based on V2G billing framework was proposed to deal with fluctuations in frequency and power generation due to large-scale response to frequency deviation [10]. These literatures discuss the charging reservation and charging priority respectively. However, they only study a certain charging process of electric vehicles without adopting optimization measures, so it may still have an adverse impact on the power grid.

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Some researchers have established user satisfaction model from the perspective of users. The literature [11] established the user satisfaction model for the charging station, quantified the user's satisfaction with the charging station, and realized the quantitative analysis of the user's choice of charging station.

Based on the research on the satisfaction of users' response to charging station strategy [11], combining with the researches on path planning and reservation priority, this paper proposes a charging user discount rebate and reservation priority strategy for EVs. A user satisfaction decision model including economic satisfaction and reservation satisfaction is established, and a charging station benefit model is established to maximize the benefits of the charging station. The proposed model is solved by genetic algorithm, and the effectiveness of the proposed model is verified by simulation.

2. SCENE DESCRIPTION

The charging process of electric vehicles is a complicated scene. Users want to make them satisfied with the charging process, and charging station operators would like greater benefits. In order to meet the needs of both parties, this paper proposes a strategy to improve users' satisfaction and maximize the benefits of charging station operators. The strategy between the user and the charging station is shown in Figure 1.

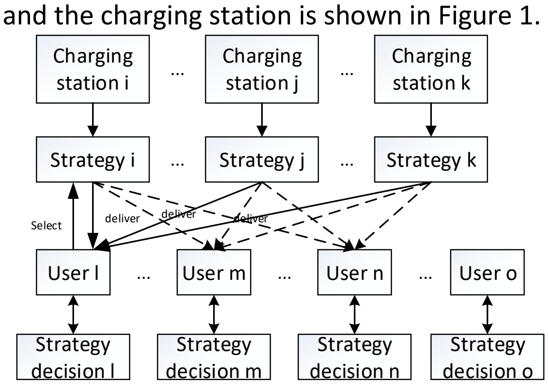

Fig 1 The strategy between users and charging stations.

In Figure 1, there are two levels, namely charging station and user. Each charging station will formulate a corresponding preferential strategy for attracting users to charge. Each user also has a decision-making strategy based on his or her actual situation. There is a communication system between charging station layer and user layer for realizing two-way communication between the two layers. Users can obtain the preferential strategy information of each charging station, and select his most satisfactory charging station for charging according to his own decision-making strategy. Each charging station can obtain the information that users select charging stations, and adjust the preferential strategy of each charging station in the next cycle.

The main contribution of this article is the optimal strategy of charging stations and users. The decision-making strategy of users is based on the users' personal preferences and the distances as well as reservation priorities from users to each charging station. The goal of the decision-making strategy of users is to maximize users' satisfaction. The model formulated according to the decision-making strategy is called the user satisfaction decision model. Strategy for each charging station is based on the strategy of power grid and various external factors, aiming at maximizing the benefits of the charging station, and formulating the electricity price and the reservation rule of each charging station. The model formulated according to the charging station strategy is called the charging station benefit model.

According to the flow sequence of the information, each charging station formulates the reference service fee and the corresponding discount and reservation rule according to the charging station benefit model. The EV users decide to go to the charging station selected by the users according to the preferential strategy of each charging station and the user satisfaction decision model.

3. MODEL CONSTRUCTION

3.1 User satisfaction decision model

The user satisfaction decision model is used to measure the degree of user satisfaction with each charging station, and selects the charging station with the highest satisfaction for charging. The objective function of the user satisfaction decision model is mainly composed of two parts: economic satisfaction and appointment satisfaction.

Economic satisfaction is mainly affected by the charging service fee of the charging station and the discount of the charging station to different users.

Define the membership matrix A as follows:

$$\mathrm{A} = \begin{bmatrix} a_{1,1} & \cdots & a_{1,n} \\ \vdots & \ddots & \vdots \\ a_{m,1} & \cdots & a_{m,n} \end{bmatrix} \tag{1}$$

Where, A is the user membership matrix; $S_c=\{1,2,\ldots,n\}$ represents the charging station set; $S_u=\{1,2,\ldots,m\}$ denotes the user set; $a_{i,j}$ represents the element in matrix A, $i \in S_u$, $j \in S_c$, and means that the user i has the membership level of the charging station j. There are three levels of membership: Level 1, Level 2, and Level 3, and the ranks increase in turn.

Each charging station will set different discount rates according to different discount strategies. The discount matrix of the users for different charging stations can be obtained by multiplying the elements in the membership matrix by the corresponding discount rates. The discount matrix Y is expressed as follows:

$$\mathrm{Y} = \begin{bmatrix} y_{1,1} & \cdots & y_{1,n} \\ \vdots & \ddots & \vdots \\ y_{m,1} & \cdots & y_{m,n} \end{bmatrix} \tag{2}$$

Where, $y_{i,j}$ means a discount degree that the charging station j can give the user i, $i \in S_u$, $j \in S_c$.

Define the charging service fee for each charging station as X_j.

Economic satisfaction is used to characterize the user's satisfaction with the cost of charging to each charging station. The economic satisfaction f_{eco} of user h to the charging station k is expressed as:

$$f_{eco} = \frac{[X_j * y_{h,j}]_{max} - [X_k * y_{h,k}]}{[X_j * y_{h,j}]_{max} - [X_j * y_{h,j}]_{min}} \tag{3}$$

Where, X_j and X_k denote charging service fee, $y_{h,j}$ and $y_{h,k}$ are elements in matrix Y.

The satisfaction of the reservation is proportional to the level of the reservation. The higher the reservation level, the higher the satisfaction.

The reservation priority is related to the user's membership level and the distance that the user is from the charging station. The membership matrix has been given above, and the distance level matrix of the priority is defined below.

Define two kind of variables: $s_{j,1}$ and $s_{j,2}$. The user can be divided into three levels based on these two variables and the distance from users to different charging stations. The distance level matrix D of the user to the charging station is expressed as:

$$\mathrm{D} = \begin{bmatrix} d_{1,1} & \cdots & d_{1,n} \\ \vdots & \ddots & \vdots \\ d_{m,1} & \cdots & d_{m,n} \end{bmatrix} \tag{4}$$

The reservation satisfaction f_{ord} of the user h to the charging station k is expressed as:

$$f_{ord} = \frac{[a_{h,k} * d_{h,k}] - [a_{h,j} * d_{h,j}]_{min}}{[a_{h,j} * d_{h,j}]_{max} - [a_{h,j} * d_{h,j}]_{min}} \tag{5}$$

Where, $a_{h,k}$ and $a_{h,j}$ are elements in matrix A, $d_{h,k}$ and $d_{h,j}$ are elements in matrix D.

The user's overall satisfaction is obtained by the combination of economic satisfaction and reservation satisfaction. The combination of these two parts is completed by the weight coefficient. The objective function of the user satisfaction decision model is expressed as:

$$f_{all,n} = \frac{w_1 * \{[X_j * y_{n,j}]_{max} - [X_k * y_{n,k}]\}}{[X_j * y_{n,j}]_{max} - [X_j * y_{n,j}]_{min}} + \frac{w_2 * \{[a_{n,k} * d_{n,k}] - [a_{n,j} * d_{n,j}]_{min}\}}{[a_{n,j} * d_{n,j}]_{max} - [a_{n,j} * d_{n,j}]_{min}} \tag{6}$$

Where, w_1 and w_2 are the weight coefficients.

The constraint is as follows. In the case of meeting the minimum safe power of the battery, the user is guaranteed to be able to reach the charging station.

$$SOC_i - \frac{D_{i,j} * W_{100}}{100 * C} \geq SOC_{min} \tag{7}$$

Where, SOC_i is the vehicle battery state of the user i; SOC_{min} is the minimum safe power of the battery; $D_{i,j}$ is the distance from the user i to the charging station j; W_{100} is the power consumption of 100 kilometers, taking; C is the battery capacity of the EV.

3.2 Charging station benefit model

The charging station benefit is equal to the sum that the amount of power that the user needs to charge multiplied by the difference between the charging cost of user going to the charging station and the grid selling price. Therefore, the objective function of the charging station benefit model is:

$$Max\ W_j = \sum_{i \in S_j} (y_{i,j} * X_j - Z_j) * \left(1 - SOC_i - \frac{D_{i,j} * W_{100}}{100 * C}\right) * C \tag{8}$$

Where, W_j is the benefit of charging station j; i represents the user; j is the charging station; $i \in S_j$ represents the set of users charging to the j station; $y_{i,j}$ is the element in the discount matrix; X_j represents the charging service fee of the j charging station; SOC_i represents the SOC of the user i ; $D_{i,j}$ represents the distance of the user i to the charging station j; W_{100} represents the power consumption per 100 kilometers; C is the battery capacity; Z_j is the electricity price of the unit electricity sold by the grid to the charging station j.

The constraints are as follows.

a) Charging station member discount level constraints. The higher the membership level, the greater the discount, and the member discount is within a certain range.

$$x_{min} \leq x_{j,3} < x_{j,2} < x_{j,1} \leq x_{max} \tag{9}$$

Where, $x_{j,1}$, $x_{j,2}$, $x_{j,3}$ are the three level member discounts of the charging station j, and x_{min} and x_{max} are respectively the upper and lower limits of the member discount.

b) The charging station hierarchically constraints.

$$s_{max} \geq s_{j,2} > s_{j,1} > 0 \tag{10}$$

Where, $s_{j,1}$, $s_{j,2}$ are the distance limits of the distance level of the charging station j, and s_{max} is the upper limit of the distance division.

c) Battery dynamic SOC constraints. When the EV is running, in order to prevent the excessive power consumption from seriously adversely affecting the battery life, the SOC_i is limited to a certain range.

$$SOC_{min} \le SOC_i \le 1 \quad (11)$$

Where, SOC_{min} is the minimum allowable battery.

4. RESURTS AND DISCUSSION

4.1 Parameter settings

To validate the proposed model and algorithm, this paper assumes that there are five charging stations in a city, and 100 EVs need to be recharged. Two kind of charging stations are set as charging stations formulated by this model, and the other three charging stations are set as normal charging stations. The algorithm for solving the problem used in this paper is genetic algorithm.

a) The membership level of each charging station owned by the users is randomly generated by the system due to the simulation, and the elements are selected between 1, 2, and 3.

b) The distance from the users to the charging stations can be obtained by the map software, and the emphasis of this paper is not to solve the problem of the distance from the users to the charging stations. Therefore, the distance matrix of the users to the charging stations is also randomly generated by the system.

c) In the user satisfaction, because the user's economic satisfaction is different from the reservation satisfaction, the user satisfaction can be divided into 3 situations, that is, economic preference, reservation preference and no preference. The economic preference means that the economic satisfaction weight is 0.75 and the reservation satisfaction weight is 0.25; the reservation preference means that the economic satisfaction weight is 0.25 and the reservation satisfaction weight is 0.75; the no preference is that the weight of two kind of satisfactions both is 0.5.

d) The most important parameter of EVs is the state of charge of the battery (SOC). When the state of charge (SOC) of the battery is reduced to 30%, the car automatically reminds the owner that it should be charged. When it drops to 20%, the car should issue a warning that it should be charged. When reduced to 10%, the warning shows that the battery will be damaged and parked immediately. So, the SOC is set to a random number between 0.2 and 0.3, considering the charging of the users' vehicle.

e) The other parameters[11] of the EVs are set as follows: the minimum battery state of charge (SOC_{min}) is set to 0.1; due to the fast charging mode, the car charging power is set to 20kW; the vehicle charging efficiency is set to 0.97; the power consumption per 100 kilometers is 14kWh; the battery capacity is set to 20kWh; the electricity price sold by the grid to each charging station is uniformly set to 0.8 yuan per kWh.

4.2 Simulation results

In order to analyze the strategy in this paper, two types of charging stations are set up, which are charging stations with strategy and normal charging stations. Normal charging station, means that the charging stations are uniformly priced according to the electricity price of the grid company. Without the discount policy, the users select the charging station according to the distance to each charging station. The charging station with strategy, means that the charging station formulates a preferential strategy to attract the user to the charging station. Which charging station users ultimately choose is still determined by the user's satisfaction with each charging station.

The impact of two kind of strategies on the users and the charging stations is mainly analyzed from two angles, that is from the perspective of the charging station and users. From the perspective of the charging station, the main benefits of the charging stations of three kind of weights and the total benefits of two kind of charging stations are analyzed. The numbers that users of three kind of weights select to charge at each charging station is analyzed. From the perspective of users, the average costs and the average reservation priorities of charging for users of three kind of weights are discussed.

The benefits of each charging station of three kind of weights and the total benefits of two kind of charging stations are shown in Figure 2.

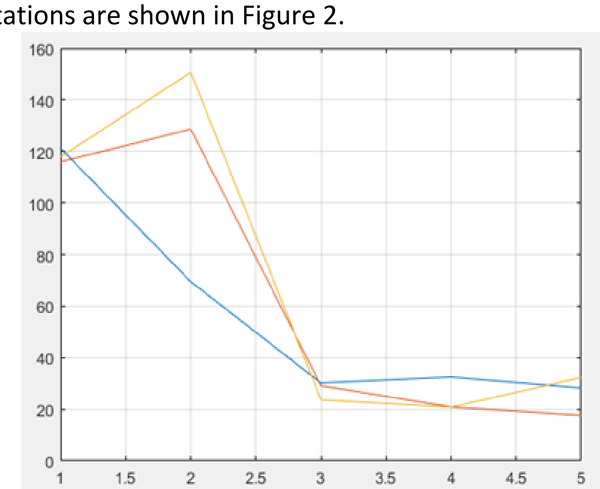

Fig 2 benefits of each charging station.

The yellow line in the figure indicates the benefits of the five charging stations, when users are all the reservation preference. The red line indicates the profits of each charging station, when users are all no preference, and the blue line indicates the benefits of economic preference. The abscissa has no specific meaning, just to indicate five charging stations. The value of the ordinate of the five nodes indicates the benefits of five charging stations, and its unit is yuan.

The numbers of users of three kind of weights charging at each charging station are shown in Figure 3.

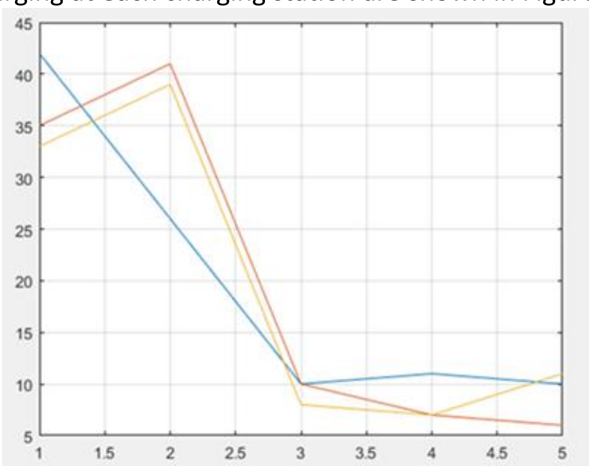

Fig 3 numbers of users at each charging station.

The colors of lines in the Figure 3 has the same meanings as the Figure 2. The abscissa also has no specific meaning and indicates five charging stations. The value of the ordinate of the five nodes indicates the numbers of users charging at five charging stations.

The average costs of charging for users of three kind of weights are shown in Table1.

Table 1 Average costs of users

Average costs of users (Yuan)	Charging station with strategy	Normal charging station
Economic preference	13.85	14.64
No preference	14.23	14.70
Reservation preference	15.00	14.75

The average reservation priorities of charging for users of three kind of weights are shown in Table 2.

Table 2 Average reservation priorities of users

Average priorities of users	Charging station with strategy	Normal charging station
Economic preference	4.32	2.64
No preference	4.42	2.63
Reservation preference	4.45	2.64

4.3 Discussion

a) Analysis from the perspective of the charging stations. As can be seen from the Figure 2, the general trend of the three preference types is that the benefits of the charging stations with strategy are much larger than the normal charging stations. It can be seen that regardless of the users' preference, the benefits of the charging stations adopting the strategy are far greater than the normal charging stations. The results show that this strategy can effectively attract users to charge.

Comparing the three lines in the Figure 2, it can be seen that the benefits of the charging stations adopting the strategy increase with the reduction of the weight of economic satisfaction. In order to make the comparison clear and make the ordinary charging station more competitive, the electricity price of the ordinary charging station is set lower than the electricity price of the charging station adopting the strategy. So, the benefits of the ordinary charging station are lower, and when users are greatly affected by the economy, they will be more inclined to ordinary charging stations. Therefore, as the weight of economic satisfaction increasing, more users will choose ordinary charging stations, and the benefits of the charging stations with strategy will be slightly reduced. However, from the macro trend, the charging station adopting the strategy will be more attractive for users and gain greater profits.

As can be seen from the Figure 3, the total trend of three preference types is that the numbers of users charging at the charging stations with strategy are much larger than the numbers of normal charging stations. This conclusion is similar to the trend of the benefits of charging stations. It shows that charging stations with strategy are far more attractive for users than normal charging stations.

Comparing the two lines represented by economic preference and no preference, it can be seen that the numbers of users with no preference charging at the charging stations adopting the strategy are more than the numbers of users with economic preference. But the numbers of users with no preference charging at the normal charging stations are less than the numbers of users with economic preference. The reason of this situation is that as the weight of economic satisfaction increasing, user decision-making process is more inclined to charging costs. Due to the parameter setting, the charging price of ordinary charging stations is lower for most of users than the charging stations with strategy. Therefore, the numbers of users with economic preference charging at the charging stations adopting the strategy are slightly lower than the numbers of users with no preference.

b) Analysis from the perspective of the users. As can be seen from Table 1, users with economic preference who choose the charging station with the strategy can enjoy lower charging costs than users with no preference and reservation preference, which is also in line with the original intention of people choosing their respective preferences. This is also in line with the original intention of people choosing their preferences. In addition, the charging costs of users who select the ordinary charging stations is not much different, because the ordinary charging stations do not adopt the differentiation strategy.

As can be seen from Table 2, users with reservation preference who choose the charging station with the strategy can enjoy higher reservation priorities than users with no preference and economic preference. This conclusion is similar to the trend of the charging costs of users.

5. CONCLUSION

Now, the short mileage of EVs and the shortage of charging stations have become one of the main concerns for people to purchase EVs. Therefore, solving and optimizing the charging problem of EVs is a key issue in the use and promotion of EVs.

The main contribution of this paper is proposing the optimal strategy of charging stations and users. The EV charging process is analyzed from the perspective of the EV users and the charging station operators. From the perspective of users, the factors affecting the users' charging choice are mainly the degree of user satisfaction with the optional charging station, and the users satisfaction with the charging station is a combination of economic satisfaction and reservation satisfaction; From the perspective of the charging stations, the factors affecting the benefits of the charging stations are mainly the charging service fee of the charging station to different users and the numbers of users charging at the charging station. The simulation results show that if the users choose the economic preference, the users' charging costs are lower than users with other preference.

The next step of the study is to consider the relationship between power grid, charging stations and users, combining the advanced applicable theory in the field of economic management and the charging station-user coupling double-layer nested optimization model, to generate a cost-benefit game model between grid companies and charging stations, so as to achieve mutual benefits between the three participants.

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