Charging Control Scheme for Electric Vehicles Based on Consumer Psychology

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Abstract. With a large number of electric vehicles connected to the grid, the orderly charging problem of electric vehicles has attracted more and more attention. The present techniques control charging load of electric vehicles mostly from the perspective of centralized control, but few reports the charging model based on consumer psychology. Based on the study of the traffic travel regularity of residents, this paper establishes consumer psychology model of the charging load influenced by the electricity price. The response of the charging load to the electricity price is described by the load shifting rate. Through the optimization of peak-valley time of use power price, the peak load shifting and load curve optimization can be achieved. Finally, testing results verify the effectiveness of the proposed method.

1. Introduction

Electric vehicles have the advantages of no pollution, low noise, etc. The replacement of traditional vehicles with electric vehicles has become an inevitable trend in the development of the automotive industry [1].

Scholars have carried out extensive research on the problem of orderly charging of electric vehicles. Reference [2] uses Monte Carlo simulation to study the daily load curve of electric vehicle charging load, and optimize peak-valley time of use power price time interval for the minimum peak and valley difference ratio. To reduce the peak-to-valley difference and improve user satisfaction, reference [3] establishes the orderly charging model of electric vehicles, in which the user's charging cost is the minimum and the initial charging time of the battery is the earliest. Reference [4] proposes an automatic breaking charging mode and a smooth adjustment charging mode for the orderly charging of electric vehicles in residential districts, thereby achieving the goal of saving cost. Reference [5] proposes a two-stage optimization model for electric vehicle charging stations, which improves the calculation efficiency while ensuring the economic benefits of the charging station and reducing the peak-to-valley difference. Through the time-space dual-scale adjustability and measured charging load data, reference [6] proposes an orderly charging method based on load forecasting, establishes an optimization model and solves it, which can obtain the optimal charging start time for each charging load. Adjust the total load power curve by changing the charging start time. Using Monte Carlo simulation method to evaluate the impact of electric vehicle charging on different development scales, reference [7] proposes an orderly charging implementation method based on peak and valley electrovalence guiding strategy and establishes response model of user behavior to peak and valley electrovalence.
Meanwhile, the peak-valley period was optimized by genetic algorithm with the goal of the peak load shifting.

Although the above research results have made important theoretical contributions to the orderly charging of electric vehicles, few scholars have studied the charging problem of electric vehicles from the perspective of consumer psychology. Although reference [2]-[3] optimizes the peak and valley electrovalence, it considers that the user's charging behavior is “rational” in the established model, that is, the user is bound to arrange the electric vehicle charging time in “Valley” power price period. However, in addition to the peak-to-valley price period, whether the electric vehicle participates in the orderly charging control depends on the influence of the price level and the user's will, so it is necessary to design the electric vehicle order control strategy based on the consumer psychology model.

To fill this gap, this paper takes electric private car as the main research object and models the electric vehicle load on the basis of fully studying the travel rules of residents. Simultaneously, the electric vehicle charging load model based on consumer psychology is established to study the influence of peak-valley time of use power price on electric vehicle charging load. Finally, testing results verify the effectiveness of the proposed method.

2. Establishment of the Electric Vehicle Load Model

The charging mode of electric vehicles mainly includes slow charging and fast charging. From the point of view of charging cost and impact on the grid, the slow charging method has lower charging cost, less impact on the grid, and does not affect the battery life, so it becomes the most widely used charging method. This paper mainly studies the "slow charge" charging method of electric vehicles [8].

The travel time of an electric car directly determines the charging time of the electric car. According to the statistics of the US Department of Transportation on the travel of household vehicles in the United States, the user's vehicle return time satisfies the normal distribution [2][5], and the probability density function can be expressed as:

\[ f(x) = \begin{cases} \frac{1}{\sigma_s \sqrt{2\pi}} \exp \left( -\frac{(x - \mu_s)^2}{2\sigma_s^2} \right) & 0 < x \leq \mu_s - 12 \\ \frac{1}{\sigma_s \sqrt{2\pi}} \exp \left( -\frac{(x - \mu_s)^2}{2\sigma_s^2} \right) & \mu_s - 12 < x \leq 24 \end{cases} \]

where \( \mu_s \) and \( \sigma_s \) are the mean and standard deviation of the vehicle return time, respectively. However, the corresponding \( \mu_s \) and \( \sigma_s \) values are different for different types of cars. The night peak of residents in Jiangsu appeared at 17:00~18:00, so the \( \mu_s \) and \( \sigma_s \) of electric vehicles in this paper are 18:30 and 1 hour respectively.

Due to the relatively random travel demand of residents, the daily mileage of different cars is also different. According to the formula [5], the mileage of residents' driving days obeys the lognormal distribution and the probability density function is:

\[ d_s = \frac{1}{x\sigma_c \sqrt{2\pi}} \exp \left( -\frac{(\ln x - \mu_c)^2}{2\sigma_c^2} \right) \]

where \( \mu_c \) and \( \sigma_c \) are the logarithmic mean and logarithmic standard deviation of the vehicle's daily mileage respectively.

Based on the known daily travel distance of the electric vehicle, the daily power consumption can be calculated by the energy consumption per 100 kilometers, and the state of charge of the electric vehicle can be further calculated:

\[ S_{\text{start}} = S_{\text{end}} - \frac{d \cdot E_{100}}{C} \]

where \( S_{\text{start}} \) and \( S_{\text{end}} \) are the state of charge corresponding to the battery at the charging start time and the charging end time of the electric vehicle, \( d \) is the daily driving range, \( E_{100} \) is consumption of the electric vehicle per 100 kilometers, and \( C \) is the battery capacity.

Further calculation of the charging duration of the electric vehicle based on the getting \( S_{\text{start}} \):

\[ T_c = \frac{(S_{\text{exp}} - S_{\text{start}}) \cdot C}{P_c \cdot \eta} \]
3. Design of the Electric Vehicle Ordered Charging Control Strategy Based on Consumer Psychology

3.1. Electric Vehicle Ordered Charging Control Strategy

In terms of technology, some charging piles have the function of “timed charging” at present. Under the influence of peak-valley time of use power price, residents will spontaneously adjust the charging period to the valley price reduction period. In order to avoid the impact of a large number of electric vehicles charging at the same time, the orderly charging control strategy randomly distributes the charging time of the electric vehicle in the low price period, and the charging start time is uniformly distributed:

\[ f_c = \begin{cases} \frac{1}{T_v - T_s} & \text{if } t_v \leq x < t_v - T_s \\ 0 & \text{else} \end{cases} \]

(5)

where \( f_c \) is the probability distribution density of the charging start time \( t_s \), \( t_v \) and \( t_v \) are the starting time and ending time of the valley electricity price respectively, \( T_v = t_v - t_v \) is the duration of the valley electricity price, and \( T_c \) is the charging duration of the electric vehicle. By adjusting the actual charging time to the distribution interval given in (5), the electric vehicle load can be evenly adjusted to the valley electricity price period to achieve orderly charging.

3.2. Electricity Price Response Model Based on Consumer Psychology

In order to express the user’s response to changes in electricity price, the concept of load transfer rate was introduced. The load transfer rate is the ratio of user load transfer after the implementation of peak-valley time of use power price. Assuming that the load transfer rate is proportional to the electricity price difference between different time periods, the formula is as follows:

\[
\lambda_{EV} = \begin{cases} 
0 & 0 \leq \Delta p_v \leq a_{EV} \\
K_{EV} \left( \Delta p_v - a_{EV} \right) & a_{EV} \leq \Delta p_v \leq \lambda_{EV, max}^{K_{EV}} + a_{EV} \\
\lambda_{EV, max}^{K_{EV}} & \Delta p_v \geq \lambda_{EV, max}^{K_{EV}} + a_{EV}
\end{cases}
\]

(6)

where \( \lambda_{EV} \) is the transfer rate of the electric vehicle load, \( \Delta p_v \) is the difference between the peak period electricity price \( p_p \) and the valley period electricity price \( p_v \), \( a_{EV} \) is the dead zone threshold, and \( K_{EV} \) is the slope of the curve region of the electric vehicle load segmental linear peak-to-valley period transfer rate, \( \lambda_{EV, max}^{K_{EV}} \) is maximum load transfer rate. Figure 1 is the schematic diagram of the peak-to-valley transfer rate.

![Figure 1. The schematic diagram of the peak-to-valley transfer rate.](image-url)
Under the influence of peak and valley electrovalence, the electric vehicle load will shift from the peak electricity price period to the valley electricity price period. Under the premise of $\lambda_{EV}$, the load of the electric vehicle at each time period can be calculated by the following formula:

$$P_{EV,t} = (1 - \lambda_{EV}) P_{base,t} + \lambda_{EV} P_{optimal,t}$$

where $P_{EV,t}$ is the fitted load of the electric vehicle at time $t$ after taking peak and valley electrovalence, $P_{base,t}$ is the baseline load at time $t$ when the electric vehicle does not adopt any orderly power control strategy, $P_{optimal,t}$ is the optimal charging load at time $t$. After the orderly power control strategy, all of them are transferred to valley electricity price period.

In addition to electric vehicles, other loads will respond to changes in electricity prices. Similarly, the following formula can be established:

$$P_{Else,t} = \begin{cases} 
0 & 0 \leq \Delta P_{pv} \leq a_{Else} \\
K_{Else}(\Delta P_{pv} - a_{Else}) & a_{Else} \leq \Delta P_{pv} \leq \frac{a_{Else}}{K_{Else}} \\
\frac{a_{Else}}{K_{Else}} & \Delta P_{pv} \geq \frac{a_{Else}}{K_{Else}}
\end{cases}
$$

where $\lambda_{Else}$ is the transfer rate of other loads, $K_{Else}$ is the slope of the curve region of other load segmental linear peak-to-valley period transfer rate, and $a_{Else}$ is the threshold of other load dead zone. The fitted load curve can be calculated by:

$$P_{Else,t} = \begin{cases} 
P_{Else,base,t} - \lambda_{Else} P_{Else,p} & t \in T_p \\
P_{Else,base,t} + \lambda_{Else} P_{Else,p} & t \in T_v
\end{cases}$$

where $P_{Else,t}$ is the fitting load of other loads after taking the time-of-use power price, $P_{Else,base,t}$ is the baseline load of other load at time $t$, $P_{Else,p}$ is the average value of other loads in the peak electricity price period.

In order to obtain the optimal value of $\Delta p_{pv}$, the electric vehicle charging problem considering consumer psychology can be transformed into an optimization problem to solve. As a decision variable, the time-of-use price will directly determine the effect of peak load shifting and affect the operating cost (because the power generation cost is a quadratic function form of its active output and the peak-to-valley difference directly determines the cost). In order to reduce operating costs and peak-to-valley difference, the objective function is defined as the form with the minimum peak-to-valley load difference:

$$\text{Min} \quad P_{max} - P_{min}$$

where $P_{max}$ and $P_{min}$ are the maximum load and the minimum load on a period of time, respectively.

In order to avoid the load exceeds the adjustment capacity of the generator after the transfer, the load change rate of the adjacent time period must satisfy certain limits:

$$R_{D} \leq P_{j} - P_{j-1} \leq R_{U}$$

where $R_{U}$ and $R_{D}$ are the upper and lower limits of the load change in adjacent periods.

By establishing the optimization problems shown in (5)-(10) and solving them, the values of the optimal peak and valley electrovalence difference $\Delta p_{pv}$ and the load transfer rates $\lambda_{EV}$ and $\lambda_{Else}$ can be obtained.

### 4. Testing Results

In the following example, the parameters of the electric vehicle refer to the BYD E6 series electric vehicle, the battery capacity is 40kWh, the energy consumption per 100 kilometers is about 20kW, the charging power is about 4kW, the charging efficiency is 0.9, the $\mu_c$ and $\sigma_c$ are 3.6 and 0.5 respectively.

Considering the different load transfer rates of 500,000 electric vehicles, the load transfer rate is increased from 0 to 1, and the simulation results are shown in Figure 3. It can be seen from Fig. 2 that...
the larger the load transfer rate is, the smaller the peak-to-valley difference is, and the more obvious the peak load shifting effect is.

In the following examples, the impact of electricity price on electric vehicle load and total load curve is considered based on consumer psychology. In addition to considering the impact of electric vehicle load on electricity price, it also considers the impact of other load on electricity price level. The residential electricity price was selected to be 0.56 yuan/kWh, and other parameters were set to $K_{EV}=2.1$, $a_{EV}=0.05$, $\lambda_{EVmax}=0.80$, $K_{Else}=1.2$, $a_{Else}=0.15$, $\lambda_{Elsemax}=0.39$. The peak-to-valley difference and load transfer rate of the load vary with the peak-to-valley electricity price difference $\Delta p_{pv}$ as shown in Fig. 3. It can be seen from Fig. 3 that as the $\Delta p_{pv}$ increases, the peak-to-valley difference of the load decreases firstly and then increases, and there is a minimum value near 0.2 (yuan). However, in the actual optimization, in addition to the minimum peak-to-valley difference, it is necessary to consider the constraint of the load change rate in adjacent periods (constraint (11)).

In the following example, consumer psychology is considered. The electricity price and load curve are optimized by establishing the optimization problems shown in (5)-(11). The optimization considers the influence of electricity price of electric vehicle load and other load. Assume that the change of load in adjacent time period is not allowed to exceed 5% of the maximum load, and the optimal values of $\Delta p_{pv}$, $\lambda_{EV}$ and $\lambda_{Else}$ are obtained. The load curves before and after optimization are shown in Figure 4.

It can be seen from Figure 4 that the optimal load curve considering consumer psychology shows a clear trend of “the peak load shifting”. The transfer rates of electric vehicle load and other loads are in the linear region, and there is a certain load transfer rate, it can be seen that by establishing an electric vehicle load optimization model considering consumer psychology, it is possible to reduce the peak-to-valley difference and provide a theoretical basis for the formulation of peak-valley time of use power price.
5. Conclusion

Aiming at the new situation of large-scale electric vehicles connecting to the power grid, this paper proposes a charging model based on consumer psychology for electric vehicles. By optimizing the peak-valley time of use power price, the peak load shifting of load is realized. The results show that:

1. The disordered charging of electric vehicles will superimpose the charging load and the original peak of the load, which pushes up the maximum load. Through the peak-valley time of use power price, the electric vehicle load will shift to the valley electricity price period, which can reduce the peak-to-valley difference and avoid the charging load and the peak load being superimposed.

2. The level of load transfer of electric vehicles is determined by the transfer rate. The peak-valley time of use power price level determines the load transfer rate. The larger the transfer rate, the more obvious the "filling valley" effect.

3. By considering multiple influencing factors to establish an electric vehicle charging load optimization model considering consumer psychology, the optimal peak-valley time of use power price is determined, which provide a theoretical basis for the formulation of peak-valley time of use power price.

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