Research on Electric Vehicles Collaborative Charging of DC and Equalizing Charger for Improving Battery Life

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Abstract. With the rapid development of electric vehicle industry, repeated charging and discharging in the process of vehicle use will lead to the deterioration of voltage consistency of single battery. How to improve battery life through battery balance has become the focus of research. The structure of charging device which cooperates with DC charging pile is described. The equalizing charging device and charging pile can be cooperated to charge the electric vehicle battery, so as to achieve the balance of battery capacity when each single battery is fully charged by means of the communications among charging pile, main control module and battery BMS. Based on the charging structure, the charging system control strategy is proposed. The shortest charging time, the smallest charging power consumption and the combination of satisfaction are considered to construct the optimal algorithm.

Keywords: Voltage consistency, Cooperative charging, Satisfaction degree, Model optimization

1. Introduction
At present, the domestic electric vehicle power battery is usually composed of single battery series / parallel connection. With the increase of operating mileage of electric vehicles, repeated charging and discharging in the process of use of vehicles will gradually lead to poor voltage consistency of single battery, and produce great differences, especially in the case of large capacity and high-rate charging and discharging, the charging and discharging capacity (total capacity) of vehicle battery will be greatly restricted. Because most of the current DC charging piles still use series charging method for battery pack of electric vehicles, the charging strategy of controlling series charging can not effectively solve the life problem caused by single battery overcharge. In this paper, an external equalization device and corresponding algorithm is designed to charge and maintain the power battery of electric vehicle by DC charging pile.

In the coordinated equipment of equalization charging and DC charging pile, the single charging and discharging module controls one battery, which makes the circuit more complex though the control is flexible. And when the single battery reaches the equilibrium point, the rest of the batteries are still in equalization, and the charging and discharging module is idle and can not be effectively used. Therefore, this paper puts forward a model of single charging and discharging module connect to multiple single batteries. The controller can quickly charge the battery pack by controlling the DC charging device. In
this process, the main problem of optimal control strategy is to ensure that the battery pack to be charged is balanced and charged in the shortest time.

In addition, most of the existing equalization charging technologies start from the charging mode and charging efficiency, and rarely consider the user experience from the overall point of view. Therefore, this paper starts to design an algorithm to solve the model composed of batteries of different capacities and brands under different preset conditions.

2. Related work

In this section, the structure model of equalization device and the basic control strategy is briefly introduced.

2.1. An equalization charging device cooperating with DC charging pile

The charging of electric vehicle power battery is realized by the collaborative charging device. The structure and working principle of the charging device are analyzed as follows:

2.1.1. Structure model of equalization charging device. In this paper, a structure of equalization charging device is designed for collaborative charging with DC charging pile. As shown in Figure 1, the controller controls the same amount of charging module and discharging module respectively, and each charging module and discharging module are in parallel with the single battery of the battery pack, and the two ends of the DC charging device and the battery pack are in parallel. The battery pack can be quickly charged by DC model. Then, the controller controls the corresponding switches of charging module and discharge module, and controls the charging switch of DC charging device. When the switch of charging module controlled to close, the switch of discharge module must be disconnected. The basic structure of each equalization charging module and each transfer switch is consistent with the battery pack. As shown in Figure 2, the equalization charging and discharging module D_q is composed of a charging and a discharging module, which are respectively connected through the charging equalization interface and the transfer switch T_q. As shown in Figure 3, the transfer switch is connected with BMS in two directions. By receiving the battery information, transfer switch uploads it to the BMS. The transfer switch controls the group, which is connected with the charging and the discharging module respectively, then achieve the purpose of charging and discharging the single battery.
Figure 1. Structure Model of equalizing charging device

Figure 2. Internal structure of equalization charge discharge module D_q
2.1.2. Battery charging state. Generally, there are many methods to measure the battery charging state, such as the concentration of electrolyte and the charging voltage of the battery. The method of measuring the charging voltage of the battery is convenient in the microcomputer based on control system. However, different types of batteries have different relationship curves. The device selected in this paper can obtain the SOC voltage curve under different charging times by obtaining the historical battery model of the battery, thus the voltage of the small battery can be corresponding to its SOC value, and the real-time SOC value of the battery can be obtained by combining with the ampere hour integration method.
2.2. Charging system control strategy and variable description

2.2.1. Variable description of the model. For convenience of description, the Table 1 is show as follow.

| Description                                      | Symbol | Description                                                                 | Symbol |
|--------------------------------------------------|--------|-----------------------------------------------------------------------------|--------|
| Number of charging and discharging modules        | q      | Time required for group I battery (charge equalization) to full charge       | tcᵢ    |
| Number of cells in a single equalization module   | k      | Time required for group I battery (discharge equalization) to full charge   | tfᵢ    |
| Charging speed of charging module                 | m      | Time required for group I batteries to be fully charged                     | tsᵢ    |
| Discharge speed of discharge module               | n      | Quantity of electricity required for the j cell of group i to be charged to the equilibrium value | scᵢj   |
| Charging speed of single battery by DC charging module | p      | Customer satisfaction with charging time                                   | θ      |
| Initial SOC of j cells in group i                 | sᵢj    | Satisfaction weight 1                                                      | α      |
| SOC value of battery's best equilibrium point     | s_best | Customer satisfaction on power consumption                                 | ε      |
| The time required for equalization when sx is set to the best balanced SOC value | T_best | The minimum charge required for all individual batteries to be fully charged | H_best |
| The setting value of SOC of a single battery      | sx     | Satisfaction weight 2                                                      | β      |
| Satisfaction with charging time and power consumption | R      |                                                                              |        |

2.3. Control strategy of charging system for model.

As shown in Figure 4, a control strategy can be provided with the device. Before balancing the power battery pack, the voltage, current and battery model of all individual batteries can be obtained through BMS. Through these parameters, the SOC of single battery, charging speed m of charging module, discharging speed n and charging speed p of DC charging device can be estimated according to the historical charging and discharging curve of battery. The best equilibrium point of the battery can be obtained through the built-in algorithm. The charging or discharging of the single battery is controlled according to the battery information, so as to make the single battery reach the best equilibrium target point sᵢ_best. After that, all the batteries are charged through the DC charge pile.
2.4. The proposed method

In this part, three different algorithms considering optimal charging time, charging quantity and combination of list before will be used to solve different charging requirements.

2.4.1. Considering the shortest charging time. The SOC of each battery was sorted from small to large by bubble sorting method to form \( s_{ij} \) (as in group \( s_{11} < s_{12} < \cdots < s_{1k} \), \( i=1, 2, \ldots, q \); \( j=1, 2, \ldots, k \)). In this paper, through theoretical judgment, a single group of batteries does not consider the charging of other groups. Because the charging speed and discharge speed of the batteries are different, each group of batteries is divided into two categories: lower than the target balanced SOC value and higher than the target balanced SOC value. The time required for charging a single battery to reach the target value is shown as follows:

\[
t_{ci} = \begin{cases} 
\frac{s_x - s_{ij}}{m} & s_x > s_{ij} \\
0 & s_x \leq s_{ij}
\end{cases} \quad i = 1, 2, \ldots, q; j = 1, 2, \ldots, k
\]  

(1)

When the SOC value is higher than the target value, the time required for the cell to reach the target value is shown as follows:

\[
t_{fi} = \begin{cases} 
\frac{s_{ij} - s_x}{n} & s_x < s_{ij} \\
0 & s_x \geq s_{ij}
\end{cases} \quad i = 1, 2, \ldots, q; j = 1, 2, \ldots, k
\]  

(2)

The accumulated time of each group after equalization charging is obtained by classification. Since each group has only one charging device and one discharging device, and the charging and discharging device can operate at the same time, and the charging speed and discharge speed are different, it is
necessary to calculate the time required for each group of equalization charging and DC charging separately.

The time required for DC charging after charging to the target power is as follows:

\[ t_{c_i} = \sum_{j=1}^{k} t_{c_{ij}} + k \left( \frac{1-sx}{p} \right) \]

(3)

When \( s_{ij} < sx < s_{i(j+1)} \) because \( p>>m \), and \( r=1 \), \( t_{c_i} \) the function of \( sx \) increases monotonically in this interval. Similarly, because \( k>>r \), and \( n>0 \), \( p>0 \), \( t_{f_i} \) function of \( sx \) decreases monotonically in this interval. Besides, according to the operation, \( t_{f_i} \) and \( t_{c_i} \) the function of \( sx \) is continuous in \([0,1]\).

The required time for a single group having fully charged, \( t_{s_i} \), is dependent on which time is greater after in charging or discharging equalization process.

\[ t_{s_i} = \max \left( t_{c_i}, t_{f_i} \right) \]

(4)

Therein the best time for all groups to charge to full charge is obtained. In other words, it is the function with the maximum time of all groups and the minimum of \( sx \).

\[ T_{best} = \min_{sx} \max_{i} t_{s_i} \]

(5)

When \( sx = s_{best} \), \( t \) gets the minimum value, \( s_{best} \) is the best equilibrium point SOC, and \( T_{best} \) is the shortest equilibrium time under the model.

2.4.2. Considering the minimum charging capacity. Based on the charging device designed in this paper, in the process of charging to full charge, the power consumption as an important evaluation index affects the charging expenditure, and the minimum power consumption for charging is considered here.

The charge required for charging a single battery can be expressed as follows:

\[ s_{c_{ij}} = \begin{cases} sx - s_{ij} & sx > s_{ij} \\ 0 & sx < s_{ij} \end{cases} \]

(6)

The minimum quantity of electricity required for all cells to be fully charged can be expressed as follows:

\[ H_{best} = \min_{sx} \left[ \sum_{i=1}^{q} \sum_{j=1}^{k} s_{c_{ij}} + (1-sx) \cdot q \cdot k \right] \]

(7)

2.4.3. Considering the combination of power consumption and charging time. Inspired by the saying, “time is the resource of the next competitive advantage” as quoted from Harvard Business Review written by George Stock Jr, the concept of time-based competitive advantage is proposed and the satisfaction model combining battery charging time and power consumption is designed. The concept of time based on competitive advantage is put forward. In the process of traditional logistics facilities location, customer satisfaction level is seldom considered. Considering that users are more sensitive to charging time, the device aims to deliver to the general public, so \( \Gamma \)- function satisfaction model is adopted for time satisfaction where \( w \) is the coefficient.

\[ \theta = e^{-w \cdot (\max_{i} t_{s_i} - T_{best})} \]

(8)

In contrast, when the power consumption set in this paper is within a threshold, it can be approximately considered that the power consumption satisfaction is linear. Therefore, the power consumption satisfaction model is set as follows:
Based on equation (8)-(9), the comprehensive satisfaction model of power consumption and charging time is obtained as follows:

\[ R = \alpha \theta + \beta \epsilon \]  \hspace{1cm} (10)

Where \( \alpha \) and \( \beta \) are the coefficients of the two elements respectively, and \( \alpha + \beta = 1 \). With the function (8) (9) (10), we can calculate the max value of \( R \).

3. Experimental results

In this part, a set of number of experiments are conducted to evaluate the proposed method.

The electrical parameters of the experimental battery system are as Table 2:

The charging speed of the equalizing device charging module is 0.005, the discharging speed \( n \) of the discharging module is 0.008, and the charging speed of the DC charging device is 0.08 (the charging speed, discharge speed and charging speed of the DC charging device are normalized to the increase and decrease speed of the SOC).

Set the number of battery packs and the number of charging and discharging modules \( q \) as 5, and set the number of single battery \( K \) as 10 in each group, respectively set the battery SOC by random function, as shown in the table below. The battery SOC has been arranged in bubble sorting method from small to large.

| Group 1 | 0.32 | 0.34 | 0.38 | 0.39 | 0.47 | 0.48 | 0.52 | 0.55 | 0.63 | 0.88 |
|---------|------|------|------|------|------|------|------|------|------|------|
| Group 2 | 0.21 | 0.44 | 0.48 | 0.59 | 0.67 | 0.88 | 0.89 | 0.91 | 0.93 | 0.95 |
| Group 3 | 0.19 | 0.22 | 0.26 | 0.31 | 0.47 | 0.48 | 0.49 | 0.51 | 0.69 | 0.88 |
| Group 4 | 0.02 | 0.21 | 0.35 | 0.49 | 0.50 | 0.52 | 0.58 | 0.59 | 0.63 | 0.98 |
| Group 5 | 0.22 | 0.34 | 0.39 | 0.45 | 0.67 | 0.77 | 0.81 | 0.86 | 0.93 | 0.96 |

3.1. Considering minimum equalization charging time

According to the solution of the model, we can draw the legend of the target equilibrium value \( s_x \) and the required time of the single battery after equalization, as shown in the figure 5. This figure is the graph of the required time for five groups of batteries to be fully charged after equalization and the target equilibrium value \( s_x \). Through the combination of the number and shape, it can be clearly obtained that (0.532271.1) is the target point, that is, under the model, all the single cells are fully charged after equalization. The best equilibrium value \( s_{best} = 0.532 \), and the shortest charging time is \( T_{best} = 271.1s \), which are consistent with the model.
3.2. Considering the minimum charging capacity

According to the solution of the model, the legend of the target equilibrium value $s_x$ and the required time for all the cells to be fully charged after equalization can be drawn and shown in Figure 6. This figure is a graph of the time required for the five groups of batteries to be fully charged after equalization and the target equilibrium value $s_x$. By combining the data and shape, it can be clearly obtained that $(0.98, 1)$ is the target point, that is, only considering the charging amount, all the single batteries can be evenly charged. The equilibrium value of the minimum charge after balance is 0.98, which is the maximum SOC of all single cells, and the minimum SOC is 22.32, which is consistent with the model.
3.3. Considering the combination of power consumption and charging time

The weight W is set to 0.001, and the graph of satisfaction degree of charging time $\theta$ with the target equilibrium value can be established, as shown in Figure 7. According to sx abscissa with the maximum satisfaction value equal to 0.53, it can be verified that the solution of the optimal equilibrium value only considering the minimum equalization charging time is correct. The satisfaction model $\alpha$ and $\beta$ are set as 0.5, that is, the weight of time response and load index is set as 0.5 respectively. The effective combination of the two models can fully reflect the satisfaction of electricity consumption.

![Figure 7. The satisfaction of charging time varies considering with combination of power consumption and charging time](image)

By observing the curve, the best equilibrium point $s_{best}$ is 0.53, and the target value can be obtained.

4. Conclusion

In this paper, a simple equalization charging device is proposed, which provides only one charging module and discharging module for multiple single batteries, aiming to simplify the equalization charging structure and improve the hardware utilization. Based on the hardware structure, the optimization analysis of the charging time and charge quantity of the device is studied. In order to be suitable for microcomputer control, the charging state of the battery can be estimated by measuring the terminal voltage of the battery, which is easy to operate. The simulation and experiment show that the equalization system has the characteristics of simple structure and flexible control.

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