Dynamic Electricity Price Guidance Analysis of Urban Electric Vehicle Based on Actual Data Drive

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Abstract. Establishing a dynamic electricity price to guide the charging behavior of car owners can better help electric vehicles (EV) to participate in peak shaving and valley filling of the grid. On the basis of this, a dynamic electricity price mechanism for electric vehicle charging stations in city was proposed in this paper. It was aimed at the distribution network where residential areas are located and mean to improve the ability of EV to cut peaks and fill valleys. Firstly, the load characteristics of residential areas were analyzed, in addition, the load status of the distribution network in the area before and after the EV charging station connected in were compared. Secondly, according to the proposed dynamic electricity price calculation process and related function based on the TOU (time-of-use) electricity price for electric vehicle charging station, the dynamic price of the day was established, then in order to predict the power load after the dynamic electricity price is implemented, the corresponding model based on the residential load elastic demand matrix was established. Finally, taking the actual data of a certain district near residential area in Anhui province and an electric vehicle charging station as an example, formulated the targeted dynamic electricity price and further verified the feasibility and effectiveness of the study.

1. Introduction
With the worldwide attention to environmental issues and the increasingly depleted energy crisis of fossil fuels, the development of clean energy is an irresistible trend. Electric vehicles use electricity instead of fuel as the power energy, which not only reduces the dependence on fossil energy, but also reduces the adverse impact on the environment. On the other hand, a large number of electric vehicle cluster loads have greater randomness in time and space compared with traditional loads, and thus have good scheduling performance. However, if a large number of electric vehicle loads are directly connected to the grid, it will bring a certain load impact to the grid. Therefore, electric vehicle clusters must be planned into the grid scheduling strategy, and use their energy storage characteristics to cut peak and fill valley.

In [1], the charging and discharging strategy of electric vehicles in micro grid was optimized for scheduling based on day-ahead load prediction combined with renewable energy generation. However, the influence of the actual electricity price on the charging and discharging behavior of electric vehicles was not considered. Study [2] considered the influence of electricity price, the charging and discharging optimization scheme for electric vehicles with the purpose of stabilizing the load curve was studied. Besides, according to the investigation, the certain realistic constraints on the interactive development of electric vehicles based on the orderly charging of electric vehicles include the lack of
enthusiasm of electric vehicle owners for network interaction. In the traditional electric vehicle charging mode, the charging piles were occupied. The network resources were opaque, and the charging price was relatively simple. There was a lack of a business model that mobilizes the owners of electric vehicles to participate in the interaction between the network and the Netherlands. TOU is now the most widely used power business model, which can effectively motivate power users to adjust their electricity consumption behavior, especially electric vehicles which is more schedulable than ordinary users. [3] studied the charging strategy optimization of electric vehicles under TOU price. While [4] proposed an electricity pricing model that took into account the satisfaction of car owners, and optimized the solution by taking the satisfaction of users, peak and valley load difference and the lowest electricity cost as multi-objective function. However, the proposal of dynamic electricity price can further close to the characteristics of dynamic load change and more accurately affect the user's choice of electricity consumption behavior. Thus [5] proposed a dynamic pricing strategy for new energy electricity price, which was divided into two parts: fixed price and floating price. The simulation results verified the correctness of electricity price formulation.

Based on the current situation of electricity consumption in urban residential areas, this paper analyzes the residential electricity habits with actual data, the impact of electric vehicle charging on the load curve of the area according to the charging station order data is analyzed at the same time. In order to reduce grid load fluctuations, the dynamic dynamic transaction price is established based on the original TOU price to guide the orderly charging of EV and participate in grid dispatching. Then forecast the station load condition under the new electricity price mechanism with the load demand elasticity matrix. Furthermore, the status quo before and after the implementation of the new price mechanism was compared and analysed. At last prove with actual data that it is feasible to realize the effective dispatch of electric vehicles by setting electricity prices, reduce the negative impact of electric vehicles on the power grid, and support the safe and effective operation of large power grids.

2. Impact of EV charging on residential distribution network

2.1. Analysis of residential load electricity characteristics

The general community can be divided into ordinary, mid-range and high-end residential areas according to the single-family area and household income level [6], but no matter which type of residential area, the main load of residential electrical equipment is mainly refrigerators, air conditioners, television sets, Washing machines, electric heating, water heaters, etc., which have strong electrical characteristics, are mostly seasonal loads, and because of the obvious peak-to-valley characteristics during residential electricity consumption in one day, the characteristics of electricity-polymerization response in residential areas are easy to generalize and analyze.

Taking a certain district of a certain city in Anhui Province as an example, draw the daily load curve as shown in figure 1, the typical daily load data plot is selected to find that the peak load of residential areas in one day is mainly concentrated from 19:00 to 23:00 in the evening, and two small peak period in the morning at 7:00 to 8:00 and 11:00 to 13:00, which is mainly related to the user's behavior habits.
2.2. Influence of electric vehicle access on load characteristics

2.2.1. Electrical vehicle charging mode. The charging modes of electric vehicles on the market mainly include three modes: fast charging, slow charging and battery switch. The battery switching method has more requirements for battery parameters and interface standards, and is suitable for public transportation vehicles of a unified model. For general electric vehicle loads, there are mainly two methods: fast charging and slow charging. In the normal charging (slow charging) mode, the charging power is low while the charging time is long, thus a long parking time is required, while the fast charging can save time, but the loss of the battery is relatively large. In general large public/commercial parking lots or residential areas, users who are not sensitive to charging time are more likely to choose slow charging mode, while the driver who travels long distances or mainly based on transportation traffic prefers the choice of fast charging mode. [6]

2.2.2. Data processing of charging station. Electric vehicle charging stations are divided into two major categories, urban charging stations in cities, and electric vehicle charging stations set up on expressways. This paper mainly studies the city's conventional charging station in residential areas. Using the actual power trading order of the charging station, the charging power, charging time, and electricity price information are extracted, thus the charging characteristics of the electric vehicle under the current electricity price mechanism are analyzed.

2.2.3. Analysis of the impact of electric vehicle access on power grid. In the context of demand-side management development, the charging of electricity charges has gradually evolved from the traditional unified electricity price to the TOU price mechanism that is generally adopted today. The use of electricity prices to guide users' electricity consumption behavior has played a certain role in the peak-cutting of the grid. However, due to the fact that the electricity consumption characteristics of residential areas are too remarkable, difference between the peaks and valleys of the power grid is still very large. But the EV charging load has a strong elastic space compared with other loads, thus the electricity price guides the EV owners' charging behavior selection and integrates it into the residential distribution network load, which can better realize the power grid shift peak filling and users and the need for economic operations.

3. Dynamic trading mechanism

3.1. Pricing principle
Utility theory is an important theory in economics. It is a theory exist when the decision makers making decision-making options. Decision-making is mainly influenced by the subjective consciousness of leaders. The charging behavior of electric vehicles is mainly influenced by the
decision of the owner. Different sensitivity levels for charging time and charging cost correspond to different decisions. For the charging decision, you can establish n time period charging utility functions as follows:

$$U(X_1, X_2, \cdots, X_n) = X_1^{\rho_1} \cdot X_2^{\rho_2} \cdots X_n^{\rho_n}$$ \hspace{1cm} (1)$$

Where $U$ is the utility function, $X_n$ represents the charging load at different time periods and $\rho_n$ is the elastic coefficient.

The new electricity price setting principle is for electric vehicles, which guides the charging and discharging behavior of electric vehicles through electricity prices and thus reduces the load peak-to-valley difference and maximum load value of the residential area.

3.2. Dynamic price based on TOU price

In Section 1.2, the analysis of the load curve of electric vehicles shows that even under the TOU price, the load of electric vehicles still has obvious periodicity with time. Based on the TOU price, this paper formulates the dynamic electricity price based on the actual load situation [7]:

$$P_f = \frac{P_{f,0} \cdot D_f}{D_{f,\text{ave}}},$$ \hspace{1cm} (2)

$$P_p = \frac{P_{p,0} \cdot D_p}{D_{p,\text{ave}}},$$ \hspace{1cm} (3)

$$P_g = \frac{P_{g,0} \cdot D_g}{D_{g,\text{ave}}},$$ \hspace{1cm} (4)

Among them, $P_f, P_p, P_g$ represents the daily peak, flat and valley electricity price predicted after adjustment, while $D_f, D_p, D_g$ represents the load value of peak, flat and valley after adjustment obtained through the load value forecast at the same period before the day. $D_{f,\text{ave}}, D_{p,\text{ave}}, D_{g,\text{ave}}$ represents the average load value of peak period and valley period respectively. The dynamic electricity price development process is shown in the figure 2 below.

![Figure 2. Process for developing dynamic electricity prices](image-url)
4. User response model based on load elastic demand

4.1. Actual road network mod Load elastic demand matrix

Price elasticity of demand refers to the degree to which the quantity demanded of a commodity reacts to its price change in a certain period of time, representing the change relationship between quantity demanded and price.

\[
E = \frac{\partial m}{\partial p} = \frac{m_0}{p_0} \times \frac{dm}{dp} \tag{5}
\]

Where \( E \) is elasticity of demand, \( p_0 \) and \( P \) are the electricity price before and after change, \( m_0 \) and \( m \) respectively correspond to the load under two electricity prices, \( dp \) and \( dm \) are the difference of the price and the load.

The change in electricity price causes the change of load to be divided into two types: 'self-elastic demand' and 'cross-elastic demand'. 'Self-elastic demand' refers to the sensitivity of a part of the non-transferable load to the price at a fixed time, and the elasticity value is a negative number; 'cross-elastic demand' refers to the load with the transfer ability (the demand for electricity which can be transferred from the peak period to the trough period) has a multi-period sensitivity and its elasticity value is positive.

The elastic matrix \( E \) consisting of self-elasticity and cross-elasticity is shown as:

\[
E = \begin{bmatrix}
\rho_{11} & \rho_{12} & \rho_{1n} \\
\rho_{21} & \rho_{22} & \rho_{2n} \\
\rho_{n1} & \rho_{n2} & \rho_{nn}
\end{bmatrix}
\tag{6}
\]

4.2. Customer response

Generally speaking, the value of price self-elasticity and price cross-elasticity between time periods in the demand elasticity matrix are within a certain range, or are based on foreign experience. Because the experience only gives a range of the elasticity coefficient, the specific value is quite uncertain, and the user type, the economic situation of each place all have differences, the power demand price elasticity matrix \( E \) obtained according to experience cannot be adapted to the users’ demand. So we can't take values based on experience. On the contrary, some studies use the linear regression method [8] to perform regression analysis on a certain type of electricity consumption data in a certain region, and then obtain the demand elasticity matrix that satisfies the user's electricity consumption law, and finally obtain the demand response model.

5. Examples

In order to prove the effectiveness of the dynamic electricity price, this section take the load data of a mid-range residential area in a certain city of Anhui Province as the basis, and select an electric vehicle charging station that adopts the TOU price mechanism in the vicinity of the community, the charging station has 30 charging piles with a power of 60 kW. Collect data and select a typical daily load to draw the corresponding load curve, as shown in Figure 3.

A simple analysis of the following parameters is selected for the typical load curve: the maximum peak-to-valley difference in the region before and after the electric vehicle charging station under the TOU tariff is reduced from the original 59.73 MW to 50.59 MW. The variance of load fluctuations was reduced from 335.89 to 269.86. It can be found that the maximum peak-to-valley difference of the load and the variance of the load fluctuation are reduced, but the target effect of the peak-shaving is still not achieved.
5.1. Establish dynamic electricity price and EV load response

Based on the load data of a certain district of Anhui Province and the current TOU electricity price information, a dynamic electricity price mechanism suitable for the electric vehicle charging station near the neighborhood is formulated.

Under the mechanism of the new dynamic electricity price, the peak-to-valley period of the load is no longer a fixed period, but is automatically divided into the corresponding level by comparing the predicted dynamic load value with the threshold of dividing the peak valley, and then according to the second chapter of this paper. Dynamic electricity prices are obtained based on TOU electricity prices.

With the forecast of the resident load at 24 hours a day and the original TOU tariff mechanism, the dynamic electricity price is set as shown in the following table 1:

| Time   | Residential load(MW) | Residential load(MW) | Dynamic electricity price(yuan) | Time   | Residential load(MW) | Residential load(MW) | Dynamic electricity price(yuan) |
|--------|----------------------|----------------------|---------------------------------|--------|----------------------|----------------------|---------------------------------|
| 1:00   | 46.5                 | 0.8769               | 0.9213                          | 13:00  | 66.3                 | 1.1048               | 1.1231                          |
| 2:00   | 44.3                 | 0.8769               | 0.8777                          | 14:00  | 57.25                | 1.1048               | 1.1343                          |
| 3:00   | 38.95                | 0.8769               | 0.7717                          | 15:00  | 54.325               | 1.1048               | 1.0763                          |
| 4:00   | 37.35                | 0.8769               | 0.7400                          | 16:00  | 57.825               | 1.1048               | 1.1457                          |
| 5:00   | 36.55                | 0.8769               | 0.7242                          | 17:00  | 65.625               | 1.1048               | 1.111                           |
| 6:00   | 42.85                | 0.8769               | 0.8490                          | 18:00  | 82                   | 1.455                | 1.4435                          |
| 7:00   | 70.175               | 0.8769               | 1.2354                          | 19:00  | 87.775               | 1.455                | 1.5452                          |
| 8:00   | 76.95                | 1.1048               | 1.3547                          | 20:00  | 93.825               | 1.455                | 1.6517                          |
| 9:00   | 70.975               | 1.1048               | 1.2495                          | 21:00  | 96.275               | 1.455                | 1.6949                          |
| 10:00  | 68.75                | 1.455                | 1.2103                          | 22:00  | 79.75                | 1.1048               | 1.4035                          |
| 11:00  | 77.625               | 1.455                | 1.3665                          | 23:00  | 63.25                | 1.1048               | 1.0714                          |
| 12:00  | 88.85                | 1.455                | 1.5642                          | 24:00  | 50.85                | 0.8769               | 1.0075                          |

Aiming to predict the response behavior of electric vehicles under dynamic electricity price, firstly, using the linear regression method to carry out regression analysis on the load data before and after the implementation of the TOU price, thus can obtain the elastic matrix of the user demand. The matrix can reflect the consumption patterns of users here, and can be used to predict the load response of electric vehicles under the established dynamic electricity price.

The electric vehicle charging station adopted the unified electricity price of 1 yuan/kW·h before adopting the time-of-use electricity price. The TOU price is set as shown in Table 2. The ten-day load
data before and after the implementation of the time-of-use electricity price is passed through the price demand matrix. Regression analysis, constructing the demand price elasticity user response model, and obtaining the user load forecast value.

**Table 2. Details of TOU price**

| Time             | Peak load period | Middle load period | Load valley period |
|------------------|------------------|--------------------|--------------------|
| 09:00-12:00      | 1.455            | 1.1048             | 0.8769             |
| 17:00-22:00      | 1.1048           | 0.8769             |                    |
| 08:00-09:00      | 1.455            |                    |                    |
| 12:00-17:00      | 1.1048           |                    |                    |
| 22:00-23:00      | 0.8769           |                    |                    |

5.2. Dynamic electricity price

Under the new dynamic electricity price mechanism, the predicted electric vehicle charging station load is incorporated into the original residential load, and the following load curve is drawn in figure 4. The curve can be used to visually find the fluctuation of the total load curve after implementing the dynamic electricity price. The electricity price has been somewhat flat. In addition, the main load characteristics can be analyzed by data:

1) The maximum peak-to-valley difference is reduced from the original 50.59 MW to 36.87 MW.
2) The maximum load is reduced from the 118.6 MW to 112 MW.
3) The variance of load fluctuation is reduced from the original 269.86 to 137.05.
4) The total load of electric vehicles increased, but the average user price dropped from the original 1.068 yuan/kW·h to 1.004 yuan/kW·h.

![Figure 4. Load curve under different electricity price mechanisms](image)

Through the above model and case analysis, it can bring a new idea to the charging price system of electric vehicles. Taking the electric vehicle charging station open to the outside of residential areas as an example, it can attract other vehicles outside the community by adopting this dynamic electricity price mechanism. Charging during the low load period. The same dynamic mechanism can also be applied to the price guidance of other loads.

6. Conclusions

This paper proposed a dynamic electricity price for electric vehicle charging stations near residential areas. Based on the data-driven, this paper analyzed the difference between the load characteristics of the original residential area before and after the electric vehicle charging load accessing in, and compared the TOU price with the dynamic price. The effectiveness of the dynamic electricity price
was verified by the ability of the network to cut the peaks and fill the valleys in the residential area. The most important results of the proposed approach are as follows.

1) The proposed dynamic electricity price is based on the original time-of-use electricity price, and the peak-to-valley period of the load is no longer a fixed period, but is automatically divided to the corresponding level by comparing the predicted dynamic load value with the threshold of dividing the peak valley.

2) The research object is aimed at the electric vehicle charging station near the residential area. Since the electricity usage habits of the residential area are difficult to change, the dynamic electricity price can be moved to attract other non-residential vehicles to charge and then load the peaks and fill the valley of this area.

3) After the guidance of dynamic electricity price, not only the demand for regional peak-cutting and valley filling is better realized, but also the average electricity price of users is reduced, and the economical efficiency of users is improved.

References
[1] Cai H and Chen Q Y 2018 J. Protection and Control of Modern Power Systems. 3 93-107
[2] Wu C X, Zhang J, Zhang X Y and Chen Z H 2019 J. Power system protection and control. 1-9
[3] Cao Y, Tang S and Li C 2012 J. IEEE Transactions on Smart Grid. 3 388-393.
[4] Gao Y J, Wang C and Lv M K 2014 J. Electric Power Automation Equipment. 34 8-12
[5] LIU J, Niu D X, Xing M, Guo L and Zheng S M 2014 J. Power System Technology 38 1346-51
[6] Chen L and LU S Y 2018 J. Southern Energy Construction 5 51-58
[7] Liu W and Zhang Z S 2019 J. Proceedings of the CSU-EPSA 1-8
[8] Li C L 2017 D. North China Electric Power University