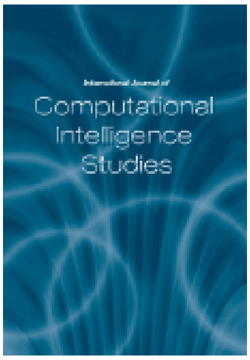

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Yalin Li, Zhen Li

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Research on the optimal charging method of parallel power batteries for smart electric vehicles

Yalin Li and Zhen Li*

Department of Automotive Engineering,
Sichuan Vocational and Technical College of Communications,
Chengdu, 611130, China
Email: lizhen_83@126.com
Email: ZhenliSVTCC@163.com
*Corresponding author

Abstract: To save charging cost on the premise of ensuring stable and efficient charging of electric vehicles, an optimal charging method for parallel power batteries of intelligent electric vehicles was proposed. Through mathematical model analysis, the RC network branch is added to construct a second-order RC equivalent circuit model. Battery parameters based on CRUISE simulation platform are optimised. By optimising the control of battery current, current sharing and voltage stability are achieved. Finally, the local voltage equalising charging principle of the inverter is used to redesign the equalising charging of the electric vehicle battery. The experimental results show that the relative cost and charging stability of the proposed charging method are 0.58 and 0.62 respectively, which are better than the other two charging methods. The results show that the method can meet the requirements of intelligent electric vehicles for charging stability and efficiency, and has high application value.

Keywords: electric vehicle; battery charging; equalisation charging; equivalent circuit model; charging power.

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Biographical notes: Yalin Li is an automotive professional instructor, mainly engaged in the research and teaching of electric vehicles. She won the first prize of the Provincial Teaching Achievement Award. She built one national-level high-quality course and three high-quality online courses. She participated in one national-level project, three department-level projects, and presided over the completion of two college projects. She participated in the compilation of one textbook of the 14th Five-Year Plan of the People's Republic of China. She published five professional papers, three solo or first authors; and authorised two patents.

Zhen Li is an Associate Professor, Senior Technician, and Senior Engineer. He has won one second prize of the National Teaching Achievement Award, one provincial teaching achievement award and one second prize. He built two national-level high-quality courses, two high-quality online courses, and one high-quality resource library. He presided over the completion of one department-level project, participated in three departmental-level projects, and presided over the completion of two college projects. He participated in the compilation of five textbooks, of which two were deputy editors. He published 13 professional-related papers and ten solo or first authors; and authorised three patents.

1 Introduction

With the intensification of energy crisis and environmental pollution, efficient, reliable and zero emission electric vehicles have become the inevitable trend of future development (Sweda et al., 2017). Power battery provides power for electric vehicles, and its performance is one of the core links to promote the development of electric vehicles. More and more attention has been paid to efficient and fast battery charging methods (Adaikkappan and Sathiyamoorthy, 2022). At present, the charging mode of battery is generally divided into conventional charging mode and fast charging mode. The conventional charging mode has low current and long charging time, generally the charging time is 8–15 h (Singh and bohre, 2020). And the fast-charging mode can have certain advantages in charging efficiency. Rapid charging methods are generally divided into pulse charging method, variable current intermittent charging method and variable voltage intermittent charging method. However, the cost of these methods is too high and the charging stability is insufficient. Therefore, it is of great significance to study a fast, efficient, cost-effective and stable charging method (Boujelben and Gicquel, 2019).

1.1 Related work

With the rapid development of electric vehicles, many methods have been applied in the field of electric vehicle charging. Aiming at the mismatch between the dynamic supply of renewable energy and the flexible charging demand of electric vehicles, Jia (2021) proposed a dual event optimisation model, which can capture the changes at both the macro level and the micro level. Through simulation experiments on this model, the results show that this method is superior to other similar methods in terms of performance and scalability. Nezamuddin et al. (2021) proposed a vehicle to vehicle charging system in order to solve the difficulties faced by electric vehicles in battery charging during the journey. The purpose of the system is to provide an innovative charging mode for electric vehicles so that they do not deviate from the route on the expressway. The modelling, analysis and simulation experiments of the system show that the system is feasible and can effectively help the electric vehicle to charge in time during the journey. In order to better predict the future charging technology of electric vehicles, Li et al. (2021) proposed a quality factor for evaluating the performance of wireless chargers based on the broadband gap device. The research proposed a road map prediction of electric vehicle charging technology through this quality factor, which is of great significance to the development of electric vehicle charging technology (Li et al., 2021).

In addition to the above methods, many teams have conducted research on the charging performance of electric vehicles. Aiming at the problem of unstable fast charging of lithium-ion battery in high and low temperature environment, Tang et al. (2021) proposed the research idea of high-power fast charging method in high and low temperature environment under the content of lithium-ion power battery thermal management system, which provides a reference for the research of fast charging algorithm of lithium-ion power battery in all climate. In order to solve the charging congestion in charging stations, Zhou et al. (2021) proposed a road electricity coupling network model based on hierarchical graph theory and a network weight calculation method. The network model includes road network layer and power network layer. This method can improve the running state of the coupling network and adjust the charging load reasonably. A circuit electricity coupling network model and a network weight calculation method based on hierarchical graph theory are proposed. Then, based on the time and space distribution of the charging load and the weight of the coupling network, an optimal charging decision-making model is established, and the optimal charging time and the minimum charging cost are proposed. The simulation results verify that this method can effectively alleviate the charging congestion and improve the overall operation of the circuit electric coupling network (Zhou et al., 2021). Liu et al. (2019) proposed an adaptive control algorithm to optimise and adjust the charging power of electric vehicles and the power supply ratio of the power supply to solve the problem of excessive load on the charging line of electric vehicles. The algorithm takes into account the charging satisfaction of electric vehicle users, the load pressure of wireless charging road, power supply cost and power supply stability. By training the neural network to estimate and minimise the long-term cost function, an approximate optimal control strategy is obtained. The simulation results show that this method can take into account the user's charging satisfaction and the load pressure of the charging road (Liu et al., 2019).

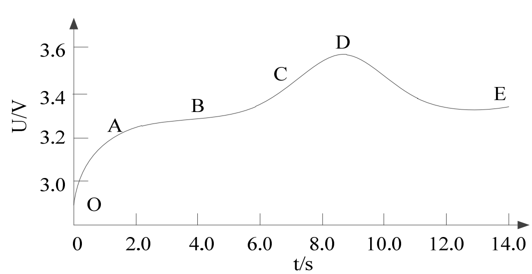
According to the above analysis, there are not only many methods applied in the field of electric vehicle charging, but also many methods to improve the charging performance of electric vehicles. However, at present, electric vehicles still have the problems of high cost and poor charging stability, which cannot effectively realise efficient and fast charging. Therefore, a new optimal charging method for parallel power battery of intelligent electric vehicle is proposed in this paper.

2 Electric vehicle battery charging process and its influencing factors analysis

2.1 Analysis of charging process of electric vehicle battery

During the charging process of intelligent electric vehicles, the battery voltage will change with time. When the electric vehicle battery is charged by the traditional constant current method, the change law of the terminal voltage with time is the charging voltage characteristic curve, as shown in Figure 1.

Figure 1 Battery voltage characteristic curve during charging



In Figure 1, OA is the initial stage of charging. During this period, due to the intense electrochemical reaction of the battery, the terminal voltage of the battery rises rapidly. AB is the middle stage of charging. During this period, the electrochemical reaction of the battery gradually reaches an equilibrium state, the terminal voltage of the battery rises slowly; as the charging continues, the battery will generate gas due to side reactions, which leads to the rise of the terminal voltage of the battery, which is shown as the BC stage in the figure. When the charging curve reaches the CD stage, the main reaction and side reactions of the battery are saturated, and the terminal voltage of the battery is the highest value; after charging is stopped, the terminal voltage of the battery will drop by a small value due to the disappearance of the polarisation phenomenon. It tends to equilibrium again, which is shown as DE phase in the figure.

The whole charging process can be divided into three stages:

1 High-efficiency stage: In this stage, the active materials at the two poles of the battery react violently, and the charging rate is high, close to 100%.

2 Mixing stage: In this stage, the main and side reactions of charging are carried out simultaneously, and the charging rate is gradually reduced. When the bipolar reaction reaches an equilibrium state, the battery tends to be fully charged (Prasad and Krishnamoorthy, 2019).

3 Gas evolution stage: At this time, the battery is fully charged, and only side reactions and self-discharge reactions are left.

2.2 Modelling analysis of influencing factors of electric vehicle charging load

According to the characteristics of the charging process of the battery of the electric vehicle, the influencing factors of the charging load of the electric vehicle are further analysed. The charging load of electric vehicles is affected by many factors, including the combined effect of many factors such as the electric vehicle's own conditions, charging facilities, and user habits (Verma et al., 2019). The influencing factors of electric vehicle charging load can be summarised into three aspects: vehicle performance, charging facilities and driving characteristics (Chauhan et al., 2022). In order to facilitate the research, some key influencing factors of charging load are reasonably selected, and mathematical probability and statistical models are established respectively.

2.2.1 Initial charging time

The initial charging time is very closely related to the user's driving characteristics. Generally speaking, the user will choose the time when the trip ends in each period of the day as the initial charging time. As far as the current situation is concerned, the pattern of large-scale popularisation of electric vehicles has not yet been completed, and there is still a lack of relevant data on the driving of electric vehicles. Therefore, in this paper, the travel characteristics of traditional fuel vehicles are used to replace the travel characteristics of electric vehicles, and the travel characteristics of electric vehicles can be roughly obtained by analysing the travel characteristics of traditional fuel vehicles (Chaudhari et al., 2018).

Through data fitting processing, it is obtained that the end time of the last trip of the car satisfies the normal distribution shown in equation (1):

$$D_u(t) = \exp\left(\frac{|t|^2}{\eta_z}\right) \times \frac{1}{\sqrt{\lambda_z}} \tag{1}$$

Among them, t represents the end time of the last trip, that is, the starting charging time; η_z represents the expectation of the end time of the last trip; λ_z represents the standard deviation of the end time of the last trip. η_z and λ_z vary with the driving characteristics of different types of vehicles.

2.2.2 Daily mileage

The daily driving mileage is an important indicator of the driving characteristics of an electric vehicle, which reflects the power consumption of the vehicle in one day, which in turn affects the charging time of the electric vehicle. Generally speaking, the size of the daily mileage is positively related to the charging time (Ji et al., 2020). In the same way, the travel characteristics of traditional fuel vehicles are used to replace the travel characteristics of electric vehicles for analysis.

Similar to the analysis of the initial charging time in Section 2.2.1, it can be deduced from the NHTS data that the daily mileage of an electric vehicle satisfies equation (2):

$$D_k(t) = \exp\left(\frac{\ln L - \lambda_k}{\eta_k}\right) \times \frac{1}{G^2\sqrt{\lambda_k}} \tag{2}$$

Among them, L represents the daily mileage in km; λ_k represents the expectation of ln L; η_k represents the standard deviation of ln L. λ_k and η_k vary with the driving characteristics of different types of vehicles.

2.2.3 Charging power

As lithium battery has the advantages of high energy, long service life, light weight and green environment protection, most electric vehicles currently use lithium battery, and the charging process of lithium battery is a constant voltage and constant current two-stage charging process (Li et al., 2020). In order to simplify the analysis, constant power is used to replace the charging power of the whole charging process. In addition, the charging power of electric vehicles is also related to charging facilities and charging modes. At present, the main charging modes of electric vehicles are slow charging, conventional charging and fast charging (Quddus et al., 2019). This paper selects the corresponding charging mode according to the driving characteristics of different types of electric vehicles.

2.2.4 Charging time

Both the charging time and the initial charging time jointly determine the charging time period, and the charging time is restricted by many factors, which can generally be derived from the daily mileage and the initial state of charge (Domínguez-Navarro et al., 2019).

If the charging time is calculated based on the state of charge, there is the following equation:

$$T_w = \frac{R(\phi - SOC)}{E_w \lambda} \tag{3}$$

Among them, T_w represents the charging time, the unit is h; ϕ represents the expected state of charge after the charging is completed (generally full, ϕ is taken as 1); *SOC* represents the initial state of charge; *R* represents the battery capacity, the unit is kW h; E_w represents the charging power, the unit is kW; λ represents the charging efficiency, generally taken as 0.9.

Since the probability distribution of the initial state of charge is very random, it varies with different types of electric vehicles. In general load forecasting methods, the value of SOC is usually given subjectively by humans, which lacks scientificity. In this paper, the charging time is calculated based on the daily mileage, as shown in equation (4):

$$T_w = \frac{L\phi_{100}}{100E_w\lambda} \tag{4}$$

Among them, ϕ_{100} represents the power consumption per 100 km traveled by the car, in (kW h)/100 km. The daily mileage can be obtained by scientifically fitting the data of the driving characteristics of the vehicle to obtain its probability distribution, which is more objective and desirable in comparison.

As mentioned above, the daily mileage *L* follows the log-normal distribution shown in equation (2). According to the nature of the normal distribution, the charging time T_w is a linear combination of the daily mileage *L*, which also conforms to the log-normal distribution, namely:

$$D_{kw}(t) = \eta_{kw}(1-\lambda_{kw}) \tag{5}$$

Among them, λ_{kw} represents the standard deviation of the charging time; η_{kw} represents the expectation of the charging time, and its expression is:

$$\lambda_{kw} = \ln\frac{\phi_0\left(100E_w\lambda\right)}{\lambda_{kw}} \tag{6}$$

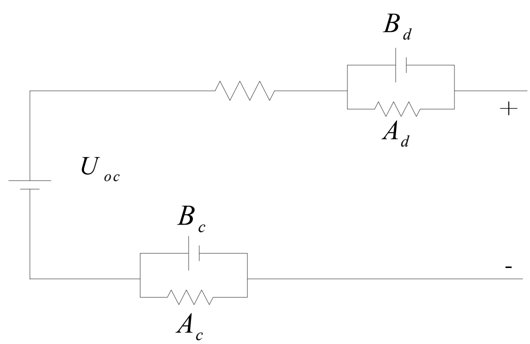
2.3 Balanced charging of electric vehicles

A reasonable charging mode and efficient equalisation topology are the basis for realising the rapid equalisation charging of battery packs. Therefore, on the basis of fully considering the factors affecting the charging load of electric vehicles, the existing charging methods and equalisation circuits are analysed. According to the analysis results, the battery equivalent circuit model is established, and the advantages and disadvantages of the equalisation scheme are verified through simulation to obtain the optimal equalisation charging scheme.

2.3.1 Equivalent circuit model

There are four commonly used battery models: electrochemical model, thermodynamic model, coupled model and equivalent circuit model. The establishment of the first three models requires in-depth research on the electrochemical mechanism of the battery, and is relatively complex, with too many factors to be considered, and is generally not used in the online management of electric vehicle power batteries. The equivalent circuit model (Xu et al., 2021) is based on the basic working principles of different types of batteries, and uses circuit elements such as voltage sources, current sources, resistors, capacitors, and inductors to form a circuit network with a certain structure to simulate the dynamic characteristics of batteries. It can be closely combined with modern control theory to derive the state equation of the model, so as to analyse the state of the battery and the dynamic response under the current excitation. It has good applicability and is widely used in the field of vehicle power battery research (Miniguano et al., 2019). Typical equivalent circuit models include Rint model, Thevenin model, PNGV model and second-order nonlinear circuit model. The Rint model is rarely used due to its simplicity. As the cycle of PNGV model proceeds, the model calculation results show a divergent trend, and the accuracy becomes worse and worse. Therefore, this paper chooses the second-order nonlinear circuit model. Because in the battery equivalent circuit model, the accuracy of the second-order RC model is much higher than that of the first-order RC model, and in order to more accurately simulate the dynamic process of the battery voltage, an RC network branch is added to the second-order nonlinear circuit model to form the second-order RC model circuit. The structural diagram is shown in Figure 2.

Figure 2 Schematic diagram of the circuit structure of the second-order RC model



In Figure 2, A_c and B_c are used to simulate the concentration polarisation effect of the battery, and A_d and B_d represent the electrochemical polarisation effect of the battery. The state equation of the second-order RC model is as follows:

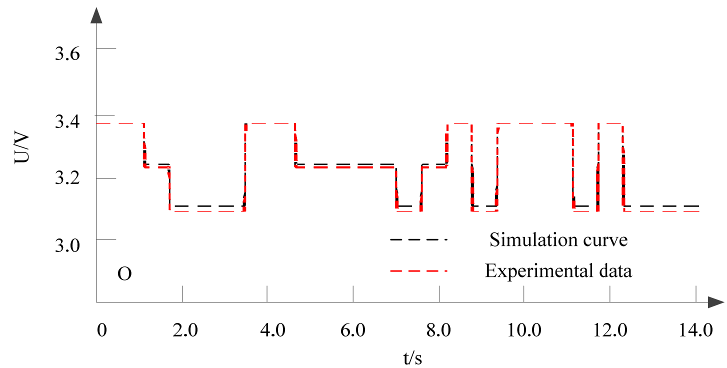
$$\begin{cases} U_c = -\dfrac{1}{B_d \cdot A_c} \\ U_d = -\dfrac{1}{B_d \cdot A_d} \end{cases} \tag{7}$$

Among them, U_c and U_d both represent the battery voltage state.

2.3.2 Model validation

According to the state equation of the second-order RC equivalent circuit model, the battery dynamic model is established in MATLAB/Simulink. In order to verify the accuracy of the model, a specific circuit including charging, discharging and static phases is selected for testing. The rated voltage of the actual circuit is 3.4 V, and the actual measured battery terminal voltage value is compared with the voltage value calculated by the model, as shown in Figure 3.

Figure 3 Accuracy test results of the second-order RC equivalent circuit model (see online version for colours)



It can be seen from Figure 3 that the voltage curve of the simulation model is basically consistent with the voltage curve obtained from the experiment, indicating that the parameters of the second-order RC model obtained at room temperature are reasonable and the model has high accuracy (Kıvrak et al., 2020).

3 Design of optimal battery charging method

3.1 Optimisation of battery parameters

Through the above derivation, after the equivalent circuit model is determined, based on the simulation platform of CRUISE, the battery parameters are optimised for the purpose of optimising the fuel consumption under the cycle conditions of the whole vehicle and meeting the dynamic performance standards (Zhang et al., 2021). AVL cruise software is an advanced simulation and analysis software used to study vehicle dynamics, fuel economy, emission performance and braking performance. The model generator can be used to establish the required vehicle system model and conduct simulation analysis on this basis. The optimal parameters of each model are determined by the results of simulation analysis. Firstly, the relationship between the battery capacity and the equivalent fuel consumption of smart electric vehicles is studied, and the battery capacity is used as the optimisation parameter to obtain the relationship between the battery capacity, fuel consumption and SOC, as shown in Figure 4.

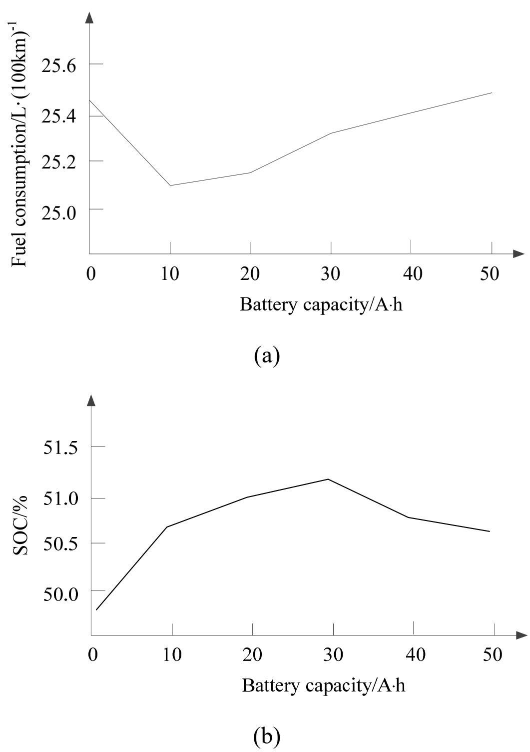
As shown in Figure 4, with the increase of battery capacity, the fuel consumption tends to decrease first and then increase, while the percentage of SOC tends to increase first and then decrease. In addition, it can also be found that when the battery capacity is 10, the fuel consumption is the lowest, and when the battery capacity is 30, the percentage of SOC is the highest. Since the energy storage conditions of the two energy sources in the smart electric vehicle have changed, the total energy consumption cannot be directly reflected. Therefore, the change of the SOC of the battery must be converted into the change of the equivalent fuel consumption. Calculate the change E_{SOC} of battery energy from the change Δ_{SOC} of the battery SOC, and obtain the equivalent fuel consumption Δ_{OC} by converting the coefficients such as battery charging efficiency, generator efficiency, engine efficiency, and diesel calorific value. The calculation equation is:

$$E_{SOC} = 3600\Delta_{SOC} P_d \overline{U_d} \tag{8}$$

$$\Delta_{OC} = E_{SOC} / 850(\theta_j \psi_h) \tag{9}$$

Among them, $\overline{U_d}$ represents the average voltage of the battery; θ_j represents the average charging efficiency of the battery, and ψ_h represents the average efficiency of the generator. After several simulation results, the optimal average charging efficiency is 0.94, and the average efficiency of the optimal generator is 0.83. According to the above parameter settings, the optimisation of the battery parameters of the smart electric vehicle is realised.

Figure 4 Relationship between battery capacity and fuel consumption and SOC, (a) battery capacity and fuel consumption (b) battery capacity and SOC

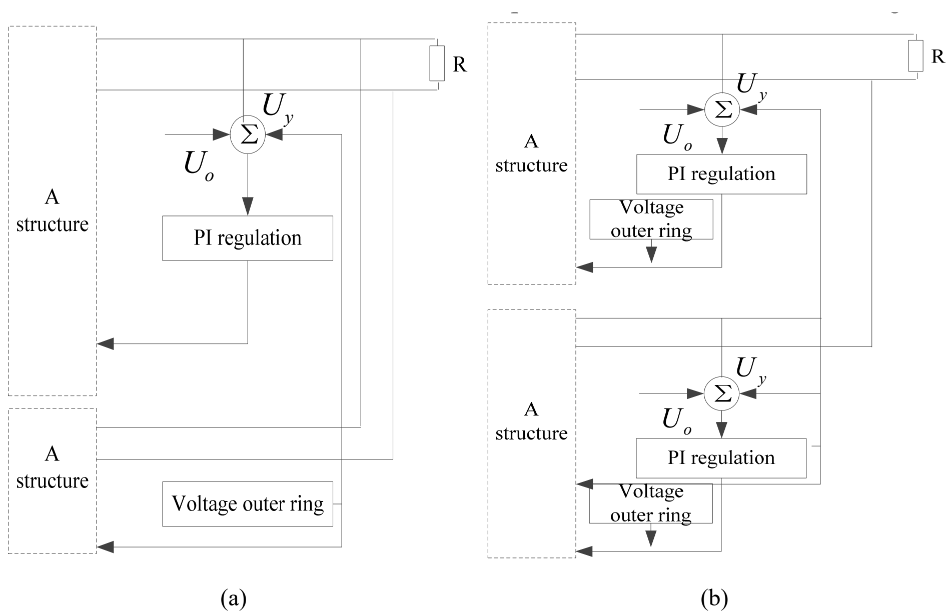


3.2 Battery current optimisation control

Under normal circumstances, the output resistance of each parallel module of the smart electric vehicle battery is a constant value, and the unbalanced output current is mainly caused by the unequal output voltage of each module. The basic idea of current sharing is to sample the respective output current signals and introduce the signals into the control loop to participate in adjusting the output voltage.

The charging module in the current control mode can automatically equalise the current without additional methods. Its implementation principle is that the sampling voltage U_y is taken at the secondary output of the parallel module. According to the same given voltage U_o, each U_y and U_o outputs the control voltage U_p through the PI regulator, U_p as the given U_{io} of the inner loop current regulator, and the input current I_c of the inverter bridge is the current feedback of the inner loop current regulator, which is adjusted by the PI of the current regulator to output the PWM signal, as shown in Figure 5.

Figure 5 Schematic diagram of multi-module current control mode regulation, (a) multiple modules share the same voltage outer ring (b) multiple modules each use a voltage outer loop



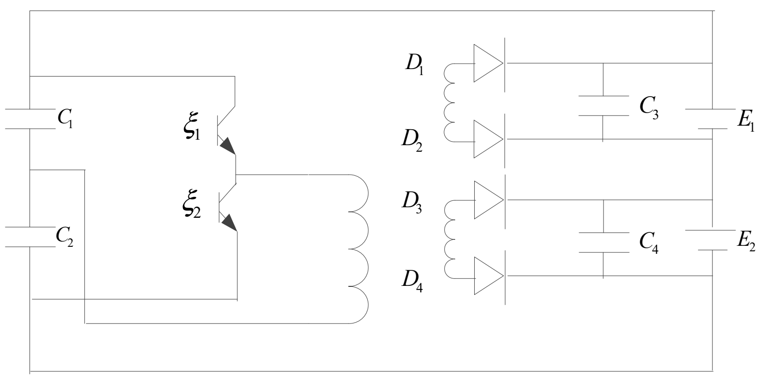
The control principles of these two parallel methods are as described above. The adjustment method of multiple modules sharing the same voltage control outer loop is that each module uses the same voltage control outer loop to adjust the current control inner loop according to U_o, while multiple modules use the same voltage control loop. A voltage control outer loop adjustment method is that each module is adjusted by its own voltage control outer loop according to U_o to perform current control inner loop adjustment. Finally, the effects of current sharing and voltage regulation are achieved.

3.3 Electric vehicle battery equalisation charging

The commonly used equalisation charging has two forms: centralised equalisation and independent equalisation. Among them, the centralised equalisation charging controls the switching of the relay network by the equalisation control unit to realise the equalisation charging control of the same equalising charging unit to different single batteries. Although the charging hardware equipment is simple in this method, the relay network control logic requirements are high, and only one battery in the battery pack can be charged equally at a time, and the equalisation efficiency is low. The independent equalisation charging has several equalising charging units, and each equalising charging unit is controlled by the distributed equalising control unit to perform equalising charging on a battery or a group of batteries. Compared with centralised equalisation charging, the hardware is complex and the equipment cost is high, but equalisation charging has a high degree of automation and flexible control, and can perform equalisation processing on multiple batteries at the same time.

Figure 6 shows the advantages of the above structure for the inverter voltage divider equalisation charging. The transformer is decoupled with multiple secondary sides. Each inverter secondary side approximates a constant voltage source equalisation unit to equalise a battery in the battery pack. All secondary-side equalisation units control the pulse width of ξ_1 and ξ_2 by the main controller to realise the adjustment of the equalising charging characteristics, which greatly simplifies the control logic and hardware structure.

Figure 6 Schematic diagram of the principle of inverter voltage divider equalisation charging



Resistance balancing and energy storage balancing are the most commonly used balancing methods for smart electric vehicle batteries that do not require additional energy. Resistance balancing generally uses a resistor network to automatically divide and balance the battery pack. This method can automatically balance multiple batteries at the same time. Controls are simple. However, if the resistance is too large during the equalisation process, the equalisation current will be too small, and the effect will be minimal; if the resistance is selected too large, the energy consumption of the system will be large, the equalisation efficiency will be low, and the system will have high requirements for thermal management.

In view of the above problems, this paper improves the battery balancing method based on the equivalent circuit model constructed in Section 2.3. The battery balancing method adopted is mainly to use the battery to charge and discharge energy storage elements such as inductors or capacitors, and realise the switching of energy storage elements between unbalanced batteries through relays or switching devices to achieve energy transfer between batteries.

To sum up, in order to realise the optimal charging of the parallel power battery of the smart electric vehicle, this paper optimises the battery charging effect and improves the performance of the electric vehicle from the three perspectives of battery parameter selection, battery current control and battery equalisation charging.

4 Experimental analysis

In order to verify the effectiveness of the proposed optimal charging method for parallel power batteries of smart electric vehicles, an experimental analysis is carried out.

4.1 Experimental platform and parameter settings

According to the experimental requirements, an experimental platform is designed. The whole experimental platform includes the following parts: controllable AC power supply, charging load group, protection control device, and central control system. Wherein, the controllable AC power supply can provide a controllable single-phase or three-phase AC power supply to the charging device. The protection control device is mainly composed of a programmable controller and various switching devices. It can automatically switch on and off the equipment according to the system instructions, and at the same time monitor the system in real time, and cut off the circuit when the system is overcurrent, overvoltage or other equipment is abnormal to protect the system equipment. The central control system is equipped with multiple communication interfaces, including the CAN communication interface with the charging equipment, to realise remote control of other equipment, monitor the working status of other equipment in real time, and automatically control the orderly progress of the experiment.

Table 1 Experimental platform parameters

Parameter	*Specification*
Rated voltage	320 V
Rated capacity	25 Ah
Battery specifications	15 * 6 + 10 * 1, a total of 7 modules in parallel
Overcharge protection voltage	3.65 V
Communication interface	CAN bus
Input power	5 kw
Input voltage	0~500 V
Maximum discharge power	65 kw

The selection of the hardware equipment of the experimental platform is mainly determined according to its functional requirements, and the final plan is determined according to the actual laboratory environment and economic conditions. Table 1 shows the specific parameters of the experimental platform.

According to the above platform, the experimental operation is carried out. In the experiment, the high-power fast charging method of lithium-ion power battery for electric vehicles and the EV charging decision optimisation method based on the road-electric coupling network are used as comparison methods, and the comparison and analysis are carried out with the proposed method.

4.2 Analysis of results

4.2.1 Comparison of charging time and state of charge

In order to compare the performance of the charging methods, the charging time and the charging state are used as evaluation indexes. Use three methods to charge the battery. Charge the battery and stop charging when the battery voltage reaches 3.65 V. The comparison results of the charging time and state of charge of the three methods are shown in Table 2.

Table 2 Comparison results of charging time and state of charge

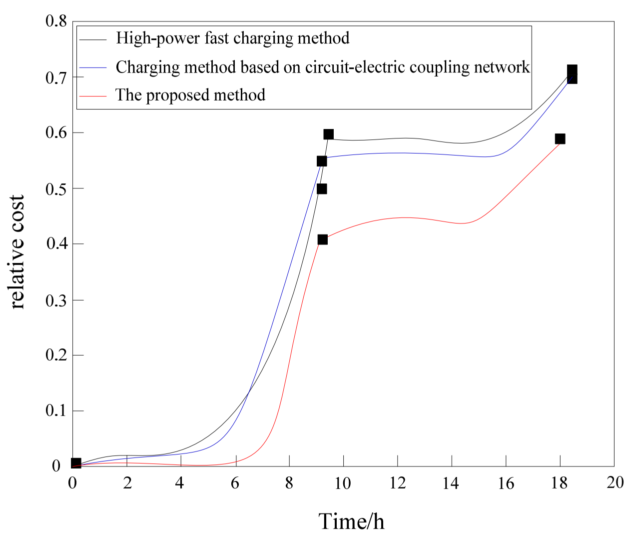
Method	*Charging time/min*	*State of charge/%*
High-power fast charging method	45	75.9
Charging method based on circuit-electric coupling network	89	90.9
The proposed method	32	93.6

It can be seen from Table 2 that although the charging time of high-power fast charging method is short, its state of charge is low. Although the charging method based on the circuit electric coupling network can obtain a higher state of charge, its charging time is too long. Considering the charging time and state of charge, the proposed method can achieve the purpose of efficient and fast charging, and is a truly suitable charging method for electric vehicle power battery.

4.2.2 Comparison of relative cost and charging stability

Figures 7 and 8 are graphs showing the relative cost and charging stability of EV charging.

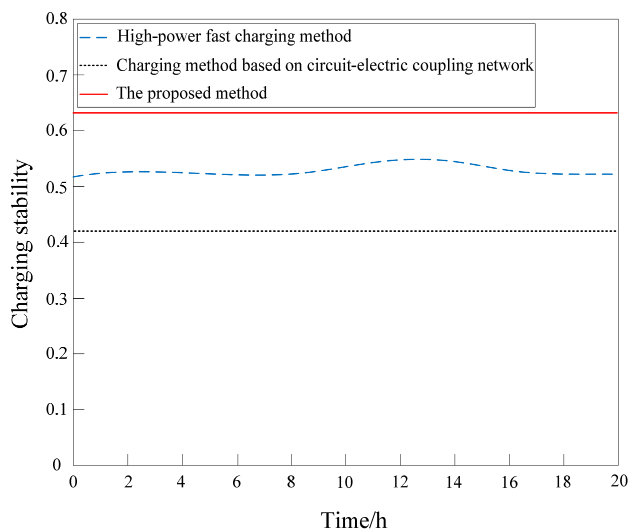
Figure 7 Relative cost of EV charging (see online version for colours)



It can be seen from Figure 7 that the relative cost of the proposed method is the lowest among the three charging methods, with a value of 0.58, which is lower than 0.71 of the high-power fast charging method and 0.70 of the charging method based on the circuit electric coupling network. The results show that from the perspective of the relative cost of charging, the method proposed in the study has better performance and can reduce the charging cost of electric vehicles.

It can be seen from Figure 8 that among the three charging methods, the charging stability of the proposed method is the highest, with a value of 0.62, which is much higher than that of the high-power fast charging method of 0.51 and that of the circuit electric coupling network-based charging method of 0.42. The results show that the performance of the proposed method is better from the perspective of charging stability. Using this method to charge electric vehicles can improve the stability of vehicle charging. From the above results, the proposed method has high stability and low cost, which is conducive to the prevention and control of power failure or fluctuation. The experimental results show that the proposed method can fully meet the stability and cost requirements of smart electric vehicle charging at the same time, and has high application value.

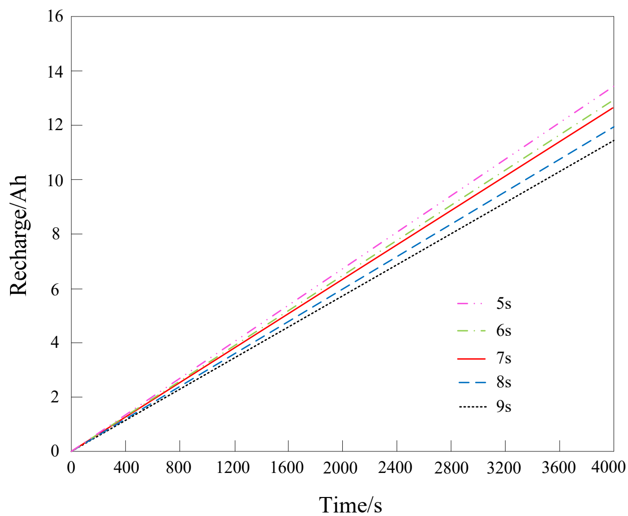
Figure 8 Charging stability (see online version for colours)



4.2.3 Experimental study of discharge negative pulse width

Adding a negative pulse of an appropriate time during the charging process of the power battery can effectively eliminate or suppress the polarisation effect and prolong the duration of high-current charging. Therefore, the width of the negative discharge pulse is also a very critical physical quantity. The setting of the negative discharge pulse width should take into account the chemical reaction speed of the power battery itself. If the discharge time is too short, that is, the pulse width is too small, the battery has not had time to change, and the discharge pulse has ended, so the purpose of improving the polarisation effect of the battery cannot be achieved. If the discharge time is too long, that is, the pulse width is too wide, although it can improve the polarisation phenomenon, it also increases the time required for the overall charging, which contradicts the rapidity principle of charging requirements. Therefore, how to choose the proper width of the discharge negative pulse is also an important part of this method. For each method tested in the experiment, new batteries of the same batch and model were selected for testing. In order to eliminate the chance brought by a single experiment, during the experiment, the same method was used to test the same battery 20 times, and the average value was taken as the final experimental value.

Figure 9 Charging effect under different discharge negative pulse widths (see online version for colours)



According to the principle of Maas's third law, combined with the data parameters of the battery manual, the experiment uses a charging current of 18 A, the charging duration is 50 s, and the negative pulses with discharge durations of 5 s, 6 s, 7 s, 8 s, and 9 s are used to carry out comparative experiments on the batteries. After charging, put the battery on hold for 3 hours, and then discharge the battery with a constant current of 3.3 A until the voltage reaches 2.5 V to detect the amount of power that the battery can discharge in different charging modes. At the same time, in order to check the actual charging capacity, after each charge, leave the battery for 3 hours and then discharge the battery with a constant current. Record the relevant data during the charging and discharging process of the battery, and obtain the corresponding experimental curves and data as shown in Figure 9.

It can be seen from Figure 9 that the charging methods with different discharge pulse widths have the same charge amount in the power battery, but the narrower the negative discharge pulse width, the shorter the time required for the battery to reach the maximum allowable charge voltage. The whole charging process shows that the proposed method has the fastest charging speed. This shows that this method can not only improve the charging stability of the power battery of the intelligent electric vehicle, but also improve the charging efficiency and reduce the charging cost.

5 Conclusions

The power battery pack for electric vehicles is composed of multiple single cells in series and parallel. During the working process, the slight differences in the initial stage of the single cells will be continuously amplified under the action of each charge and discharge. The inconsistency of the bulk battery will gradually increase, which in turn leads to a decrease in the capacity utilisation rate of the battery pack and a shortened cycle life. Therefore, it is of practical significance to design an optimal charging method for parallel power batteries of smart electric vehicles. The proposed charging method is compared with the high-power fast charging method and the charging method based on the circuit electric coupling network. The experimental results show that the relative cost of the proposed method is 0.58, which is better than the high-power fast charging method and the charging method based on the circuit electric coupling network. The charging stability of the proposed method is 0.62, which is also better than the other two charging methods. Experiments have verified that this method has the advantages of stability, high efficiency, and high economic value, which can improve the efficiency of charging and reduce the cost of charging.

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