Research on Electric Vehicles Considering V2G Technology in Photovoltaic Residential Areas

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Abstract. With the emergence of global energy crisis, electric vehicles and photovoltaic power generation have been widely used as an effective way. However, the connection of large-scale electric vehicles and the uncertainty of photovoltaic power generation also do harm to the operation of the power distribution system. In order to solve the problem that electrical load of resident varies big between peak and valley caused by disordered charging of electric vehicles, this paper constructed a cooperative scheduling model for V2G electric vehicles and photovoltaic power generation. Taking residential community as research background, this paper try to solve the SOC threshold of electric vehicle discharge by reducing the grid load variance and the objective function. The reasonable SOC threshold is optimized by the improved particle swarm optimization algorithm, and the reasonable SOC threshold can be compared and analyzed to reduce the load variance value more effectively. Finally, the paper takes one residential area as an example to prove the rationality and practicality of the proposed model.

1. Introduction
In recent years, energy issues have become one of the most important issues facing the world. A series of renewable energy sources such as photovoltaic power generation and wind power generation are gradually slowing down the dependence on traditional energy sources. EVs(electric vehicles) are powered by electric energy and do not produce greenhouse gases. With the in-depth study of electric vehicle V2G (vehicle-to-grid) technology, electric vehicle batteries can be used as a load or as a power source[1]. Therefore, making full use of the characteristics of electric vehicle charging and discharging and renewable energy is of great significance to the reduction of grid load fluctuations.

The literature [2] discussed that the charging time of electric vehicles is mostly the same as that of grid load, and the phenomenon of peak load on the grid load occurs. Therefore, a reasonable load management scheme is needed to distribute electric vehicle charging. In [3], the random charge and discharge behaviors of hybrid electric vehicles and the rules of wind power generation and photovoltaic power generation are analyzed. The cooperative scheduling model considering V2G is constructed to optimize the system network loss. In the above literature, the disordered charging of electric vehicles and the original load of the distribution network are discussed, which makes the load peak-to-valley difference increase, especially in the residential area load. At the same time, although the V2G strategy can reduce the load network loss, it does not specifically study the impact of different electric vehicle discharge states on the system.

Based on the research background of residential community, this paper constructs a V2G electric vehicle charging and discharging and photovoltaic output collaborative scheduling model to reduce the
total load peak-to-valley difference of residential areas. Firstly, according to the probability density distribution of the electric vehicle V2G and the photovoltaic power generation system, the driving law and photovoltaic power generation characteristics of the electric vehicle are obtained. Secondly, with the load variance and minimum as the objective function, a reasonable SOC threshold is optimized to respond to the discharge state of the electric vehicle. Finally, the results of the optimization by the improved particle swarm optimization algorithm are compared.

2. Probability distribution of electric vehicles and photovoltaic power generation systems

2.1. Electric vehicle slow charging and discharging power model

At present, the battery of electric vehicles is mainly a lithium battery\(^\text{[4]}\). The charging and discharging powers \( P_C(t) \) and \( P_F(t) \) of electric vehicles are normally distributed within 3-4kW\(^\text{[5]}\).

2.2. Electric vehicle charging and discharging time

The approximate charging and discharging time calculation formula for electric vehicles is as follows:

\[
T_C = \frac{LW_{100}}{100P_C \eta}
\]

Where \( T_C \) is the charging time, the unit is h; \( L \) is the daily driving mileage, the unit is km; \( W_{100} \) is the power consumption per 100 km, the unit is kWh; \( \eta \) is the charging efficiency, which is 0.95.

In 5 minute intervals, the day is divided into 288 time periods. Then the charging period of each electric vehicle \( T_n \) is (the time period \( T_n \) is rounded up):

\[
T_n = \frac{T_C}{5}
\]

2.3. Driving rules of electric vehicles

According to the US Department of Transportation's survey of household cars in the United States, more than 85% of EVs are not used in one day, and there is plenty of time to charge at home.

(1) Travel/return time probability density distribution function:

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

Where \( x \) is a moment between [0, 24], \( \mu_x = 17.6 \), \( \sigma_x = 3.4 \).

(2) Probability density function for daily mileage:

\[
f_d(x_d) = \frac{1}{x_d \sigma_d \sqrt{2\pi}} \exp\left[-\frac{(\ln x_d - \mu_d)^2}{2\sigma_d^2}\right]
\]

Where \( x_d \) is the daily mileage (unit: mile); and \( \mu_d = 3.20 \), \( \sigma_d = 0.88 \).

2.4. Probability distribution of photovoltaic power generation system output

Photovoltaic has a strong intermittent nature. Studies have shown that the sun's light intensity \( r(t) \) at a certain moment satisfies the Beta distribution.

\[
f(r(t)) = \frac{\Gamma(\alpha + \beta)}{r(t)^{\alpha - 1} r(t)^{\beta - 1}} \left( \frac{r(t)}{r_{\text{max}}(t)} \right)^{\alpha - 1} \left( 1 - \frac{r(t)}{r_{\text{max}}(t)} \right)^{\beta - 1}
\]

Where: \( \Gamma(\cdot) \) is the Gamma function; \( r_{\text{max}}(t) \) is the maximum illumination intensity at time \( t \); \( \alpha \) and \( \beta \) are the Bate distribution shape parameters.

Photovoltaic power generation system output function\(^\text{[6]}\):
\[ P_G(t) = r(t) A \eta \]  

Where: \( A \) is the total area of the photovoltaic power generation array; \( \eta \) is the photoelectric conversion efficiency.

Photovoltaic power generation probability density function\(^7\):

\[
f(P_g(t)) = \frac{\Gamma(\alpha + \beta)}{r(\alpha)r(\beta)} \left( \frac{P_g(t)}{P_{\text{max}}(t)} \right)^{\alpha-1} \left(1 - \frac{P_g(t)}{P_{\text{max}}(t)} \right)^{\beta-1}
\]  

Among them, \( P_{\text{max}}(t) \) is the maximum output value of the photovoltaic generator set at time \( t \):

\[
P_{\text{max}}(t) = A \eta r_{\text{max}}(t)
\]

3. Based on V2G of electric vehicle optimization scheduling mode

3.1. Objective function

According to the conventional V2G, every electric vehicle energy storage battery can discharge a certain amount of remaining SOC. According to the driving law of electric vehicles, the number of EVs returned at time 19:00 and after is larger. If the vehicle with the remaining value of the stored power at the electric vehicle at this time satisfies the conventional set value (0.2), the vehicle selects to discharge, and the load peak sharply drops during the late peak period, resulting in a larger peak-to-valley difference. Therefore, a reasonable SOC threshold is determined, and the SOC value of the electric vehicle discharge is controlled to change the number of electric vehicles. This paper chooses to use the total variance of the load to measure the peak-to-valley difference of the whole system. The variance load is minimized by optimizing a reasonable overall SOC threshold.

Use the grid total load variance and minimum to optimize the objective function, namely:

\[
\min F(t) = \sum_{j=1}^{100} \sum_{i=1}^{288} \left( P(t) - \frac{1}{T} \sum_{i=1}^{T} P(t) \right)^2
\]  

Where: \( P(t) \) is the total load of the residential area of the system during the \( t \) period of the day. It includes the initial load \( P_i(t) \) of the entire residential area, the power \( P_G(t) \) of the photovoltaic output, and the charging and discharging powers \( P_C(t) \) and \( P_F(t) \) of the electric vehicle participating in the V2G strategy, and the set power consumption is positive.

\[
P(t) = P_i(t) - P_G(t) - P_F(t) + P_C(t)
\]

3.2. Restrictions

1) Electric vehicles charging and discharging time constraints

According to the daily load law of the residential area, it is assumed that the peak load time of the system is the noon time period \([t_{f1}, t_{f2}]\), the evening time period \([t_{f3}, t_{f4}]\), and the rest is the valley period. The charging time of the electric vehicle at the peak time and the starting time of the discharge are \(t_{fc1}\) and \(t_{ff1}\), and the charging time and the discharging time at the end are \(t_{fc2}\) and \(t_{ff2}\). The initial charge and discharge start time in the valley is \(t_{gc1}\) and \(t_{gf1}\), and the charge and discharge time at the end of the valley is \(t_{gc2}\) and \(t_{gf2}\).

Charging time constraint:

\[
\begin{align*}
& t_{fc1} < t_{f1} < t_{f4} < t_{fc2} \\
& t_{fc2} - t_{fc1} \leq 24 - T_c \\
& t_{fc2}, t_{fc1} \in [0, 24]
\end{align*}
\]

Discharge time constraint:

\[
t_{f4} \leq t_{ff1} \leq t_{ff2} \leq t_{fc2}
\]

(2) Electric vehicle battery storage capacity constraints
\[ S_{\min} \leq S(t) \leq S_{\max} \]  

(13)

Among them, \( S_{\min} \) is the minimum storage capacity of the electric vehicle battery, and \( S_{\max} = eS \), \( S \) is the rated capacity of the electric vehicle battery storage, \( e \) is the minimum retained electricity ratio. \( S_{\max} \) is the maximum storage capacity of an electric vehicle battery. Due to battery loss, it cannot reach 100%, that is \( S_{\max} = (1 - \delta)S \), and \( \delta \) is the percentage of battery loss.

3.3. Algorithm features and processes

The main flow of this algorithm is as follows:

Step 1: According to the probability density function, sample the PV output, the return time of each electric vehicle, the charging and discharging power of EVs, the mileage of each electric vehicle, and the electric vehicle number that responds to V2G in each period, and extract 100 samples respectively;

Step 2: Using the improved particle swarm optimization algorithm to find the optimal SOC threshold for the whole day and the optimal SOC threshold for the time period, and make the load variance of 100 samples minimum;

Step 3: Compare the results of the three SOC thresholds to verify the effectiveness of the optimization.

4. Case analysis

4.1. Conditional assumption

(1) The users of electric vehicles are rational people. Users have all the information about charge and discharge electricity prices and can respond to V2G strategies.

(2) With the popularity of electric vehicles, it is assumed that 80% of the users in this community own electric vehicles.

(3) The charging device for electric vehicles fully meets the charging needs of residents.

4.2. Research object and parameter settings

This paper selects a total of 750 housing units in a residential area in a certain city in China. The number of EVs is 600. The model of the EV selected in this paper is Nissan Leaf 2, and it is \( S = 24 kWh \), \( \delta = 8\% \), \( e = 20\% \). Investigation of the collected light intensity characteristics residential city, the actual situation of photovoltaic function and output density residential area of 2.4 part. And then, \( A = 3042m^2 \), \( \eta = 0.15 \). Take the photovoltaic power of Figure 1 as the basic data.

![Figure 1. Photovoltaic power generation output graph.](image1)

![Figure 2. Residential area daily load curve.](image2)

The electricity consumption of residential areas has a strong regularity. This paper conduct statistics on the daily load of residential areas. At the same time, the electric vehicle random access cell is recorded for disorderly charging, and a typical daily maximum load curve is obtained as shown...
in Figure 2. The peak daily load of this cell is 3,080 kW, and there are two distinct peak load periods, [11:00-13:00] and [19:00-22:00].

4.3. Case study analysis

4.3.1. Comparison of daily load of residential area without optimized SOC threshold

It can be seen from Figure 3 and Figure 4 that when 600 EVs are disorderly charged, an obvious "peak peaking" phenomenon occurs in the daily load peak of the original residential area. Adding photovoltaics can effectively alleviate the load demand of residential areas during the day. During the 10:00-16:00 period, the peak hour load is significantly reduced. In order to study the influence of the SOC threshold on the load peak-to-valley difference when the EV is not optimized, this paper designs two programs for comparison. The first program is the disordered charging of electric vehicles. The second program is that the EV accesses the photovoltaic community and participates in the V2G strategy. It can be discharged when it meets the traditional setting value of 0.2. Since the peak of photovoltaic output is around 13:00, the peak load at noon is significantly lower than the original. At the same time, according to the daily driving law of electric vehicles, since there are more vehicles coming back after 16:00, there are relatively many vehicles that choose to discharge at this time, and the second load peak is particularly obvious.

4.3.2. Optimized SOC threshold

The third program is to set a reasonable discharge SOC value based on V2G and photovoltaic power generation. In this paper, the improved particle swarm optimization algorithm and optimization model are programmed and solved by MATLAB software. In the program, the number of particle groups is set to N=50, and the maximum number of iterations is 500.

Table 1. Load variance value under different conditions.

| Different schemes       | Load variance (GW^2) |
|-------------------------|----------------------|
| Original load           | 10.170               |
| The first program       | 11.241               |
| The second program      | 6.929                |
| The third program       | 4.026                |
Figure 5. Load curve of SOC in different programs.

Through simulation optimization, the SOC threshold of the whole day is 0.72. At the same time, calculate the variance of the load under different programs, as shown in Table 1. It can be seen from Table 1 that the implementation of the V2G technology can reduce the load peak-to-valley difference. By determining the SOC threshold of the discharge, the load peak-to-valley difference can be more effectively reduced.

5. Conclusion
(1) This paper establishes a collaborative scheduling model for electric vehicles and photovoltaic power generation that takes into account V2G for residential communities. In this paper, the SOC threshold of electric vehicle discharge is solved by reducing the variance of grid load as the objective function, and compared with other methods, the rationality of the model is verified.

(2) In practical applications, when building a new residential area or when the residential power distribution is not expanded, adding a photovoltaic system and optimizing a reasonable SOC threshold will not only effectively increase the access volume of the system electric vehicle, but also effectively reduce peak-to-valley difference and reduce system cost.

(3) The SOC threshold at the time of electric vehicle discharge can be optimized for multiple periods. This will further reduce the peak-to-valley difference of the load, and also select the optimal optimization scheme based on actual economic and technical considerations.

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