Study on Orderly Charging of Electric Vehicles Based on Time-of-use Electricity Price

Zhixin Zhou¹*, Bin Song²
¹School of Wuhan University, Wuhan, China
²School of Wuhan University, Wuhan, China

*Corresponding author e-mail: 844847299@qq.com

Abstract. The huge power grid load caused by large-scale centralized charging of electric vehicles is the main factor restricting the development of electric vehicles. At present, there is no definite method to reasonably allocate the charging load of electric vehicles to reduce the load of the power grid. Aiming at the problem of electric vehicles charging, a method of electric vehicles orderly charging is proposed. The model of electric vehicle charging is built, and the method of using time-of-use electricity price to guide users to arrange charging time reasonably is put forward, which meets the differentiated needs of users. In order to verify the correctness of the conclusion, the Monte Carlo method is adopted to simulate the charging behavior of users, and the orderly charging mode is compared with the original disordered charging mode. The results show that compared with the traditional disordered charging mode, the orderly charging method can reduce the load of the power grid and achieve the effect of peak load shifting. In addition, it plays a certain role in reducing user charging cost and increasing charging pile utilization efficiency.

1. Introduction

The gradual depletion of fossil fuels leads to the rise of fuel price, which objectively promotes the development of electric vehicles (abbreviation for electric vehicles is ev) [1,2]. According to the survey, the sales of electric vehicles in the United States will account for 12% of the total sales of automobiles by 2025 [3]. By 2030, China will build 140,000 charging stations and 50 million charging piles. If such a large-scale ev adopts the current disordered charging mode, it will bring serious load to the power grid, which is expected to become an inevitable problem in 2030 [4].

At present, the related literatures on orderly charging of evs mainly focus on the use of time-of-use electricity price to control user behavior, literature [5-8] proposed different time-of-use electricity price models from the perspectives of economy, reducing grid fluctuations, and weakening peak-to-valley differences which has certain reference value. But there is no specific price division method is put forward, does not take into account the user's cooperation degree, no specific feasible orderly charging scheme. Literature [9-10] discusses the impact of users' charging demand on grid load, but does not consider the impact of different users' charging behaviors.

In this paper, the models of disordered charging and ordered charging are firstly constructed, and the method of orderly charging for evs based on time-of-use electricity price is proposed. This method allows users to decide charging time according to their own needs and the current load margin of charging piles, which greatly promotes the efficiency improvement of charging piles. At the same time,
it significantly reduces the charging expense of users, improves the profit of charging piles, and reasonably distributes the load of the power grid. It successfully realized the goal of peak load shifting.

2. Establishment of disordered charging model

2.1. Disordered charging model under natural conditions
Suppose that 20% of users' charging behavior can satisfy the probability model $N(9, 0.52)$, 50% of ev users can satisfy the probability model $N(19, 1.52)$, and 30% of ev users can satisfy the probability model $U(0, 24)$. Combine the probability models of these ev users to get the overall probability distribution model.

$$f_i = \begin{cases} \frac{1}{\sigma_1 \sqrt{2\pi}} e^{-\frac{(x-\mu_1)^2}{2\sigma_1^2}} & (\mu_1 - 12) < x < 24 \\ \frac{1}{\sigma_2 \sqrt{2\pi}} e^{-\frac{(x-\mu_2)^2}{2\sigma_2^2}} & 0 < x < (\mu_1 - 12) \end{cases}$$

Where: $i$ is 1, 2; $\sigma_1$ is 0.5; $\sigma_2$ is 1.5; $\mu_1$ is 9; $\mu_2$ is 19.

$$f_T = 0.2 \times f_1 + 0.5 \times f_2 + 0.3 \times \frac{1}{24}$$

3. Establishment of orderly charging mode

3.1. Orderly charging model under time-of-use tariff
It is assumed that the maximum charging power of the $i$ ($i=1, 2, 3, ..., N$) charging pile in the station during operation is $P_i$, and the charging management system is set to change state every 15 minutes. When the ev is charged at a constant power $P_i$, it can be considered that it takes $J_i$ time period for the electric car that is charged in the $i$-th charging pile to charge the battery to the $D_i$. The number of time periods this user spends at the charging station is $T_i$. The respective calculation methods of these data are as shown in the following formula

$$J_i = \left[ \frac{B_i}{P_i \times \Delta t \times q} \right]$$

$$T_i = \left[ \frac{T_i}{15} \right]$$

Where: $\Delta t$ represents the time length represented by a specified time period (default: 15min); $\eta$ for charger charging efficiency; $[\cdot]$ for not less than the minimum integer ; $\lceil \cdot \rceil$ as the largest integer no greater than.

Set the rated capacity of the transformer responsible for the power supply task in the charging station area to $S_T$. Setting $A_j$ means the ratio of the charging power of the charging station and the rated power of the transformer that the transformer can withstand in the $j$ ($j=1, 2, 3, ..., 96$) time period. The load margin for the transformer to charge the charging station during the $j$ period is $A_j \times S_T$. It is assumed that the duration of the charging behavior of ev user and the duration of the period of low electricity price are a certain proportion, $D$. When a new ev user drives into the station, the charging management system in the station will rewrite its internal information. After that, based on the obtained battery information of the ev, the number of time periods $J_i$ in which the ev will need to be charged, the number of time periods $T_i$ staying in the station, and the charge load margin $M_i$ in the $T_i$

$$M_i = A_S \times T_i, t = 1, 2, ..., T_i$$

Where: $\lambda$ represents the power factor of the ev battery charging. When $M_t \geq P_i$ occurs during this period, the ev can be charged at the station

$$A_t = \{ t \mid M_t \geq P_t, t = 1, 2, ..., T_i \}$$
When $|J| < J$, the state that the charging station can charge up to the battery of the EV during the period from the user charging to the user leaving is $S_{\text{Pmax}}^{\text{t}} = S_t^+ + P_t \times M \times \eta \times 9$. When $|J| > J$, it indicates that the charging station can fully charge the user and can choose the most economical starting node $C_{J} = \{M_t \geq P_t, t = t_1, ..., t_s\} \subset \{t_1 < t_2 < ... < t_s\}$. Where

$$C_{J} = \{M_t \geq P_t, t = t_1, ..., t_s\} \subset \{t_1 < t_2 < ... < t_s\}$$

$$C_{J} = \{M_t \geq P_t, t = t_1, ..., t_s\} \subset \{t_1 < t_2 < ... < t_s\}$$

$$C_{J} = \{M_t \geq P_t, t = t_1, ..., t_s\} \subset \{t_1 < t_2 < ... < t_s\}$$

$$C_{J} = \{M_t \geq P_t, t = t_1, ..., t_s\} \subset \{t_1 < t_2 < ... < t_s\}$$

$$C_{J} = \{M_t \geq P_t, t = t_1, ..., t_s\} \subset \{t_1 < t_2 < ... < t_s\}$$

$$C_{J} = \{M_t \geq P_t, t = t_1, ..., t_s\} \subset \{t_1 < t_2 < ... < t_s\}$$

$3.2. \text{Orderly charging management based on time-of-use electricity price}$

When $|J| < J$, the charging management system will inform the user that the state that the charging station can charge the battery of the EV at most during the period is $S_{\text{Pmax}}^{\text{t}}$. And will inform the user that it will charge according to the highest price. If the user decides to continue charging at the highest price, the on-site charge management system will schedule the user to charge to the period. In addition, the system will rewrite the load margin $A_t \times S_t$ as $A_t \times S_t \times P_t$. When $|J| > J$, charging station can calculate the beginning of the low price period $t_1^*$. After that, the charge management system needs further calculation to determine that during $[t_1^*, t_2^* + T_{ \text{tmax} } + 1]$ time period, the EV charging price is the trough price, and other time periods are peak price with high electricity price. After the calculation is completed, the user needs to know about these conditions and choose whether to continue or wait for a lower price of electricity. When the user decides to charge during the high electricity price period, the station charging management system will charge the user to the time period $M_t \geq P_t, t = t_1, ..., t_s$ and until the battery is fully charged up. The system will rewrite the load margin $A_t \times S_t$ to $A_t \times S_t \times P_t$. When the user decides to charge during the trough price, the charging management system will arrange the user to the trough price period, and start the EV into the load margin $M_t \geq P_t$ period from $t_1^*$. The battery is charged and until the EV’s battery is fully charged up. The system rewrites the load margin $A_t \times S_t$ as $A_t \times S_t \times P_t$. Whenever a user drives an EV into the station for charging, the charging system performs the above calculation process accordingly for the user to select the corresponding charging plan according to his own needs. The system will ensure that the load margin is greater than the rated charging power of the EV during each period. Through these calculations, the most basic guarantee will be achieved for the smooth charging of EVs.

$4. \text{Comparative analysis of disorder and order simulation}$

$4.1. \text{Supplement of simulation parameters}$

According to the statistical data of a charging station, the applicable formula of disordered charging is obtained. The probability density function at the start of charging is in the form of variation:

$$f_{J} = 9.129e^{-\left(\frac{t - 8.929}{0.37}\right)^2} - 8.785e^{-\left(\frac{t - 15.13}{0.37}\right)^2}$$

The probability density function of charging duration is in the form of variation:

$$f_{\tau} = 1.467e^{-\left(\frac{\tau - 8.841}{0.377}\right)^2}$$

$4.2. \text{Simulation analysis of disordered charging}$

Monte Carlo method is used to simulate the charging behavior of EVs, assuming that the proportion and charging power of large-scale EVs are shown in Table 1. Define user charging way as the random variable $J$, in AC level $J = 1$, AC level $J = 2$, DC $J = 0$, corresponding $P_{J=1}, P_{J=2}, P_{J=0}$. The charging power is expected to be:

$$P_{J} = P(J = 1)P_{J=1} + P(J = 2)P_{J=2} + P(J = 0)P_{J=0}$$

The state value of $I$ indicating that the EV is charging and the state value of $0$ indicating that the EV is not in the charging state. $P(I = 0) = P_{J}(t_i + t_s < t) + P_{J}(t_i + t_J + t_s < t + 24h)$ is the probability that an EV will
not be charged daily. Wherein, $F_{w}$ represents a joint probability distribution function of the start time node of the ev charging and the charging duration, and is specifically expressed as $F_{w} = F_{\tau} \cdot F_{\tau}$, $t_{\tau}$ and $t_{\tau}$ are given by (8) and (9). At $t_{\tau}$, single ev charging load is $P_{\tau} = P_{\tau} \cdot t_{\tau}$, the probability distribution is $P(P_{\tau} = 0) = P(t_{\tau} = 0), P(P_{\tau} = P_{\tau}) = P(t_{\tau} = 1)$. Assume that an ev needs to be charged once a day, and there are N electric cars a day. According to the probability distribution model of evs charging given in (1) and (2), the charging load model of 10,000 evs in 24 hours is calculated, and the proportion of charging power of evs in three levels is substituted. There are $P_{i} = 0.1P_{i} + 0.4P_{i} + 0.5P_{i}$. For the three samples of $P_{i}, P_{i}, P_{i}$, according to (8) charging start time, (9) connection duration, combined with the probability of charging power of each level (1) and (2). The interval uses a normal distribution Monte Carlo method to estimate the charging load curve of 10,000 evs, and Fig 1 is obtained.

Table 1. Lager-scale ev charging parameters

| Charging power interval (kw) | Random power sample | Cost per device |
|-----------------------------|---------------------|-----------------|
| 10.000%                     | $P_{1,c}$           | 3000.000        |
| 40.000%                     | $P_{2,c}$           | 15000.000       |
| 50.000%                     | $P_{3,c}$           | 500000.000      |

Figure 1. Disordered charging load curve of 10,000 electric vehicles

Figure 2. Orderly charging load curve of 10,000 electric vehicles

The horizontal axis of Fig.1 and Fig.2 is 96 time periods of a day, each time period is 15 minutes; The vertical axis of Fig.1 is the total power of the system in this period. It can be seen from the Fig1 that when a large number of cars are charged out of order, a huge load will be generated, which will have a peak-on-peak impact on the power grid and cause a huge burden to the power grid. As shown in Table 2, the economics of power supply under disordered charging are also not satisfactory.

| Charging mode | Daily cost | Daily income | Daily profit | charging fee | Maximum load | Overload | Improve load distribution |
|---------------|------------|--------------|--------------|--------------|--------------|----------|--------------------------|
| Disordered    | 1394.00    | 2241.00      | 747.00       | 34.48        | 1.13         | Yes      | No                       |
4.3. Simulation of orderly charging

Also, according to the method of disorderly charging, combined with the number of charging time periods proposed by (3) and (4), and the method of time-of-use and price-dividing proposed by (5)(6)(7) and 3.2, the load model under orderly charging conditions is constructed. According to the model in 3.2, the proportion of the three levels of evs charging power is calculated, and let \( P(J=1)=80.20\% \), \( P(J=2)=15.30\% \), \( P(J=0)=4.50\% \).

There are \( P_c = 0.8020P_{c1} + 0.1530P_{c2} + 0.0450P_{c3} \). The Monte Carlo algorithm with normal distribution was adopted to calculate the orderly charging load curve of 10,000 evs, as shown in Fig 2.

When the charging method based on the ordered charging of the time-of-use electricity price is adopted, it can be seen from the above charging load curve that the peak-to-valley difference of the load curve is significantly reduced. It shows that this method can effectively reduce the load on the peak caused by a large number of charging vehicles, and effectively realize the peak clipping and valley filling. As shown in Table 3, in the case of orderly charging, the economics of the charging station have been greatly improved, which can bring greater economic benefits.

| Charging mode | Daily cost (yuan/day) | Daily income (yuan/day) | Daily profit (yuan/day) | Charging fee (yuan/car) | Maximum load * | Overload | Improve load distribution |
|---------------|----------------------|-------------------------|------------------------|------------------------|----------------|----------|--------------------------|
| Orderly charging | 716.92               | 1500.50                 | 786.6                  | 23.09                  | 0.83           | No       | Yes                      |

| Charging mode | Orderly charging | Disordered charging |
|---------------|-----------------|---------------------|
| Daily cost (yuan/day) | 716.92 | 1394.00 |
| Daily income (yuan/day) | 1500.50 | 2241.00 |
| Daily profit (yuan/day) | 786.60 | 747.00 |
| Charging fee (yuan/car) | 23.09 | 34.48 |
| Maximum load * | 0.83 | 1.13 |
| Overload | No | Yes |
| Improve load distribution | Yes | No |

5. Comparative analysis of orderly charging and disordered charging

When the charging station uses the disorderly charging method to charge the ev, many users will accumulate charging after work, which will cause the transformer responsible for this area to increase the electric load based on the conventional load. The load brought by the car leads to the peak on the peak. From the calculation results of the model, it can be seen that the load after peaking on the peak reaches 1.3 times of the rated capacity, which will greatly affect the normal operation of the grid. When the charging station uses the orderly charging method to charge the ev, these loads will be allocated to the evening trough period under the premise of satisfying the user's demand, reducing the burden of the peak period of power consumption, and effectively utilizing the power resources.

As shown in Table 4, the cost incurred by the charging station due to the power purchase during the peak period can be significantly reduced. Since most of the charging load is adjusted to the trough price, the cost per day due to electricity purchase is reduced by 48.7%. Reduced operating costs by adjusting the charging strategy to increase operating daily profit by 5.3%. The users of evs have reduced the per-capacity charging cost by about 33% by adjusting to the trough price. This achieves a win-win situation for both users and operators, while power companies are also operating more efficiently due to reduced grid load pressure.
6. Conclusion

After the preliminary modeling of the two charging modes, this paper analyzes the charging data of a certain number of evs by studying the charging record data of a charging station. The starting and ending time points and charging duration data of evs are studied to calculate the data of large-scale evs. In addition, this paper explored the charging rules of evs.

Through data, completed the setting of simulation background and parameters, and established the model completely. Then Monte Carlo simulation method is used to simulate the disorderly charging of charging piles and the charging of piles based on time-of-use electricity price. It is found that through orderly charging, it can play the role of peaks load shifting, reducing grid load and improving the economic efficiency of charging stations. Orderly charging has great advantages over disordered charging. In addition, specific methods for charging stations to reasonably arrange charging time and electricity price according to users' demands are put forward, which has a certain guiding role for large-scale charging stations.

7. Acknowledgments

At the completion of this paper, I would like to express my heartfelt gratitude and sincere respect to my teacher Song Bin. Mr. Song's persevering scientific research spirit, profound knowledge, modest, and selfless dedication have always inspired me to continuously learn knowledge. At the same time, I am also grateful to a charging station in Wuxi, Jiangsu Province, for providing me with valuable research data so that the paper can go on smoothly.

References

[1] Zhang jian, Yao xiaoyi and He yigang. “Dynamic optimization algorithm for dual interior point of electric vehicle orderly charging source”. north China electric power university, vol 45, pp.48-57, 2018.
[2] Zhang xiaolin. “Research on electric vehicle scheduling strategy in intelligent community” ,Southwest jiaotong university, 2018.
[3] Haitong. “Study on orderly charging and discharging strategies of electric vehicles in residential areas”. Shandong university, 2018.
[4] Pan yinji, Qiu xiaoyan, Xiao jiankang, Wu jiawu. “Spatiotemporal double-layer optimal scheduling strategy for electric vehicle charging load”, China southern power grid technology, vol 12, pp.62-70, 2018.
[5] Mohd Redzuan Ahmad, Ismail Musirin, Muhammad Murtadha Othman, Nur Azzammudin Rahmat, "PHEV charging strategy via user preferences and its differences on power system network", Energy Conversion (CENCON) 2014 IEEE Conference on, pp. 19-24, 2014.
[6] Carlos f. Sabillon a., John f. Franco, Marcos j. Rider, Ruben Romero, "A MILP model for optimal charging coordination of storage devices and electric vehicles using V2G technology", Environment and Electrical Engineering (EEEIC) 2015 IEEE 15th International Conference on, pp. 60-65, 2015.
[7] Nataly Banol a., John f. Franco, Marina Lavorato, Marcos j. Rider, Ruben Romero, "plug-in electric vehicle charging coordination in electrical distribution systems using A Tabu Search algorithm", Environment and Electrical Engineering (EEEIC) 2015 IEEE 15th International Conference on, pp. 1510-1515, 2015.
[8] Nataly Banol Arias, Ruben Romero, John f. Franco, Marina Lavorato DE Oliveira, "GRASP algorithm for charging coordination of plug-in electric vehicles in electrical distribution systems", Transmission & Distribution Conference and Exposition-Latin America (PES t&d-la) 2016 IEEE PES, pp. 1-6, 2016.
[9] Wu hongbin, Hou xiaofan, Zhao bo and Zhu chengzhi. “Economic dispatching of micro-grid system for grid accessible electric vehicles”, Automation of power system, vol 38, pp.77-84+99, 2014.
[10] Tian wenqi, He jinghan, Jiang jiuchun, Niu liyong and Wang xiaojun. “Study on orderly charging scheduling strategy for electric vehicle electrical changing station”, Power system protection and control, vol 4XXXXX0, pp.114-119, 2012.