Aggregation Optimization Method of Virtual Energy Storage for Electric Vehicles Considering User Elasticity

Lu Liu¹, Meng Niu¹, Bei Li¹, Yue Zhang²,³*, Mengjiao Zou²,³, Dunnan Liu²,³, Tingting Zhang²,³, Lingxiang Wang²,³, Shanshan Shang²,³ and Mingguang Liu²,³

¹ State Key Laboratory of Operation and Control of Renewable Energy & Storage Systems (China Electric Power Research Institute), Beijing 100192, China
² Beijing Huadian Energy Internet Research Institute Co., Ltd, Beijing, 102206, China
³ North China Electric Power University, Beijing, 102206, China

*Corresponding author’s e-mail: 120202206130@ncepu.edu.cn

Abstract. With the continuous development of electric vehicle charging facilities, the impact of electric vehicles on the power grid is growing. Considering the automatic demand response technology of smart grid, charging pile operators participate in the demand response plan and guide users to charge according to the price signal or incentive mechanism, which can ensure the safety of the power grid and reduce the negative effects of electric vehicles on the grid influence. Based on the theory of demand side response elasticity, this paper analyzes the whole process of electric vehicle users’ participation in demand response and its influencing factors, classifies electric vehicle users based on demand response, and then quantitatively analyzes users’ demand response from the perspective of electricity price elasticity and consumption psychology. Finally, the demand side response model with user participation is established. The application of the model can effectively improve the enthusiasm of electric vehicle users to participate in demand side response, and reduce the negative impact of electric vehicles on the power grid.

1. Introduction

With the continuous promotion of electric vehicles, the number of charging piles is increasing, and the impact of electric vehicles on the power grid is becoming more and more serious, especially its charging mode and using time. Regional centralized charging will increase the valley peak difference of power grid, reduce the security of power grid, and cause certain economic loss and resource waste, and even cause the load rate of power equipment to increase safety accident[1]. Considering the automatic demand response technology of smart grid, charging pile operators participate in the demand response plan of power grid company through recommendation model, which can not only provide personalized recommendation service for users, but also guide users to charge orderly according to price signal or incentive mechanism. This can effectively ensure the security of the power grid, reduce the negative impact of electric vehicles on the power grid, and is of great significance to promote the vigorous development of the electric vehicle industry[2].

Based on the theory of demand side response elasticity, this paper analyzes the whole process of electric vehicle users’ participation in demand response and its influencing factors, classifies the electric vehicle users based on the demand response, and then quantitatively analyzes the users’ demand response from the perspective of price elasticity and consumption psychology. Finally, the demand side response model of user participation is established to improve the enthusiasm of electric vehicle users to...
participate in demand side response, and reduce the negative impact of electric vehicles on the power grid.

2. Influencing factors of user response

2.1. Battery cost
Participation in V2G will lead to the cost of battery life degradation. Obviously, the user's acceptance of V2G will also change with the change of battery cost. When the battery cost is high, the unit cost of vehicle participating in energy storage of power system is higher, and the actual acceptance of users is lower; when the battery cost drops significantly, the cost of V2G will also decrease, and the user's acceptance will be improved.

2.2. Rebate price
According to the principle of consumer psychology, there is a minimum perceptible difference (difference threshold) between price and user's stimulation. Within the range of this difference threshold, the user basically has no response or very small response, that is, the insensitive period (equivalent to the dead zone); when the range of the difference threshold is exceeded, the user will respond, and it is related to the stimulus degree, that is, the normal response period (equivalent to the linear zone); The user also has a saturation value to the stimulus. Beyond this value, the user has no further response, that is, the response limit period (equivalent to the saturation region).

3. Classification of electric vehicle users based on demand response
In the actual situation, the power consumption mode of users is related to many factors, not only related to their consumption behavior, but also to the characteristics of users' load and the type of vehicles. Therefore, according to the demand response degree, the electric vehicle users are divided into the following three categories.

Class A, flexible EV: In the process of grid connection, it can be in the discharge state, and the charging and discharging power can be flexibly adjusted within the adjustable range. That is to say, after the implementation of time of use price, users actively change the electricity consumption habits of electric vehicles, participate in orderly charging, and choose to use V2G technology to participate in the operation of discharging the grid.

Class B, reducible EV: The power can be reduced in the process of grid connection, but it is not fed to the aggregator, that is, it can not be in the discharge state. That is to say, after the implementation of time of use tariff, users actively change their electricity habits and participate in orderly charging. However, due to battery quality problems or concerns about V2G technology, such users choose not to use V2G technology to discharge the power grid.

Class C, rigid EV: Charging at rated power immediately after grid connection until reaching the expected power. After the implementation of time of use tariff, that is, consumers will not change the electricity consumption habits of electric vehicles, nor participate in the discharge operation of V2G technology to the power grid. Such users are usually electric vehicles with strict charging time requirements, such as buses, taxis, etc.

The following table summarizes the characteristics of these three types of users.

| Classification of electric vehicle users | Participate in response or not | Involved in charging or not |
|-----------------------------------------|-------------------------------|-----------------------------|
| Class A (flexibility)                   | Yes                           | Yes                         |
| Class B (reducibility)                  | Yes                           | No                          |
| Class C (rigid)                         | No                            | No                          |
4. Quantitative analysis of user demand response

4.1. Demand response model based on electricity price elasticity

Demand elasticity matrix is one of the typical characterization and analysis methods of user demand response behavior, which is composed of self-elasticity coefficient and cross elasticity coefficient in different periods[3].

Demand elasticity of electricity price refers to the sensitivity of demand to price changes. The demand decreases with the increase of electricity price. The demand price elasticity model (also called electricity price elasticity model) can be used to represent the response of electric vehicle users to charging price, which is shown in Figure 1. The slope of the curve in the figure is the demand elasticity of electricity price, which can be obtained by formula (1).

\[ e_{k,t} = \frac{\partial q}{\partial p} = \frac{\Delta q_t / q_t^0}{\Delta p_t / p_t^0} = \frac{q_0}{p_0} \cdot \frac{dq}{dp} \]  

Where:
- \( e_{k,t} \) is price elasticity of demand; 
- \( k \) represents user \( K \); 
- \( t \) represents time, \( t = 1, 2, ..., n \); 
- \( q_t^0 \) represents power load at time \( t \) before implementation of demand response; 
- \( p_t^0 \) represents electricity price at time \( t \) before demand response implementation; 
- \( \Delta q_t \) represents load variation at time \( t \) after demand response implementation; 
- \( \Delta p_t \) represents the price change momentum at time \( t \) after the implementation of demand response.

In practice, the electricity consumption of most users at a certain time is not only related to the electricity price at that time, but also affected by the electricity price of neighboring times. Therefore, using the self-elastic coefficient and cross elastic coefficient, the formula is as follows:

\[ e_{ij} = \frac{\partial q_i / q_i^0}{\partial p_j / p_j^0} \]  

and

\[ e_{ij} = \frac{\partial q_i / q_i^0}{\partial p_i / p_i^0} \]  

Where \( i \) and \( j \) represent different time periods.

Therefore, after users participate in the price type demand response, the load demand change is calculated as follows:

\[
\begin{bmatrix}
\partial q_1 / q_1^0 \\
\partial q_2 / q_2^0 \\
\vdots \\
\partial q_n / q_n^0
\end{bmatrix}
= e_{k,t} \times
\begin{bmatrix}
\partial p_1 / p_1^0 \\
\partial p_2 / p_2^0 \\
\vdots \\
\partial p_n / p_n^0
\end{bmatrix}
\]  

Where
\[ e_{k,t} = \begin{bmatrix} e_{k,11} & e_{k,12} & \cdots & e_{k,1n} \\ e_{k,21} & e_{k,22} & \cdots & e_{k,2n} \\ \vdots & \vdots & \ddots & \vdots \\ e_{k,n1} & e_{k,n2} & \cdots & e_{k,nn} \end{bmatrix} = \begin{pmatrix} e_{k,1} & e_{k,2} & \cdots & e_{k,n} \end{pmatrix} \]  

\( e_{k,t} \) is the demand elasticity matrix of user \( k \) in time period \( t \), the diagonal element is the self elasticity coefficient, the other elements are the cross elasticity coefficient, vector \( \epsilon_{k,t} \) reflect the response of time period \( i \) to itself \( e_{k,ii} \) and the response \( e_{k,ji} \) of other periods to period \( i \).

The load demand \( q_t \) is calculated after the user participates in the response of price type demand.

Finally, we can get the final price type demand response model, the specific formula is[4]:

\[ q_t = q^0_t \times \left( 1 + \sum_{t=1}^{24} e_{k,t} \times \frac{[P_t - P^0_t]}{P^0_t} \right) \]  

4.2. Demand response model based on consumer psychology

The theory of electricity price elasticity can explain the influence of price leverage on the sensitivity of consumers to electricity consumption, but it ignores the saturation problem and threshold problem in the price theory. Therefore, based on the theory of electricity price elasticity, it is necessary to further study the consumer psychology to describe the user's response to TOU price more accurately.

The demand response of electricity price is to guide users to charge when the price is low and discharge when the price is high, so as to earn the price difference[5]. The difference between peak and valley prices will affect the demand response ratio of users. Users are not willing to change the charging mode and respond in all ranges of electricity price changes. Only when the change of electricity price exceeds a certain range, users are willing to change their electricity consumption habits, that is, there is an upper and lower threshold value for customer response.

4.2.1. Load transfer rate curve from peak period to valley period

The following figure shows the quantitative model of demand responsiveness of electric vehicle users under the peak valley transfer mode, in which the abscissa \( \Delta p_{pv} \) represents the charging price difference between peak charging period and valley charging period, ordinate \( \lambda_{pv} \) is the load transfer rate, that is, the response of user participation.

![Figure 2. Load transfer rate curve from peak period to valley period.](image)

There are three main sections in this model: Dead Zone, linear growth zone and saturation zone. To determine the function, three parameters, namely dead zone threshold, linear segment slope and saturation threshold, are needed. The concept of load transfer rate is introduced, and the load transfer rate is defined as the ratio of the user load transferred from the high price period to the low price period and the high price period load after the implementation of the peak valley price, that is, the user's demand response. Lambda \( \lambda_{pv}^{max} \) is the maximum demand response. As we can see, \( l_{pv} \) is the threshold value of customer demand response, which is also the threshold of dead zone. Only when PV is used can users participate in the response of electricity price demand. The area of PV less than \( l_{pv} \) is called dead zone.
When the peak valley price difference is within this range, it can be considered that no user is willing to participate in the time of use price response of electric vehicles. When the difference between peak and valley price is greater than $l_{pv}$ and less than $h_{pv}$ at the same time, it is a Linear growth region of demand response. In this range, the demand responsiveness of consumers increases linearly with the increase of time-of-use price difference between peak and valley. When the difference between peak and valley price is greater than $h_{pv}$, the user's demand response will no longer increase and enter the saturation region. $h_{pv}$ is the saturation threshold of user demand response, which is also the saturation region threshold. To sum up, $\lambda_{pv}$ can be expressed as:

$$
\lambda_{pv} = \begin{cases} 
0 & 0 < \Delta p_{pv} < l_{pv} \\
\frac{k_{pv}(\Delta p_{pv} - l_{pv})}{\lambda_{max}} & l_{pv} < \Delta p_{pv} < h_{pv} \\
\frac{\Delta p_{pv}}{\lambda_{max}} & \Delta p_{pv} > h_{pv} 
\end{cases}
\tag{7}
$$

Among them, $k_{pv}$ is the function slope of the linear region.

Similarly, there will be load transfer rate curve from peak period to normal period and load transfer rate curve from time period to valley period.

4.2.2. Load transfer rate curve from peak period to normal period

$$
\lambda_{pf} = \begin{cases} 
0 & 0 < \Delta p_{pf} < l_{pf} \\
\frac{k_{pf}(\Delta p_{pf} - l_{pf})}{\lambda_{max}} & l_{pf} < \Delta p_{pf} < h_{pf} \\
\frac{\Delta p_{pf}}{\lambda_{max}} & \Delta p_{pf} > h_{pf} 
\end{cases}
\tag{8}
$$

Among them, $k_{pf}$ is the function slope of the linear region.

![Figure 3. Load transfer rate curve from peak period to normal period.](image)

4.2.3. Load transfer rate curve from normal period to valley period

$$
\lambda_{fv} = \begin{cases} 
0 & 0 < \Delta p_{fv} < l_{fv} \\
\frac{k_{fv}(\Delta p_{fv} - l_{fv})}{\lambda_{max}} & l_{fv} < \Delta p_{fv} < h_{fv} \\
\frac{\Delta p_{fv}}{\lambda_{max}} & \Delta p_{fv} > h_{fv} 
\end{cases}
\tag{9}
$$

Among them, $k_{pf}$ is the function slope of the linear region.
Figure 4. Load transfer rate curve from peacetime to Valley.

Based on the above three types of load transfer rate curves, the load estimates of each period can be expressed as follows:

\[
L_t = L_{t0} + \lambda_p L_{p0} + \lambda_v L_{v0} + \lambda_f L_{f0}, \quad t \in T_v
\]

\[
L_t = L_{t0} + \lambda_p L_{p0} - \lambda_v L_{v0} - \lambda_f L_{f0}, \quad t \in T_f
\]

\[
L_t = L_{t0} - \lambda_p L_{p0} - \lambda_f L_{f0}, \quad t \in T_p
\]

(10)

Where: \( T_v, T_f, T_p \) refers to valley period, normal period and peak period respectively, and \( t \) is any of them; \( L_{t0} \), \( L_t \) are the measured load of \( t \) period before the implementation of time of use tariff and the fitting load of \( t \) period after the implementation of time of use tariff; \( \bar{L}_{p0}, \bar{L}_{v0}, \bar{L}_{f0} \) are the average values of the total load in the corresponding periods before the implementation.

5. Conclusion

The participation of electric vehicle users in demand side response is an important means of power grid management in the future. Electricity price is the main factor that affects consumers' electricity consumption behavior. This paper analyzes the whole process of electric vehicle users' participation in demand response and its influencing factors, classifies electric vehicle users based on demand response, and finally establishes a demand response model based on electricity price elasticity and consumer psychology. The model simulates the power consumption of consumers through demand elasticity, and provides the optimal dynamic electricity price for electric vehicle users, forming a market environment in which the price affects the demand. Users can actively participate in the optimization process and change the consumption pattern according to the price signals of the electricity market, so as to increase the efficiency and flexibility of the electricity market.

Acknowledgments

This paper is supported by the project “Research and demonstration of key technologies of virtual energy storage optimization and load control for electric vehicle cluster” (contract number: 5418-202018247A-0-0-00). I would like to express my heartfelt thanks to them.

References

[1] Jin, Z.P. (2019) Analysis of the impact of large-scale electric vehicle access on power grid safe operation and control measures. Equipment maintenance technology, 4: 159

[2] Shi, L., Ge, X.L., Gu, W., Yang, X. (2020) Research on electric vehicle charging load considering demand response. Electrical measurement and instrumentation: 1-6.

[3] Konda, S.R., Al-Sumaiti, A.S., Panwar, K.L., Ketan, B. (2019) Impact of Load Profile on Dynamic Interactions Between Energy Markets: A Case Study of Power Exchange and Demand Response Exchange. IEEE Transactions on Industrial Informatics,15: 5855 - 5866

[4] Ju, L.W. (2017) Research on demand response participation in clean energy integrated consumption and benefit evaluation model. North China Electric Power University (Beijing).
[5] Yang, H.J., Wang, L., Zhang, Y.Y., Tai, H.M., Ma, Y.H., Zhou, M.(2019) Reliability Evaluation of Power System Considering Time of Use Electricity Pricing. IEEE Transactions on Power Systems, 34.