Coupling mechanism of electric vehicle and grid under the background of smart grid

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Abstract. With the development of smart distribution technology in the future, electric vehicle users can not only charge reasonably based on peak-valley price, they can also discharge electricity into the power grid to realize their economic benefit when it’s necessary and thus promote peak load shifting. According to the characteristic that future electric vehicles can discharge, this paper studies the interaction effect between electric vehicles and the grid based on TOU (time of use) Price Strategy. In this paper, four scenarios are used to compare the change of grid load after implementing TOU Price Strategy. The results show that the wide access of electric vehicles can effectively reduce peak and valley difference.

1. Introduction
In the future, with the development of smart power technology, the coupling and interaction characteristics between the load end and the grid will become more and more significant [1]. For electric vehicles, they can carry out the real time electric energy exchange with the grid based on V2G (Vehicle-to-Grid) technology. V2G technology refers to the technology that electric vehicles act as mobile energy storage sources to realize the mutual flow of energy with the grid. Unlike the current ordered charging technology, V2G can use battery energy storage devices to transmit power to the grid during peak load or emergency situations. This technology can use the price signal to guide users to charge and discharge so that users can realize the target of optimizing the power consumption, and the power grid can realize the economic dispatch and alleviate the pressure in peak periods [2-5]. At present, many scholars have done relevant research, such as discussing the benefit of different charging modes and combining the EVs with energy storage technologies [6-7], but the research which integrates electric vehicle and real-time electricity price is less. Balijepalli et al. analysed the benefits of demand response and reviewed the correlational research on it, including research on EVs [8] and this study has referential value for our research to a certain extent. This paper analyses the interaction effect of electric vehicles and grid based on the real time electricity price under different scenarios. The research framework is illustrated in the figure 1 below.
Figure 1. Conceptual Framework.

2. Analysis on coupling characteristics of electric vehicles under TOU price

2.1. Coupling principle of an electric vehicle under TOU price

Time of use (TOU) price is a kind of electricity price scheme which is set up by the power company at different power consumption time. At present, some parts of China adopts TOU price, which divides the period into three sections, and sets up different electrovalence at different time [9]. The peak and valley TOU price can be expressed by formula (1).

\[
f(t) = \begin{cases} 
  p_p & t_p \leq t \leq t_p + p_2 \\
  p_s & t_s \leq t \leq t_s + s_2 \\
  p_o & t_o \leq t \leq t_o + o_2 
\end{cases}
\]  

(1)

Where \( p_p \) is the price at peak period; \( p_s \) is the price at flat load period; \( p_o \) is the price at low load period. And \([t_1, t_2]\) represents the duration of different load level.

Based on the above TOU pricing strategy, the price demand elasticity can be used to describe the charging decision made by users at different levels of electricity price, that is to say, the ratio of charge change rate to price change rate of electric vehicles:

\[
\varepsilon_{uv} = \frac{\Delta Q_u / Q_u^{(0)}}{\Delta \rho_v / \rho_v^{(0)}} 
\]  

(2)

\[
\Delta Q_u = Q_u - Q_u^{(0)} 
\]  

(3)

\[
\Delta \rho_v = \rho_v - \rho_v^{(0)} 
\]  

(4)

Where \( Q_u^{(0)} \) is the charging load before implementing TOU price at the period \( t_u \); \( Q_u \) is the charging load after implementing TOU price at the period \( t_u \); \( \rho_v^{(0)} \) is the price before implementing TOU price at the period \( t_v \); \( \rho_v \) is the price after implementing TOU price at the
period $t_v$. If $t_u$ is equal to $t_v$, $\varepsilon_{uv}$ ($\varepsilon_{uv} < 0$) is the self-elasticity coefficient, while $\varepsilon_{uv}$ represents the cross-elasticity coefficient which is greater than zero.

After the implementing of TOU price, as rational consumers, users can change the charging load from the high price period to the low price period without changing the charging demand and charging position so that they can reduce their charging cost. In this paper, the peak and valley TOU price is used as an incentive signal, and the situation classification is shown in table 1.

2.2. Coupling scenarios of electric vehicles under TOU price
Considering the difference in preferences for electricity prices of different users, the consumers can choose whether to change the charging starting time and whether to participate in the V2G after implementing the TOU price policy. Thus this paper divides response behaviours of electric vehicle users into the following four scenarios and then calculates the response behavior under the first three scenarios. Scenario D is not considered in the calculation because there is no change in both of the parts. The scenarios are showed in table 1.

Table 1. Scenario classification.

| Scenarios | Change The Charging Start Time | Participate In V2G |
|-----------|---------------------------------|-------------------|
| A         | √                               | ×                 |
| B         | ×                               | √                 |
| C         | √                               | √                 |
| D         | ×                               | ×                 |

2.3. Response behaviour of electric vehicles under scene A
Suppose that after implementing the TOU price, the users will change the charging starting time because of the price incentive, but not participate in the V2G. The charging load $\Delta Q_{uv}$ that transfers from the $T_u$ period to the $T_v$ period of the user can be expressed by equation (5). And the charging load $Q_u$ during the period $T_u$ can be expressed as equation (6).

$$\Delta Q_{uv} = \varepsilon_{uv} \times Q_{u}^{(0)} \times \frac{P_u - P_v}{\rho_v}$$  \hspace{1cm} (5)

$$Q_u = Q_u^{(0)} - \Delta Q_{uv} + \Delta Q_{vu}$$  \hspace{1cm} (6)

2.4. Response behaviour of electric vehicles under scene B
Suppose that after implementing the TOU price, the user does not change the charging start time, but instead they supply electricity to the grid when the electricity price is high.

In the scene B, the daily discharge coefficient $\beta$ is the ratio of the daily discharge energy to the total battery capacity. Assume that each car has a full initial battery state and won't charge until the battery has very low capacity. We can get the number of days per charge $C_d$. When considering discharge, the ratio of average daily consumption electricity to the total capacity is $\beta + 1/C_d$. The daily charge coefficient $\gamma$ is $C_d \times (\beta + 1/C_d)$. The charging load during trough period, flat period and peak period are respectively shown as equation (7), (8) and (9).

$$Q_o = Q_o^{(0)} + (\gamma - 1) \times (Q_o^{(0)} + Q_s^{(0)} + Q_p^{(0)})$$  \hspace{1cm} (7)

$$Q_s = Q_s^{(0)}$$  \hspace{1cm} (8)

$$Q_p = Q_p^{(0)} - \beta \times (Q_o^{(0)} + Q_s^{(0)} + Q_p^{(0)})$$  \hspace{1cm} (9)
Where \( Q_o^{(0)} \) is the charging load at valley period before implementing the policy of TOU price.

2.5. **Response behaviour of electric vehicles under scene C**

In this scene, users change the beginning time to charge and also participate in V2G. They supply power to the grid only during peak hours and will give priority to charge during the trough hours. The charging load during trough period, flat period and peak period are respectively shown as equation (10), (11) and (12).

\[
Q_o = Q_o^{(0)} - \Delta Q_{op} + \Delta Q_{po} - \Delta Q_{os} + \Delta Q_{so} + \alpha \Delta Q_{v2g} \tag{10}
\]

\[
Q_s = Q_s^{(0)} - \Delta Q_{sp} + \Delta Q_{ps} - \Delta Q_{so} + \Delta Q_{os} + (1 - \alpha) \Delta Q_{v2g} \tag{11}
\]

\[
Q_p = Q_p^{(0)} - \Delta Q_{ps} + \Delta Q_{sp} - \Delta Q_{po} + \Delta Q_{op} - \Delta Q_{v2g} \tag{12}
\]

2.6. **Response behaviour of electric vehicles under scene D:**

In the scenario D, assuming that the electric car users will not change user behaviour under the TOU price. And this paper doesn’t consider.

3. **Case study**

3.1. **Coupling results of electric vehicles under scene A**

Before electric vehicles coupling with the grid, the power grid does not carry out TOU price policy, and electric vehicle only randomly charge and discharge. Table 2 shows the price of each kind of users before participating in the coupling and the price of each period after the coupling.

| Items  | Time Periods       | TOU Price | Initial Price |
|--------|--------------------|-----------|---------------|
| Peak   | 8:00-11:00, 17:00-20:00 | 0.6851    |               |
| Shoulder | 12:00-16:00, 21:00-23:00 | 0.4538    | 0.4           |
| Valley | 1:00-7:00, 24:00    | 0.2429    |               |

Electricity demand elasticity takes into account the self-price elasticity and cross-price elasticity. That is to say, the fluctuation of the power load at a given time is not only affected by the change of the price at that time, but also by the change of the price at other times. The elastic matrix is 24 x 24 dimensions. Using equations (1)-(6) can calculate load variation under different electric vehicle penetrations.

**Figure 2.** Grid load of different electric vehicle market penetration under scenario A.
The figure 2 shows the power load after electric vehicles coupling with the grid at 1%, 3%, and 6% penetration respectively. The result reveals that the peak and valley difference of the power grid is significantly reduced after electric vehicles coupling with the grid. And the greater the penetration rate of electric vehicles is, the smaller the fluctuation of the load curve.

In order to estimate the influence of different price levels on the load change of power grid, different TOU prices are selected to calculate. The price levels are shown in table 3.

Table 3. Different Price Levels (unit: yuan / kWh).

| Num | Price Category | Peak  | Shoulder | Valley  |
|-----|----------------|-------|----------|---------|
| 1   | Low price      | 0.6851| 0.4538   | 0.2429  |
| 2   | Medium price   | 0.7208| 0.4805   | 0.2571  |
| 3   | High price     | 1.0592| 0.7061   | 0.3778  |

Figure 3 shows the calculation results at three price levels. The results show that only considering the charging behaviour of EV, the higher the price is, the better of the effect for peak shaving and valley filling will be.

3.2. Coupling results of electric vehicles under scene B
During peak period, load change of power grid is different in different discharge ratios. In this section, the paper selects the different ratios to calculate the change situation of the grid load. The peak discharge ratios are 40%, 60% and 80% respectively. The result is shown in figure 4.
Figure 4. Power load variation under different discharge ratios.

It can be seen that the higher the discharge ratio is, the more obvious the peak shaving and valley filling benefits of the power grid will be. Therefore, in the future, with the popularity of V2G technology, the impact of electric vehicles on the power grid load will gradually emerge. Unlike scenario A, it is assumed that electric vehicles' recharge is only compensated in valley periods, so there is no change in the load curve at shoulder periods.

3.3. Coupling results of electric vehicles under scene C

In scenario C, the change of power grid load after the electric vehicle involving in power grid interaction is calculated under different electricity prices and different discharge ratios.

Figure 5. Grid load changes under different price conditions (electric vehicle discharge ratio of 60%).

Figure 5 shows the change of grid load under 60% discharge ratio of the electric vehicle. The result reveals that the higher the electricity price level is, the more obvious the effect of peak shaving and valley filling will be.

3.4. Comparison

Based on the above three cases, this paper introduces the peak to valley ratio to compare the coupling effect of the three scenarios. The peak to valley ratio refers to the ratio of maximum load to minimum load of grid load which can reflect the peak load difference within one day. The greater the peak to
valley ratio is, the more unstable the load on the grid will be. This section calculates the ratio of the grid load under different scenarios, and the results are shown in figure 6.

![Figure 6. Peak to valley ratio of grid load in different scenarios.](image)

As can be seen from the figure 6, the peak to valley ratio is relatively large before electric vehicles participating in coupling. The first three scenarios reduced the peak to valley ratio at different degrees. The greater the difference in TOU prices is, the lower the ratio will be. The higher the penetration rate of electric vehicles is, the lower the peak to valley ratio of power grid load will be. Based on the above research, it can be seen that the charging and discharging behavior of the electric vehicle users will bring significant fluctuation effect to the grid load. A reasonable TOU pricing strategy can motivate EV users to charge and discharge reasonably to stabilize the peak to valley difference.

4. Conclusions

In the future, with the continuous popularization of V2G technology for electric vehicles, the power grid load will face greater fluctuation. In order to restrain the fluctuation of large scale charging and discharging behavior of electric vehicles, a corresponding TOU pricing mechanism should be developed. It can guide electric vehicle users to reasonably participate in coupling and interacting with grid.

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