Optimization of Charging Method for Scaled EVs

Xincheng Zhang¹, Zhizhen Liu¹,a, Yan Cao², Lijin Duan¹, Guoshen Tang¹ and Wenchang Liu¹

¹Departments of Electrical Engineering, Shandong University, Jinan, China
²Departments of Intelligent Manufacturing, Shandong Technician Institute, Jinan, China

aCorresponding author: liuzhizhen@sdu.edu.cn

Abstract. At present, EVs (electrical vehicles) charging strategies are mainly focusing on reasonable optimization of EVs’ charging. However, previous researches have rarely studied optimizing the charging power of each EV, and the algorithms are always too complicated to implement. Based on this, this paper examines the lowest total load charging method and proposes the automatic breaking charging method which do not rely on complicated algorithms. Through Monte Carlo simulation, the simulation results of the two charging methods are compared respectively, and it is verified that the automatic breaking charging method has a better effect on peak load shifting and it can contribute to the reduction of energy loss.

1. Introduction

Recently, under the centralized control method, the orderly charging behavior of EVs is environmental, efficiency and clean[1]. EV charging behavior which adopts an orderly optimization control, takes advantage of EV as a distributed energy storage element. And then it can achieve the purpose of peak load shifting and stabilizing the output fluctuation of renewable energy, playing an auxiliary role in peaking and frequency modulation in power grid[2].

When the scale of EVs increase, the users’ charging behaviors will reflect greater randomness, which will not only increase the complexity of optimization calculation, but also lead to the problem of distribution transformer capacity over the limited. In [3], the electric vehicles with different permeability is randomly connected to the IEEE33 node system through simulation to obtain the node voltage variation curve. The research results show that when the electric vehicle penetration rate is gradually increased from 0 to 70%, there is a risk that the end of the line with a heavier load will have a voltage limit. The access of electric vehicles has an impact on the safe and economic operation of the distribution network and the planning of the power grid. The most important of these is the impact on network loss[4-5] and transformer operation[6-7]. Literature [4] calculates the change of network loss after large-scale electric vehicles access. The calculation results show that as the electric vehicles access volume increases from 0% to 35%, the network loss gradually increases from 4.07% to 4.25%. The literature [6] shows through simulation that when the electric vehicles with a permeability of 50% is disorderly charged in the summer for one day, the distribution transformer will lose 313 minutes of life.

V2G (Vehicle-to-Grid) is a technology that electric vehicles access to the grid. The “access” here is controlled and orderly. It means that there is a purposeful and planned two-way information and energy exchange between the electric vehicles and the grid. The core of V2G is to require electric
vehicles to recharge electricity when the electricity is low. While at the peak of power consumption, as a flexible and controllable power supply, EVs supply power to the grid through inverter, providing auxiliary services for power system to “cut peaks and fill valleys”[8-9].

The above-mentioned ordered charging strategies mainly optimize the charging sequence of electric vehicles, but there are few studies on optimizing the charging power of each electric vehicle. In order to meet the users’ charging demands, without upgrading the original residential distribution transformer, this paper examines the reverse recursion charging method and proposes the automatic breaking charging method. By observing the simulation results of the two charging methods, we can see that both of them can decrease the peak-valley ratio of total load, and the automatic breaking charging method is more effective.

2. Factors affecting the charging of EVs

2.1 Charging characteristics of lithium battery
At present, lithium battery is the mainly power battery used in EV. Considering the efficient use of the battery, the charging process commonly adopts 3-stage charging method in order to balance the safety and rapidness of charging process. The method divided the process into three parts based on fitting the characteristic curve of the battery charge and discharge, balanced current charging, balanced voltage charging and float charging.

Take battery which is 4.1V as example. Firstly, in the early stage of charging, if the battery voltage is less than 2.9V, then charging circuit enter the current limiting stage, using a constant rate of 0.1C to charge, with 1C represents the battery is full of 1 hours in the ideal state. The current limiting stage is mainly to avoid the impact of current when the battery voltage is too low. And then the charging mode is converted to balanced charging, adopting constant current to speed up the charging, when the monomer battery voltage rises to saturation voltage(4.1V/4.2V), the capacity of the charge is close to 40% -70% of total capacity at this point. Next, adopting the constant voltage to charge with charge current gradually decreasing. When the current down to 0.1C, it is therefore rational to consider that the battery is full. After that, charging process will enter the floating stage, charging with 0.01C until the end of the charge. Fig 1 shows the three-stage curve diagram of the battery.

![Fig 1. The three-stage curve diagram of the battery diagram](image)

2.2 The PDF(probability density function) of private EVs’ return time and daily mileage
According to a research report of National Household Travel Survey (NHTS) proposed by the U.S. Department of Transportation (DOT) in 2009[10], taken all private vehicles into account, during a certain day, 14% of EVs are out of use, 43.5% of EVs drive less than 20 miles (about 32km), 83.7% of EVs drive less than 60 miles (about 97km). Usually most of EVs have returned to the district at 10 pm. It can be seen from the above statistics that generally private EVs have enough time to charge up the batteries at home.

Equation (1) is the PDF of returning time of private EVs return time. Equation (2) is the PDF of the daily mileage of private EVs.
In equation (1), the independent variable \( x \) represents a certain time between \([0, 24]\), the expectation value \( \mu_s = 17.47 \), standard deviation \( \sigma_s = 3.41 \).

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

\( \mu_s = 24 \) and \( \sigma_s = 22 \).

In equation (2), \( x_L \) is the daily mileage (unit: mile), the expectation value \( \mu_D = 3.2 \), standard deviation \( \sigma_D = 0.88 \).

Based on the lithium battery characteristics, the approximate charging time can be expressed in equation (3).

\[
T_C = \frac{L W_{100}}{100 P_C \eta}
\]  

In equation (3), \( L \) is the daily mileage, \( W_{100} \) is the electricity consumption per 100 kilometers, and \( P_C \) is the charging power.

3. Optimization model of EV

3.1. Charging demand model of a single EV

Assuming that all the battery types of EVs are lithium batteries. To simplify the study, the charging power is approximated to constant power throughout the charging process. Figure 2 shows a general graph of battery power variation during charging.

Due to adopting the constant power model, the charging load of the EV--\( P_{\text{ev}}(t) \) is

\[
P_{\text{ev}}(t) = P_0(t_L < t < t_A)
\]  

As shown in (4), \( t_A \) and \( t_L \) represent the actual start and end time of battery charging, and \( P_0 \) is the power of a single EV.

The relationship between required charging time \( T_{\text{need}} \) and charging power \( Q_{\text{need}} \) is shown in (5).

\[
T_{\text{need}} = \frac{Q_{\text{need}}}{P_0}
\]  

When EV arrives at charging station, it is normally expected that battery can achieve the desired power status at the time of picking up the car. Thus, the charging process should satisfy two following constraints.

1) Charging time constraint
\[ T_{\text{need}} \leq T_l - T_A \]  
\[ (6) \]
In the formula, \( T_{\text{need}} \) is the actual duration of charge; \( T_l \) is the leaving time; \( T_A \) is the arriving time.

2) Battery SOC (State Of Charge) constraint
\[ SOC_{\text{min}} \leq SOC \leq SOC_{\text{max}} \]  
\[ (7) \]
\[ SOC_{\text{min}} \leq SOC \leq SOC_{\text{max}} \]  
\[ (8) \]
\( SOC_{\text{min}} \) is the lower limit of battery SOC, by contrast \( SOC_{\text{max}} \) is the upper limit of SOC. \( SOC \) and \( SOC_{\text{E}} \) represent the initial and final SOC of charging process and \( SOC_{\text{E}} \) is the expected battery SOC.

3.2 Charging method analysis
Based on the typical daily load curve of resident community, this article divides a day into 96 control periods. The intervals between each period were 15 minutes. Assuming that the basic load curve of the \( k \text{th}(i=1,2,\ldots, 96) \) period was \( P_k \). This article separately adopts the lowest total load charging method and the automatic breaking charging method to control the EV charging behavior.

3.2.1 Lowest total load charging method
The total load of power grid of the \( k \text{th} \) period is consisted of M EVs charging load \( P_k \) and superposition of basic load \( P_0 \).
\[ P_{\text{sum}} = P_k + \sum_{j=1}^{m} P_0 \]  
\[ (9) \]
After each EV participates in charging, re-calculating the total load of power grid in the 96 period, to find out the lowest point of the total load \( T_{\text{min}} \) and arrange the charging time for next car. Specifically, when the \( m \text{th} \) EV’s charging time was arranged, the minimum value of the total load could be shown as (12):
\[ \min_{m} P_{\text{sum}} = \min_{m} \left( P_k + \sum_{j=1}^{m} P_0 \right) \]  
\[ (10) \]

The lowest total load charging method adopts the principle of preferred arrangement to choose charging start time of EV (it refers to the beginning of this time period), after finding the period \( T_{\text{min}} \) which includes the lowest load point in charging process. That is to say, EV will adopt off-peak charging as much as possible.

The advantage of this method is that it can make full use of the time-of-use price mechanism and arrange the electric vehicles to charge as much as possible in the valley of the load curve. There is no doubt that it will bring more benefits to users. However, if there are too many electric vehicles gathered and charged at the valley, it may lead to a new peak in the load curve, which will have a bad influence. Therefore, when applying this method, it is necessary to consider the influence of the number of electric vehicles being charged.

3.2.2 Automatic breaking charging method
Automatic breaking charging method starts or ends the EVs charging behavior automatically according to the corresponding algorithm within each time period. When the total load of distribution network reaches the set value at some period of time, charging management system will stop one or a few EVs charging behavior automatically. On the contrary, when it is below the set value, charging management system will start one or a few EV charging behavior.

This method fully considers the impact of the charging load of the electric vehicles on the power grid at any time, and achieves the goal of controlling the load curve by setting the threshold value, and at the same time taking into account the interests of the user. By setting the size of the threshold value, the degree of emphasis on the grid and the users can be reflected. In terms of control effect, this method can be optimal, but its degree of scheduling capability for the power grid and related supporting equipment are correspondingly higher.
3.2.3 Comparison of two charging methods
Relative to ordered charging, disordered charging means that when the users need to recharge EVs, they would immediately connect to the electricity grid. Considering the travel habits, users typically concentrate charging during 16:00 to 21:00. In contrast, the lowest total load charging method and the automatic breaking method arrange charging during night based on different strategies. Specifically, the charging time distribution is shown in Fig 3.

![Fig 3. Comparison of two charging methods](image)

4. Example analysis
4.1. Simulation parameters setting
This paper uses a certain district as an example to prove the validity of both methods. The district (including 200 units, average size is 100 square meters) total load includes daily base load and EV charging load. This article assumes that the permeability of EV is 50%. That is to say, this district has 100 EVs. According to the current development situation of EVs, this article makes the following assumptions about the simulation scenario.

- The batteries of EVs are all lithium batteries, and their capacities are 32kW·h, their charging power is $P_c = 7$kW
- The capacity of distribution transformer is 960kVA, the average power factor of load is 0.85, and the upper limit of its active power is $P_{tm} = 960*0.85*0.95 = 775.2$kW
- The initial SOC of EV adopts research results from a brand, as shown in the figure 4.

![Fig 4. The initial SOC of each EV](image)

4.2. Simulation results and analysis
Based on the above-mentioned assumptions, in this paper, the Monte Carlo method is used to simulate the charging of 100 electric vehicles in three different situations to observe power grid load curve of different charging method. The simulation results are shown in Fig 5.
Fig 5. Power grid load curve of different charging mode

From Fig 5, we can see that in the lowest total load charging method, charging behavior concentrated in the load valley, which effectively avoids the peak load during the day. But the concentration of charging led to a new peak at night. In the automatic breaking method, charging load uniformly distributed throughout on-peak period. In consideration of that the more flat the load curve is, the more the network loss reduces, the automatic breaking method has an advantage over the lowest total load charging method, and it can cut peak and fill valley more effectively.

5. Conclusion

Based on the development status and prospect of EVs, as well as some rational assumptions, this paper proposes the automatic breaking method and examines the lowest total load charging method. Through the simulation and analysis, we find that two kinds of coordinated charging methods can both decrease the peak-valley ratio of total load effectively. In particular, the valley period will be smoother under the mode of automatic breaking method.

References

[1] Energy Conservation and New Energy Vehicle Industry Development Plan(2012-2020).
[2] Y.M. Wang, Research on the Soft Environment of Arctic Wind Energy Development[J]. Electric Power, 49(2016)
[3] L.D Zhang, et al. Study on the influence of electric vehicles random charging on distribution network[J] Journal of Electric Power Science and Technology, 31(2016)
[4] L.Z Xu, et al. The impact of electric vehicle charging load on Danish distribution system[J]. AEPS, 35(2011)
[5] J.S Chen, et al. Strategies for Electric Vehicle Charging with Aiming at Reducing Network Losses[J]. Proceedings of the CSU-EPSA. 24(2012)
[6] J.L Sun, et al. Impact of Plug-in Electric Vehicles on the Operating Life of Distribution Transformer[J]. High Voltage Engineering. 41(2015)
[7] Y.N Cai, Analysis of the Influence of Large-scale Electric Vehicle Charging on the Life of Distribution Transformer[D], Chongqing University(2016)
[8] L.L Ma, et al. Summary of Research on Influence of Electric Vehicle Charging and Discharging on Power Grid[J]. Power System Protection and Control. 3(2013)
[9] W Pan, et al. Review of coordinated control strategy between electric vehicle and power grid[J]. Power Demand Side Management. 4(2013)
[10] L.T Tian, et al. A Statistical Model for Charging Power Demand of Electric Vehicles[J]. Power System Technology, 34(2010)