A Coordinated Charging Strategy for Electric Vehicles Based on Valley Load Tracking

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Abstract. Considering the negative impact of large-scale application of Electric Vehicles (EVs) on power network planning and operation, this paper proposes a coordinated charging strategy for EVs based on valley load tracking, aiming at reducing load fluctuation. By optimizing the charging sequence of EVs, the valley period of the daily load curve tends to be smooth, which plays a better role in filling the valley and reduces the peak-valley difference. Finally, an example is analyzed by Monte Carlo simulation, which proves that the proposed coordinated charging strategy is efficient and practical.

1. Introduction

Faced with the increasingly severe pressure of energy and environment, people pay more and more attention to environmental issues. Developed countries have actively begun to seek strategic emerging industries. New energy automobile industry is one of the strategic emerging industries that all countries in the world are competing to pursue. They have launched electric vehicles (EVs) development plans one after another to increase the development and application of core technologies in the EVs industry.

With the large-scale development of EVs, a large number of EVs connect to the grid which inevitably increases the load of power grid. The charging behavior of EVs is random, which may gather in a peak period to charge, resulting in the increase of peak-valley difference. Some studies in the United States have shown that[1], on the basis of fully controlling the charging behavior of EVs, the six regional power grids can only satisfy 50% of EVs charging demand. However, by controlling the charging load of EV with a reasonable method, it can not only optimize the load curve, but also combine with distributed power supply to improve the absorption capacity of distributed power supply. Most importantly, the Vehicle-to-grid (V2G) viewpoint is put forward[2], which means that EVs are regarded as a special energy storage device, which can interact with the power system and participate in the operation of power system.

Reference [3] Predicts users' actual driving habits by recording a large number of parking time and location data, designs a fuzzy logic reasoning system to simulate users' charging decision-making process, and finally calculates the charging load of EVs in hours. Reference [4] analyses the influence of EVs on the distribution network of two voltage levels in Gothenburg. The results show that when
the EVs charge at the same time, the load is heavy, and the line and transformer will be overloaded. Reference [5] evaluates the impact of EVs on the power system under different voltage control modes, taking into account the iterative relationship between the transmission network and the distribution network. Reference [6] also considers the demand of grid side and customer side. Aiming at reducing network loss and charging cost, a real-time intelligent charging control strategy is proposed. This strategy can make the EVs start charging as soon as possible while satisfying the constraints of safe operation of power system. Reference [7] proposed a fully distributed solution for PEVs Cooperative Charging problem which is a convex multi-time step problem. Reference [8] presented a Lyapunov optimization method to minimize the supply cost under unknown renewable supply, EV mobility, and grid electricity prices. Reference [9] proposed two strategies with objective functions considering minimization of total daily cost and peak-to-average ratio.

This paper takes the private EVs as the main research object, modeling the EV load, and analyzing the impact of a large number of EVs on the power system. On this basis, a coordinated charging control strategy of EVs based on valley load tracking is proposed. The coordinated charging strategy formed in this paper is simulated by Monte Carlo method. The simulation analysis shows that the coordinated charging strategy is effective. This simple and practical charging strategy can effectively reduce the peak-valley difference.

2. Charging characteristics of EVs

Establishing the charging model of EVs is the basis of studying the coordinated charging strategy. This paper only takes the electric private car as an example to analyze. The factors affecting charging characteristics of EVs mainly include the following:

1. Battery characteristics of private EVs. Battery characteristics mainly include type, capacity, charging rate and so on. In this paper, lithium-ion batteries are studied as an example. Lithium batteries have the characteristics of no memory. Intermittent charging has no effect on the life of lithium batteries. Charging characteristic curve can be approximated to constant power. Assuming that the battery capacity is 30 kWh, the power consumption per 100 km is 15 kWh, and the charging power is set to 3.2 kW, which is limited by the family charging facilities.

2. Travel rules and usage habits. Travel rules and usage habits mainly refer to users’ daily mileage and return time. These factors determine the total amount of charging. According to the survey results of the United States Department of Transportation in 2009[10], after normalizing the statistical data, the return time of vehicles can be expressed as a normal distribution function by the maximum likelihood estimation method, and its probability density function is shown as

\[
f_s = \begin{cases} 
\frac{1}{\sigma_s \sqrt{2\pi}} \exp \left( -\frac{(x - \mu_s)^2}{2\sigma_s^2} \right), & 0 < x < \mu_s - 12 \\
\frac{1}{\sigma_s \sqrt{2\pi}} \exp \left( -\frac{(x + 24 - \mu_s)^2}{2\sigma_s^2} \right), & \mu_s - 12 < x < 24 
\end{cases}
\]  

(1)

where, \( x \) is the return time of EV, \( \sigma_s \) is the standard deviation of 3.4, \( \mu_s \) is the expected value of 17.6.

The daily driving mileage of private EV is a normal distribution with \( N(\mu_D, \sigma_D^2) \) as its obedience parameter, and its probability density function is calculated as

\[
f_D(L) = \frac{1}{L \sigma_D \sqrt{2\pi}} \exp \left( -\frac{(\ln L - \mu_D)^2}{2\sigma_D^2} \right)
\]  

(2)

where, \( L \) is the daily driving mileage of EV, \( \sigma_D \) is the standard deviation of 3.2, \( \mu_D \) is the expected value of 0.88. In this paper, the above probability distribution model is used to simulate the coordinated charging strategy for EVs.
3. Coordinated charging strategy based on valley load tracking

Coordinated charging strategy is to use some methods to make charge during the valley period, to prevent the peak-valley difference of system load from increasing, in other words, to reduce load fluctuation. This paper divides 24 hours a day into 288 periods, each time interval is 5 minutes. When the nth EV starts charging, the total load of the grid is given as

\[ P_j^n = P_{gj} + \sum_{i=0}^{n} P_{cij}x_{ij} \]  

(3)

where, \( P_{gj} \) is the original load of the grid in j period, \( x_{ij} \) is 0-1 variable, n is the number of EVs, 0 represents that the ith EV is not charged in j period, and 1 represents that it is charged.

The control method proposed in this paper is to arrange the EVs to start charging near the valley load. Before the current EV starts charging, the forecasting original load and the previously loads of EVs are superimposed to track the minimum load in real time. When the nth electric vehicle is connected, its charging time is given as

\[ T_c^n = \frac{LW_{100}}{100P_c} \]  

(4)

Where, \( T_c \) is the charging time, L is the daily driving mileage, \( W_{100} \) is the power consumption per 100km, \( P_c \) is the charging power. After adopting coordinated charging strategy, the starting time of charging for the nth electric vehicle is

\[ T_{st}^n = T_{\min(p^+)} - \frac{1}{2}T_c^n \]  

(5)

Where \( T_{\min(p^+)} \) is the corresponding time of the lowest valley of grid load after the n-1 EV starts charging. The diagrammatic sketch of coordinated charging strategy based on valley load tracking is illustrated in Figure 1.

![Diagram of coordinated charging strategy](image.png)

**Figure 1.** The sketch of the proposed charging strategy.

The coordinated charging strategy based on valley load tracking proposed in this paper is an optimal charging strategy on the basis of meeting the travel demand of private EVs. According to the daily load curve of a certain area and the assumed number of EVs, the charging behavior of EVs is simulated by Monte Carlo method. The specific implementation process is as follows.

1. Read the initial state of charging (SOC) and the minimum required SOC when the EV leaves (the minimum EV is determined by the requirements of user's driving mileage ), and calculate the charging time.

2. Users input vehicle demand information. If coordinated charging strategy can be completed before users need to use the car, coordinated charging mode should be adopted. If not, uncoordinated charging mode should be adopted.

4. Simulation results

In this paper, a city H in Hubei province is taken as an example. According to the strategy mentioned above, Monte Carlo method is used to simulate the behavior of EVs. The flow chart is shown in Figure 2.
Dividing 24 hours into 288 periods (a period of 5min)

Using Monte Carlo method to simulate the charging demand of EVs

Calculating arrival time and daily mileage of EVs based on probability density function (equation 1 and 2)

Calculating charging time of EVs based on equation 4

Calculating start and end charging time of EVs based on coordinated charging

Adopting coordinated charging

Control instruction

Superposition of EVs Load and Power Grid Load

Y

N

Calculating start and end charging time of EVs based on uncoordinated charging

Figure 2. Simulation flow chart of coordinated charging strategy

The daily grid load curve of city H on a certain day in winter is shown in Figure 3, the maximum load is 1770MW at 5am, and the minimum load is 1335MW at 6pm.

Figure 3. The daily grid load curve of city H

City H currently has 250,000 vehicles, assuming that the number of EVs is 50,000. If the EVs all start charging as soon as arriving home, the daily grid load curve of the city H is shown in Figure 4. Due to the large number of EVs charging at dusk, it will cause an increase in peak load and impact on the power system.
Figure 4. The daily grid load curve of city H with uncoordinated charging strategy

According to the coordinated charging strategy proposed in this paper, the daily grid load curve of the city H after coordinated access of EVs is shown in Figure 5. With coordinated charging strategy, most of the charging loads are guided to starting within 0-6am, and the grid load curve in valley period is smoother.

Figure 5. The daily grid load curve of city H with coordinated charging strategy

The peak-valley difference of load curve with different charging modes is shown in Table 1. Compared with the original load, the peak-valley difference of the grid load increased by 26 MW in uncoordinated charging mode. Compared with the original load, the peak-valley difference of the grid load is reduced by 98MW in coordinated charging mode, that is to say, this strategy has obvious effect on reducing the peak-valley difference of grid load.

Table 1. The peak-valley difference of load curve with different charging modes

| Charging modes                   | Peak-valley difference(MW) |
|----------------------------------|-----------------------------|
| Original load                    | 435                         |
| Uncoordinated charging mode      | 461                         |
| Coordinated charging mode        | 357                         |
5. Conclusion
With the increase of the number of EVs, "peak-plus-peak" and "new peak" problems in grid load appear due to the uncoordinated charging mode of EVs. In this paper, an coordinated charging strategy for EVs based on valley load tracking is proposed, which can guide EVs to charge in valley periods orderly and has strong practicability. According to the simulation example, the charging strategy proposed in this paper can make the load curve in valley period smoother, effectively reduce the peak-valley difference of grid load, and can access more EVs without increasing the capacity of grid.

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