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To cite this article: Jiaoru Song et al 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* 677 052103

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A Coordinated Charging/Discharging Strategy for Electric Vehicles Based on Price Guidance Mechanism

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Abstract. In view of the contradiction between the rapid growth of electric vehicles' ownership and the imbalance of electric vehicles’ charging demand and the lower distribution network service ability, a coordinated charging/discharging strategy maximizing the discharge depth on the basis of satisfying the charging demand of electric vehicles is proposed. This paper analyses the relationship between the charging/discharging time intervals of electric vehicles and the division of time-of-use electricity price, the vehicles’ arrival/departure time and the daily driving mileage. Take minimizing load fluctuation as the objective and take meeting the charging demand of electric vehicle users as the restrains based on time-of-use electricity price. Monte Carlo simulation and PSO algorithm are used for simulation and calculation. The results show that with the coordinated charging and discharging strategy, it can not only realize the peak load shifting, but make the customers’ charging cost lower.

1. Introduction

Electric vehicles (EVs) are being pushed by government around the world as an alternative to fossil fuel transport. EV industry has made a rapid development under the incentives of multiple policies, such as government subsidies and the restrictions of fossil fuel vehicle [1-2]. The centralized and uncoordinated charging will cause adverse impacts on the distribution network: power demand will exceed distribution transformer ratings; phase unbalance may lead to excessive current; excessive power may cause reserve capacity of the system [3]. Therefore, it is significant to formulate a strategy to shift EV charging load to a time when there is more capacity in the network, such as overnight.

The scale of EVs will become larger and larger. Without increasing the reserve capacity of power system, it is significant to improve the acceptance ability to EVs for charging field. Research shows that most of the vehicles stay 95% of one day in the charging field, so vehicle to grid (V2G) emerges [4]. EVs can be considered as distributed energy storage equipment, which can store power in the low load period and discharge in the peak load period. This means the EV users can reduce the charging cost through the price difference [5]. The “smart charging and discharging” strategy can realize the benign interaction between large-scale EVs and power grid [6].

Reference [7] proposes a coordinated charging control method combining online control and offline optimization. Through the power limit value obtained from the non-control period to control sum of residential area’s regular load and electric vehicle’s charging load to prevent power limit exceeded. Reference [8] proposes a two-stage optimal EV charging model under the premise of satisfying the
charging demand of EV and complying with the restriction of distribution transformer capacity. And the results show that the two-stage optimization model can play a significant role in reducing peak-valley difference and smoothing the load curves. However, the above References only consider the charging process of EVs. For the residential areas that have been built for a long time, the capacity of transformer is limit, which is not conducive to the EVs’ large-scale development. Reference [9] proposes a coordinated charging and discharging strategy based on peak-valley electricity tariffs for EVs with power limitation. The results show that the load tends to be smooth by the power limitation in this strategy. Reference [10] proposes a coordinated charging/discharging strategy considering customer’s factors. According to a customer's comprehensive credit index and his EV’s state of charge, the operator select the EVs participate reverse power supply. However, the above References are all from the point of the grid or operators, and haven’t taken into account the discharge depth of EV users participating in V2G reserve power supply.

Our strategy is implemented and simulated on a validated model of a real distribution network. According to the EV behavior simulated from real travel profile, we calculate the number of time intervals of charging and discharging under the premise of maximum discharge depth. Take minimizing load fluctuation as the objective. PSO is used to calculate the initial charging and discharging time of EVs. It is shown that existing network can sustain more electric vehicles without additional investment into distribution network. It is also shown that this strategy can solve the harmfulness of uncoordinated charging to the power grid.

2. Travel habits
The driving parameters of EVs mainly include the vehicles’ arrival/departure time and the daily driving mileage. According to the survey of U.S. department of transport, household vehicles’ last end of the travel time approximately obey the normal distribution and daily driving distance can be expressed by logarithmic normal distribution[11].

The probability density function of returning time can be expressed as follow:

\[ f_{r}(x) = \frac{1}{x\sigma_{D}\sqrt{2\pi}} \exp\left[-\frac{(\ln x - \mu_{D})^2}{2\sigma_{D}^2}\right] \]  

In the formula: the expectation is 3.2, the standard deviation is 0.88, \( x \) indicates the daily driving distance.

\( t_{1} \) indicates the time when electric vehicles are connected to the charging pile, and the probability density function can be expressed as follow:

\[ f_{c}(t) = \begin{cases} 
\frac{1}{\sigma_{s}\sqrt{2\pi}} \exp\left[-\frac{(t-\mu_{s})^2}{2\sigma_{s}^2}\right], & (\mu_{s} - 12) < t < 24 \\
\frac{1}{\sigma_{s}\sqrt{2\pi}} \exp\left[-\frac{(t+24-\mu_{s})^2}{2\sigma_{s}^2}\right], & 0 < t < (\mu_{s} - 12) 
\end{cases} \]  

In the formula: the expectation is 17.6, the standard deviation is 3.4

3. The coordinated charging/discharging strategy
In this paper, a coordinated charging and discharging strategy maximizing the discharge depth of EVs is proposed. In order to realize the destination of peak shaving and valley filling with EV load. EVs load will be arranged to charge in the valley load period and discharged in the peak load period. According to the returning time, during peak load period or valley load period, two different strategies will be
formulated for EVs. The optimization period is one day, which is divided into 24 periods with an interval of 1 hour.

First, two notions are proposed: peak critical state of charge $SOC_f$ and valley critical state of charge $SOC_v$. The former refers to the remaining SOC at end of peak load period for the EV returning during peak load period, which starts discharging immediately. The latter refers to the initial SOC at the start time of valley load period for the EV returns during peak period, which starts charging until leaving the charging field and can arrive at expected SOC. The calculation of $SOC_f$ and $SOC_v$ are as follows:

$$SOC_f = SOC_{1} - \frac{(t_0 - t_1)P_d}{\eta_d B}$$

$$SOC_v = SOC_{de} - \frac{(t_2 - t_1)P_c \eta_c}{B}$$

Here, $SOC_{1}$ indicates the remaining SOC when the EV returns to the charging field; $t_0$ indicates the initial time of valley load period; $P_c$ and $P_d$ represent charging and discharging power respectively; $B$ indicates battery capacity; $SOC_{de}$ indicates expected SOC, $\eta_c$ and $\eta_d$ indicate charging and discharging efficiency, respectively.

Before calculating the number of charging and discharging time intervals of each EV, it is necessary to judge whether the EV satisfies the condition of delayed charging or not. As shown in the formula (4). If not satisfied, charge the EV immediately and notify the EV user of the max SOC.

$$SOC_{1} + \frac{(t_2 - t_1) P_c \eta_c}{B} \leq SOC_{de}$$

$$S_{max} = SOC_{1} + \frac{(t_2 - t_1) P_c \eta_c}{B}$$

3.1. The calculation of charging/discharging period of EV returning to charging field during peak load period

1) Peak critical state of charge is greater than valley critical state of charge

If $SOC_{f} \leq 0.2$, the charging/discharging strategy as follows: During peak load period, the battery is discharged from $SOC_{1}$ to 0.2, and at low load period, the battery is charged from 0.2 to $SOC_{de}$. The calculation of charging/discharging time intervals as follows:

$$t_c = \frac{(SOC_{de} - 0.2) B}{P_c \eta_c}$$

$$t_d = \frac{(SOC_{1} - 0.2) B \eta_d}{P_d}$$

If $SOC_{v} < 0.2 < SOC_{f}$ or $SOC_{f} \geq 0.2$, the charging/discharging strategy as follows: During peak load period, the battery is discharged from $SOC_{1}$ to $SOC_{v}$, and at low load period, the battery is charged from $SOC_{f}$ to $SOC_{de}$. The calculation of charging/discharging time intervals as follows:

$$t_c = \frac{(SOC_{de} - SOC_{f}) B}{P_c \eta_c}$$

$$t_d = \frac{(SOC_{1} - SOC_{f}) B \eta_d}{P_d}$$

2) Peak critical state of charge is less than Valley critical state of charge
If \( SOC \leq 0.2 \), the charging/discharging strategy as follows: During peak load period, the battery is discharged from \( SOC_1 \) to 0.2, and at low load period, the battery is charged from 0.2 to \( SOC_{de} \). The formula of calculating the charging and discharging time intervals are shown in equation (6).

If \( SOC < 0.2 < SOC_v \) or \( SOC \geq 0.2 \), the charging/discharging strategy as follows: During peak load period, the battery is discharged from \( SOC_1 \) to \( SOC_v \), and at low load period, the battery is charged from \( SOC_v \) to \( SOC_{de} \). The calculation of charging/discharging time intervals as follows:

\[
t_c = \frac{(SOC_{de} - SOC_v)B}{P_\eta_c} \\
t_d = \frac{(SOC_v - SOC_{de})B\eta_d}{P_d}
\]  

(8)

3.2. The calculation of charging/discharging period of EV returning to charging field during valley load period

For the EVs returning to the charging field during the valley load period, there is only charging process. The charging strategy is that the battery is charged from \( SOC_1 \) to \( SOC_{de} \). The calculation of charging/discharging time intervals as follows:

\[
t_c = \frac{(SOC_{de} - SOC_v)B}{P_\eta_c}
\]  

(9)

4. Optimization model

4.1. Optimization target

Under the time-of-use electricity price mechanism, EV users follow their own willingness if the process of charging/discharging is out of control. In this condition, a larger peak load may be formed during the low load period. Therefore, an optimal EV charging/discharging model, which takes the minimized variance of the total load as the objective, and takes the starting charged/discharged time as the optimization variables, is established.

\[
\min f(t_{c1}, t_{d1}, \ldots, t_{cN}) = \frac{1}{24} \sum_{i=1}^{24} [P_i(t) + \sum_{i=1}^{N} P^c_i(t) - \sum_{i=1}^{N} P^d_i(t) - P_a] ^2 \]

\[
P_a = \frac{1}{24} \sum_{i=1}^{24} [P_i(t) + \sum_{i=1}^{N} P^c_i(t) - \sum_{i=1}^{N} P^d_i(t)]
\]  

(10)

Here, \( P_i(t) \) indicates conventional load power; \( P^c_i(t) \) represents the charging power of the \( i \)-th EV in \( t \)-period; \( P^d_i(t) \) represents the discharging power of the \( i \)-th EV in \( t \)-period; \( N \) indicates the total number of EVs.

4.2. Particle swarm optimization

Particle swarm optimization was introduced in 1995 by Kennedy and Eberhart. In order to realize the optimal of charging and discharging, the program takes the start charged/discharged time of each EV as the input parameters and particle swarm optimization algorithm is used on simulation calculation. Consider a flock or swarm of 50 particles, and the max iteration is 100. For each particle \( i \), Kennedy and Eberhart proposed that the position \( x \) be updated in the following manner:

\[
x_i(k+1) = x_i(k) + v_i(k+1)
\]  

(11)
With a pseudo-velocity calculated as follows:

\[ v_i(k+1) = w v_i(k) + c_1 r_1 (p_{best,i}(k) - x_i(k)) + c_2 r_2 (g_{best}(k) - x_i(k)) \]  (12)

Here, \( k \) indicates a pseudo-time increment, \( p_{best,i} \) represents the best ever position of particle \( i \) at time \( k \), and \( g_{best} \) represents the global best position in the swarm at time \( k \). \( r_1 \) and \( r_2 \) represent uniform random numbers between 0 and 1. \( c_1 \) and \( c_2 \) are cognitive and social scaling parameters, which can be selected such that \( c_1 = c_2 = 2 \).

The solving process of PSO is as follows.
1. Initialize.
   (a) Set constants \( w, c_1, c_2, k_{\text{max}} \)
   (b) Randomly initialize particle positions \( x_i(0), i = 1, 2, \ldots, 50 \)
   (c) Randomly initialize particle velocities \( v_i(0), i = 1, 2, \ldots, 50 \)
   (d) Set \( k = 1 \)
2. Optimize.
   (a) Evaluate function value \( f_i(k) \) using design space coordinates \( x_i(k) \)
   (b) Update \( p_{best,i}(k) \) and \( g_{best}(k) \)
   (c) If the iteration up to the maximum then go to 3.
   (d) Update \( x_i(k+1) \) using Equation(11)
   (e) Update \( v_i(k+1) \) using Equation(12)
   (f) Increment \( i \), If \( i > 50 \) then increment \( k \).
   (g) Go to 2(a).
3. Report results
   Record the global best position in the swarm in the all iterations
4. Terminate

5. Example analyses
5.1. Parameter setting
1) In order to verify the implementation effect of the coordinated strategy proposed in this paper, we implement and test our solution on a validated model of a real network in a residential area. The curve is presented in Figure.1. This article assumes that the EV charging tariff is based on peak and valley price. The time-of-use electricity price is shown in Table 1.
2) Considering that EVs stay most of the day in the charging field, thereby, we take the slow charging mode as the research object.
3) Assuming that the charging and discharging power are invariable, and the values are both 3 kW. Charging and discharging efficiency are both 0.95.
Figure 1. Regular load curves of residential area

Table 1. Time-of-use electricity price of residential area

| type    | time                  | price/(yuan (kWh)) |
|---------|-----------------------|--------------------|
| peak    | 8:00-21:00            | 0.56               |
| valley  | 21:00-next day8:00    | 0.36               |

4) In this paper, we assumed the vehicles to have a 30 kWh Li-ion battery, take NISSAN LEAF as an example. The power consumption of 100 km is 15 kWh. Assuming that each electric vehicle is equipped with a charging pile, so there is no waiting time [12].

5) Assuming that the time of EVs leaving the charging field obey the normal distribution with the expectations of 7 and the standard deviation of 0.5, and EVs have left the charging field and arrived at company before 9 o'clock.

5.2. Simulation result

In this paper we expressed electric vehicle charging and discharging optimization problem that takes into account the depth of discharging for the EV users participating in V2G reserve power supply. Monte Carlo method is used to simulate the travel parameters of EVs, including the vehicles’ arrival/departure time and the daily driving mileage. Multiple charging data of EVs are generated randomly, which are used to calculate the number of charging/discharging time intervals. PSO is used to optimize the start charging and discharging time of EVs so as to slow down the load fluctuation. The results are presented in Figure 2. It shows the load fluctuation after the access of EVs load and the contrast of the conventional load curve. The blue line represents the original load and the red line represents the total load after the EV involvement. From the figure, it can be seen that there is an increase in valley demand and decrease in peak demand. Electrical vehicles reduce rates at particular time in order to reduce the fluctuation of the total load and prevent power demand exceed distribution transformer ratings.
Figure 2. Load curves of coordinated charging/discharging

6. Conclusion
The proposed strategy can better consider the continuity and economy of EV charging, and provide a decision basis for the orderly charging management of EVs parking in residential areas under the premise of the high completion rate of EV charging and the stability of residential load. The coordinated control strategy takes minimizing load fluctuation as the objective based on time-of-use electricity price. Take maximizing discharged depth as the condition to calculate the number of charging/discharging time intervals for the customers participated in V2G reserve power supply. PSO algorithm is used for calculation.

This method is simple and easy to implement, and the implementation effect is fine. Some conclusions are drawn as follows:

(1) Price-based optimal charging and discharging can effectively schedule vehicle charge during times when price is low and discharge when price is high, thereby users can obtain additional revenue from the process of charging and discharging.

(2) Besides, by implementing charging and discharging control as proposed in this paper, existing network can sustain more electric vehicles, without the need for infrastructure upgrades. And it is conducive to the development of electric vehicle.

(3) EV users can reduce the charging cost via the different price of storage and discharging. This can enhance users’ enthusiasm participated in V2G and reserve power supply, which is conducive to the safe operation of power grid.

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